Modelling of spatio-temporal precipitation relevant for urban hydrology with focus on scales, extremes and climate change

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DTU Environment
Department of Environmental Engineering

PhD Thesis
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The synopsis part of this thesis is available as a pdf-file for download from the DTU research database ORBIT: http://www.orbit.dtu.dk

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Preface

This thesis presents the outcome of a PhD project carried out in collaboration between the Department of Environmental Engineering (DTU Environment), Technical University of Denmark (DTU) and the Danish Climate Centre at the Danish Meteorological Institute (DMI), in the period from December 2010 to September 2014. The project was supervised by Professor Peter Steen Mikkelsen (DTU Environment), Senior Researcher Ole Bøssing Christensen (DMI) and Professor Karsten Arnbjerg-Nielsen (DTU Environment). The PhD project was funded by the Danish Council for Independent Research through the collaborative PhD scholarship project "Reducing Uncertainty of Future Extreme Precipitation", contract no. 09-067455.

The thesis is organized in two parts: the first part summarises the main findings of the PhD and places them in the context of the international literature; the second part consists of the papers listed below. These will be referred to in the text by their paper number written with the Roman numerals **I-V**.

I **Sørup H.J.D.**, Lerer S.M., Arnbjerg-Nielsen K., Mikkelsen P.S. and Rygaard M. (in prep) Efficiency of alternative stormwater control measures: How the "Three Points Approach" (3PA) can guide the interpretation of strategic management approaches for rainwater harvesting, stormwater drainage and flood risk management.

II Sunyer M.A., **Sørup H.J.D.**, Christensen O.B., Madsen H., Rosbjerg D., Mikkelsen P.S. and Arnbjerg-Nielsen K. (2013) On the importance of observational data properties when assessing regional climate model performance of extreme precipitation. Hydrology and Earth System Sciences, 17, 4323-4337.

III **Sørup, H.J.D.**, Madsen, H. and Arnbjerg-Nielsen, K. (2012) Descriptive and predictive evaluation of high resolution Markov chain precipitation models. Environmetrics, 23(7) 623-635.

IV Gregersen I.B., **Sørup H.J.D.**, Madsen H., Rosbjerg D., Mikkelsen P.S. and Arnbjerg-Nielsen K. (2013) Assessing future climatic changes of rainfall extremes at small spatio-temporal scales. Climatic Change, 118(3-4), 783-797.

V **Sørup H.J.D.**, Christensen O.B., Arnbjerg-Nielsen K. and Mikkelsen P.S. (in prep) Downscaling future precipitation extremes to urban hydrology scales using a spatio-temporal Neyman-Scott weather generator.

In addition, the following publications, not included in this thesis, were also concluded during this PhD study:

Christensen O.B., Yang S., Boberg F., Maule C.F., Olesen M., Drews M., **Sørup H.J.D.** and Christensen J.H. (in review) Europe in a 6 Degrees Warmer Climate.

Mayer S., Maule C.F., Sobolowski S., Christensen O.B., **Sørup H.J.D.**, Sunyer M. Arnbjerg-Nielsen K. and Barstad I (in review) Identifying added value in high-resolution climate simulations over Scandinavia.

Sørup H.J.D., Arnbjerg-Nielsen K., Mikkelsen P.S. and Rygaard M. (2013) Quantitative potentials for rainwater handling using the "Three Points Approach" (3PA).In Proceedings. NOVATECH 2013: 8th International Conference on Planning and Technologies for Sustainable Urban Water Management, June 23-27. Lyon, France.

Sørup H.J.D., Christensen O.B., Arnbjerg-Nielsen K. and Mikkelsen P.S. (2012) Evaluation of high resolution spatio-temporal precipitation extremes from a stochastic weather generator. In: Urban Challenges in Rainfall Analysis, UrbanRain12: 9th International Workshop on Precipitation in Urban Areas, December 6-9, St. Moritz, Switzerland. Proceedings, CD-ROM, pp. 27-31. ETH, Zürich.

Sørup H.J.D., Madsen H. and Arnbjerg-Nielsen K. (2011) Markov chain modeling of precipitation time series: Modeling waiting times between tipping bucket rain gauge tips. In: Proceedings of the 12th International Conference on Urban Drainage, September 11-16, Porto Alegre, Brazil. CD-ROM.

In this online version of the thesis, the papers are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from.

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I would like to thank all my colleagues at DTU Environment and at DMI for making office life interesting, fun and more than just work. Moreover, I would like to thank my collaboration partners from the Bjerknes Centre for Climate Research, DHI, DTU Compute and DTU Management for valuable discussions and fruitful collaborations.

Finally, I would like to thank my family for putting up with me in stressed times and supporting me through this journey.

"Essentially, all models are wrong, but some are useful."

- George Edward Pelham Box

Summary

Time series of precipitation are necessary for assessment of urban hydrological systems. In a changed climate this is challenging as climate model output is not directly comparable to observations at the scales relevant for urban hydrology. The focus of this PhD thesis is downscaling of precipitation to spatio-temporal scales used in urban hydrology. It investigates several observational data products and identifies relevant scales where climate change and precipitation can be assessed for urban use. Precipitation is modelled at different scales using different stochastic techniques. A weather generator is used to produce an artificial spatio-temporal precipitation product that can be used both directly in large scale urban hydrological modelling and for derivation of extreme precipitation statistics relevant for urban hydrology.

It is discussed why precipitation time series from a changed climate are necessary for assessment of urban hydrological systems under climate change. For this, a quantification of the tool "Three Points Approach" is introduced along with a municipal water balance approach. This is done to highlight why it is important to assess the performance of urban water structures for all possible weather and not only for extreme precipitation where problems are expected.

Observational data is investigated at different spatio-temporal scales and relevant scales for assessment of climate change for urban application are identified.

Four different observational data sets of precipitation are compared and used to rank climate models with respect to performance metrics. The four different observational data sets themselves are compared at daily temporal scale with respect to climate indices for mean and extreme precipitation. Data density seems to be a crucial parameter for good representation of extreme precipitation and gridding lowers the peak levels of the extremes.

Measurements from a tipping bucket rain gauge are investigated and modelled at the temporal scale of minutes using Markov chain models. The noise at this temporal scale is considerable and the model framework is not considered feasible for spatial application and inclusion of climate change.

Correlated point measurements are compared to regional climate model output and the spatial correlation structure of extreme precipitation at the event level is assessed for both. Clearly, regional climate models have too long de-

correlation lengths for sub-daily extreme precipitation besides having too low intensities. Especially the wrong spatial correlation structure is disturbing from an urban hydrological point of view as short-term extremes will cover too much ground if derived directly from bias corrected regional climate model output.

A weather generator is introduced to statistically downscale precipitation to urban scales. The weather generator is fitted using data from a dense network of tipping bucket rain gauges. The weather generator is operated at hourly time step and generates output on a 2 km grid. The output from the weather generator performs very well when compared to observations both with respect to absolute intensities and spatial correlation of precipitation extremes at event level. Furthermore, the weather generator is able to produce an output with a realistic seasonal behaviour with most of the hourly extremes happening in summer and most of the daily extremes in fall. This behaviour is in good accordance with reality where short term extremes originate in convective precipitation cells that occur when it is very warm and longer term extremes originate in frontal systems that dominate the fall and winter seasons.

The weather generator is perturbed with climate change signals derived from six different regional climate model runs. The regional climate model runs represent several emission scenarios, RCMs, GCMs and spatial model resolution and result in six very different perturbation schemes. Even so, the resulting precipitation outputs have comparable extremes for comparable emission scenarios and the estimated change in extremes is in accordance with other studies for the area. The study furthermore shows that there is no simple scaling between moderate emission scenarios and high-end emission scenarios as the sub daily extremes seem to grow faster in magnitude than the daily and multi daily ones for the high-end scenarios.

This study shows that spatio-temporal data products representing realistic precipitation in a changed climate can be produced at scales relevant for urban hydrology using stochastic weather generators. Good observational data for present conditions are however required as the correlation structures between different time series are important.

If more sophisticated models are to be implemented at finer spatio-temporal scales models including physical behaviour describing precipitation movement and link it to synoptic scale weather are required. Alternatively, very high resolution regional climate models or simplifications hereof could be used for generation of data products at the desired scales.

Dansk sammenfatning

Tidsserier med regndata er nødvendige for at analysere urbanhydrologiske problemstillinger. I et forandret klima giver dette en særlig udfordring, da klimamodeloutput ikke direkte kan sammenlignes med observationer på de skalaer, der er relevante for urban hydrologi. Fokus for denne ph.d.-afhandling er nedskalering af nedbør til rum- og tidsskalaer relevante inden for urbanhydrologi. Afhandlingen undersøger flere forskellige observationsprodukter for at fastslå relevante skalaer, hvor klimaforandringer og nedbør kan behandles i urban sammenhæng. Nedbør bliver modelleret i forskellige opløsninger ved hjælp af forskellige stokastiske teknikker. Et spatialt kunstigt nedbørsprodukt er genereret med en vejrgenerator. Formålet er direkte brug som input til modelsimulationer samt beregning af statistiske størrelse til karakterisering af ekstreme regnhændelser.

I afhandlingen diskuteres, hvorfor tidsserier, der repræsenter et ændret klima, er nødvendige for at forholde sig til urbanhydrologiske systemer udsat for klimaforandringer. Til dette introduceres en kvantificering af værktøjet "trepunktsmetoden" i sammenhæng med vandbalancer. Dette gøres for at sætte fokus på, hvorfor det er vigtigt at analysere effektiviteten af vandinfrastruktur for alle typer hændelser og ikke kun ekstremhændelser, hvor der forventes problemer.

Efterfølgende er observationsdata undersøgt på forskelige rum- og tidsskalaer, og relevante skalaer for vurdering af klimaforandringer inden for urbanhydrologi er identificeret.

Fire forskellige observationsdatasæt for regn sammenlignes og bruges til at rangordne regionale klimamodeller med hensyn til forskelige effektivitetsmål. De fire datasæt er ydermere sammenlignet direkte på daglig tidsskala ved hjælp af forskellige klimaindeks for middel- og ekstremnedbør. Datatæthed ser ud til at være et afgørende parameter for god repræsentation af ekstremer, og udjævning på et gitter sænker ekstremerne betydeligt.

Målinger fra en vippekar-regnmåler bliver undersøgt og modelleret på minutskala ved hjælp af Markovkædemodeller. Støjen på minutskala er betydelig og modellerne anses ikke som anvendelige til at beskrive regns rumlige udbredelse og inklusion af klimaforandringer.

Korrelerede punktobservationer sammenlignes med klimamodeloutput og den spatiale korrelationsstruktur af ekstremer på hændelsesniveau vurderes for

begge. Regionale klimamodellers output på timebasis har for lange spatiale korrelationslængder og for lave ekstremintensiteter. Specielt den forkerte spatiale struktur er foruroligende i urbanhydrologisk sammenhæng. Korttids ekstremer får alt for stor spatial udbredelse, hvis de baseres direkte på justeret output fra regionale klimamodeller.

En vejrgenerator bruges til statistisk nedskalering af nedbør til urbane skalaer. Vejrgeneratoren kalibreres til data fra et tæt netværk af vippekarregnmålere. Vejrgeneratoren opererer på timebasis på et 2km gitter. Dataproduktet fra vejrgeneratoren udmærker sig ved at have sammenlignelige værdier for spatial korrelation og ekstreme intensiteter på hændelsesniveau når det sammenlignes med observationsdata. Vejrgeneratoren er endvidere i stand til at reproducere observerede sæsonvariationer med flest timeekstremer om sommeren og flest dagsekstremer om efteråret. Dette er i god overensstemmelse med at virkelige korttidsekstremer stammer fra konvektive nedbørsceller der optræder når det er varmt, mens ekstremer over længere tid optræder i forbindelse med frontregn som er den dominerende vejrtype om efteråret og vinteren.

Efterfølgende modificeres vejrgeneratoren på baggrund af klimaforandringer taget fra seks forskellige regionale klimamodelkørsler. klimamodelkørslerne repræsenterer forskellige emissionsscenarier, regionale klimamodeller, globale klimamodeller og spatiale modelopløsninger og resulterer i seks meget forskellige modifikationsskemaer. På trods af det har de resulterende nedbørsoutput sammenlignelige ekstremer for sammenlignelige emissionsscenarier og de beregnede klimaforandringer er på linje med tidligere undersøgelser for Danmark. Studiet viser yderligere, at det ikke er muligt umiddelbart at skalerer ekstremer mellem middelemissionsscenarier og højemissionsscenarier da niveauet for timeekstremerne vokser hurtigere end for dagsekstremerne.

Dette studie viser, at det er muligt at generere et spatialt dataprodukt der repræsenterer realistisk nedbør under klimaforandringer på skalaer relevante for urban hydrologi ved hjælp af en stokastisk vejrgenerator. Dette kræver imidlertid gode observationsdata, og den spatiale korrelationsstruktur mellem observationstidsserier er af afgørende betydning.

Hvis mere sofistikerede modeller skal implementeres på endnu finere spatial og tidslig skala er modeller som inkluderer bevægelse af nedbør og kobling til synoptisk vejrskala nødvendige. Alternativt kan regionale klimamodeller med ekstrem høj opløsning, eller forsimplinger af disse, bruges til at generere nedbørsdata på den ønskede skala.

Table of contents

1 Introduction

As urban settlements have grown over the last centuries, densification and increased imperviousness have led to a situation where the urban environment has become less resilient to problems associated with water (Brown et al., 2009). At the same time the world population has increased dramatically, making water a scarce resource many places in the world (Hanasaki et al., 2013). Today, at least in the more wealthy parts of the world, much focus is put on exploiting the existing urban water resource as intelligently and efficiently as possible, resulting in "greening" and "blueing" of existing urban environments (Zhou et al., 2013). This is of course a positive development as "blue-green" cities tend to have a positive impact on human health and society (Roy et al., 2008; Zevenbergen et al., 2008; Brown et al., 2009). But, these improvements have to be implemented alongside flood protection measures as local water infrastructure might alter the urban water paths (Mitchell et al., 2007) depending on the actual weather they are exposed to. To analyse urban infrastructure models are used; models that rely on precipitation data as input.

Precipitation is the result of several atmospheric processes. Hence, it is difficult to understand (and model) in detail at the scales where it is usually measured (Ignaccolo and De Michele, 2011). However, the two important processes advection and convection are relatively well described (Lord and Arakawa, 1980). These are overall responsible for a lot of the characteristics of precipitation considered important in an urban context.

For small scale urban drainage infrastructure the discrete nature of precipitation become ever important; precipitation falls in drops and is as such never uniform in any respect (Ignaccolo and De Michele, 2011). Urban hydrological systems are dynamic systems, and have to be analysed using precipitation time series rather than precipitation statistics. System performance does not always rely solely on individual precipitation events but on the sequence and history of precipitation events (Arnell et al., 1984; Jacobsen et al., 1996; Mikkelsen et al., 2005; Schaarup-Jensen et al., 2009). Furthermore, it is recognised in urban hydrology that the spatio-temporal resolution with which precipitation is measured has great influence on the output from hydrological models (Schilling 1991; Nielsen et al., 2012; Thorndahl and Rasmussen, 2013; Bruni et al., 2014).

In this thesis I distinguish between weather and climate. In brief, the input required to model urban hydrology realistically is weather data. Weather; as

opposed to climate. Weather in the form of time series. Where weather is the sequences of precipitation events, the long time series of data that assure a realistic response of the modelled hydrological system, climate is the long-term statistics one can derive from these data.

Ideally, weather time series are not just point observational time series but a spatially distributed data that represents the actual dynamic behaviour of precipitation in time and space on the surface of the earth (Thorndahl and Rasmussen, 2013). **Figure 1** shows the immense variation in space and time of actual precipitation recordings from a measurement campaign in Lund (Niemczynowicz, 1988). This Figure in many respects highlights why spatio-temporal precipitation is difficult to model and describe. From left to right the differences observed in the hyetographs between gauges represent the difference in precipitation perpendicular to the direction of rainfall movement. The amount of rainfall different parts of the city receive is very different depending on which part of the event they are struck by. From bottom to top the figure illustrates the temporal development of the precipitation event. The similarities in hyetographs are explained as being the same part of the event hitting the different gauges. The lines between hyetographs show how distinguishable features of the rain event are visible at several different gauges and how they change as the event moves. Especially from the 11-5-8-9 sequence it is clear that the peak intensity changes rapidly and is very different from one gauge to another. At the event level precipitation cannot be expected to be uniform in space and time. This is a real issue when climate change is discussed: Climate is statistics of weather, and climate change can be modelled using climate models (General Circulation Models (GCMs) and/or Regional Climate Models (RCMs)). It is not climate that causes the actual problems in urban hydrology; weather does. A changed climate will inevitably result in changes to the weather and changing problems for urban hydrology as a result. How exactly these changes in weather will be depending on the changes in climate, and how to model actual weather with small scale variability similar to the one observed in **Figure 1** under climate change, is a challenge.

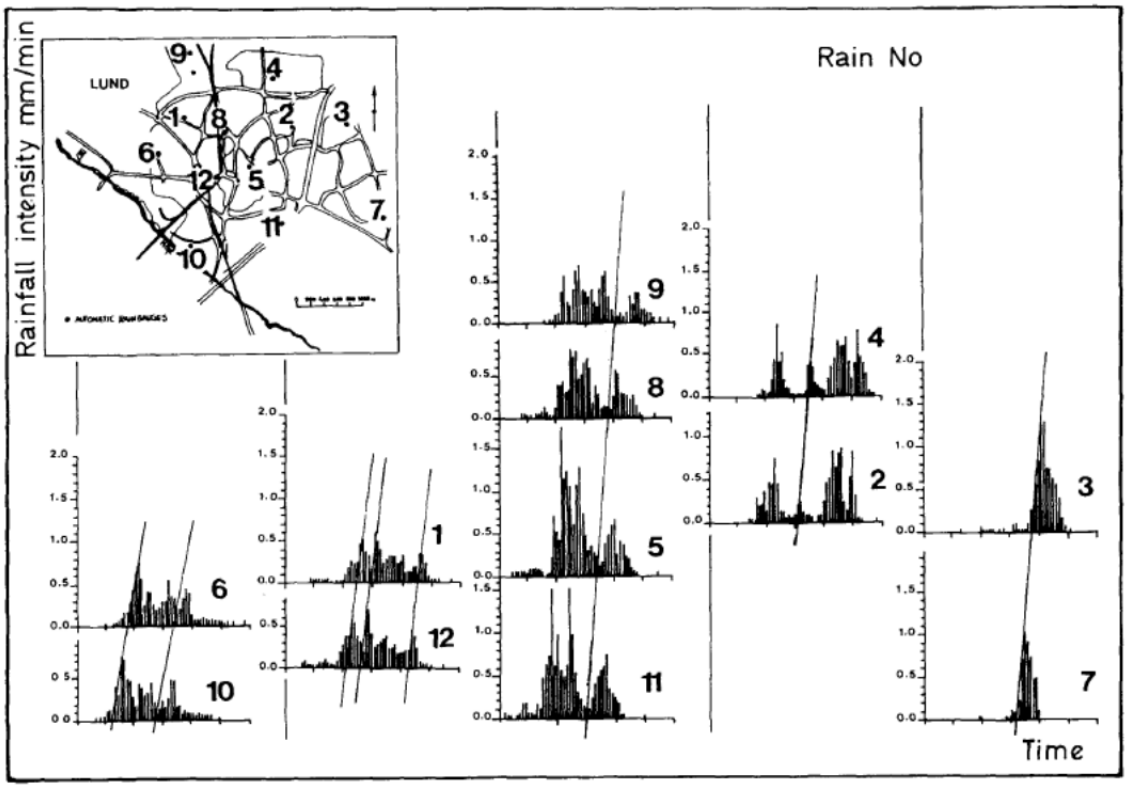

Figure 1 An Example of hyetographs recorded in 12 gauges during one rain event in Lund, Sweden. From Niemczynowicz (1988).

In the present study, the aim is to model spatio-temporal weather under climate change. Precipitation is in the Danish urban hydrological context the only really important part of weather (thus, temperature, wind etc. are excluded). The focus is therefore on spatio-temporal precipitation downscaling. In short, the specific objectives of this study are to:

- Explain using the Three Points Approach why precipitation time series are necessary in addition to extreme event statistics for model based analysis of urban hydrological problems.
- Assess using statistics for extreme precipitation and spatial correlation structure how observational data compare with output from state-of-the art RCM runs.
- Model and downscale precipitation using stochastic techniques at the finest possible temporal scales relevant for urban hydrology.
- Perturb the downscaling model with climate change signals, compare the resulting climate factors against findings from previous studies and evalu-

ate the representativeness and applicability in urban hydrology of the modelled precipitation time series.

Overall, the five papers included in this thesis focus on the four different objectives as listed in **Table 1**. The same structure is generally found for this thesis. Section 2 focusses on motivating this study through the explanation of the three points approach. In Section 3 relevant scales are determined and assessment of data products and modelling of precipitation used to justify these. Section 4 explains downscaling in general and Section 5 how spatio-temporal downscaling of precipitation is done for this study and how the models are perturbed with climate change signals from RCMs. Section 6 holds a discussion to further put the findings into a broader perspective and, finally, Sections 7 holds the conclusions.

Table 1 The specific objectives of this thesis paired with the relevant papers.

	Papers				
	I	**II**	**III**	**IV**	**V**
Explain	X				
Assess		X		X	
Model			X		X
Perturb					X

2 Motivation and framing

Traditionally, different sectors in society have had the responsibility of exploiting the water resource and protecting society from water related problems (Fratini et al., 2012). Today, this leads to misunderstandings and misconceptions between urban planners, engineers, politicians and citizens as there is no shared understanding of how the urban water system is working, what the important features of a modern urban water system are and how these needs are phrased (Fratini et al., 2012). The Three Points Approach (3PA) presented by Fratini et al. (2012) is a tool to describe this problem. It helps the involved stakeholders to form a common lingual platform for interdisciplinary communication regarding urban water management. This is important as there is a fundamental difference between perceiving and managing precipitation in the urban environment as a resource, as a problem potentially causing pollution and surcharge, and as one that causes large floods.

Paper **I** quantifies the 3PA. This is done to showcase how stormwater control measures (see e.g. Fletcher et al, (2014) for terminology) designed for frequent overflows (as in e.g. rainwater harvesting tanks) react when exposed to flood-causing precipitation events they were never designed for. The quantification is done through analysis of precipitation time series from observational rain gauges and classification of events into the three points of the 3PA according to event magnitude and return period, see **Figure 2**. The three points in **Figure 2** delineate three distinct domains where precipitation is handled:

A) Frequent precipitation events with short return periods. All together these represent the largest part of the total annual precipitation volume. Rainwater harvesting and other stormwater control measures are generally designed to handle all events from this domain.

B) Infrequent events with considerably magnitude and return periods of several years. These represent the typical design standard for sewer systems. Systems designed for handling events of this size will, on an annual volumetric basis, be able to handle almost all precipitation.

C) Extremely rare events with very long return periods and very high magnitude. These events cause floods as the cost of preventing them are higher than the damage costs.

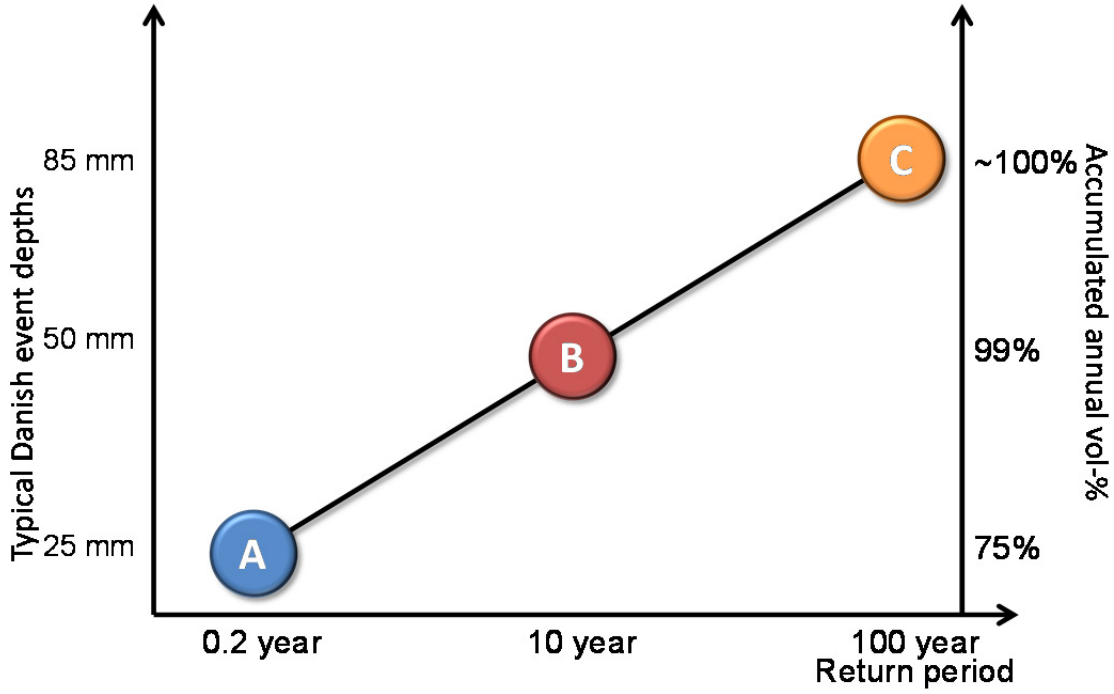

Figure 2 Quantification of the 3PA as done in paper **I**. Source: paper **I**.

For Danish conditions the quantification of the 3PA in paper **I** leads to the conclusion that typical combined sewers designed for controlling precipitation events with return periods up to 10 years actually handle individual events up to 50 mm of volume and virtually all (99%) precipitation volume on an annual basis. Also, stormwater control measures, as in point A in **Figure 2**, is able to handle up to 80% of the annual precipitation volume and individual events with up to 25 mm of volume.

Brought down to the very basics, the necessity of the analysis in paper **I** can be explained by the difference in how pipes and basins work, as shown in **Figure 3**. A pipe has a maximum flow capacity. As long as the precipitation intensity does not lead to higher flows, the pipe will control (via conveyance) all the stormwater; overflow will only occur when the precipitation intensity crosses a threshold given by the pipe capacity (**Figure 3**a). A basin, on the other hand, controls stormwater via storage; it will fill up gradually until its volume is filled completely. Then overflow will occur onwards irrespective of the precipitation intensity (**Figure 3**b).

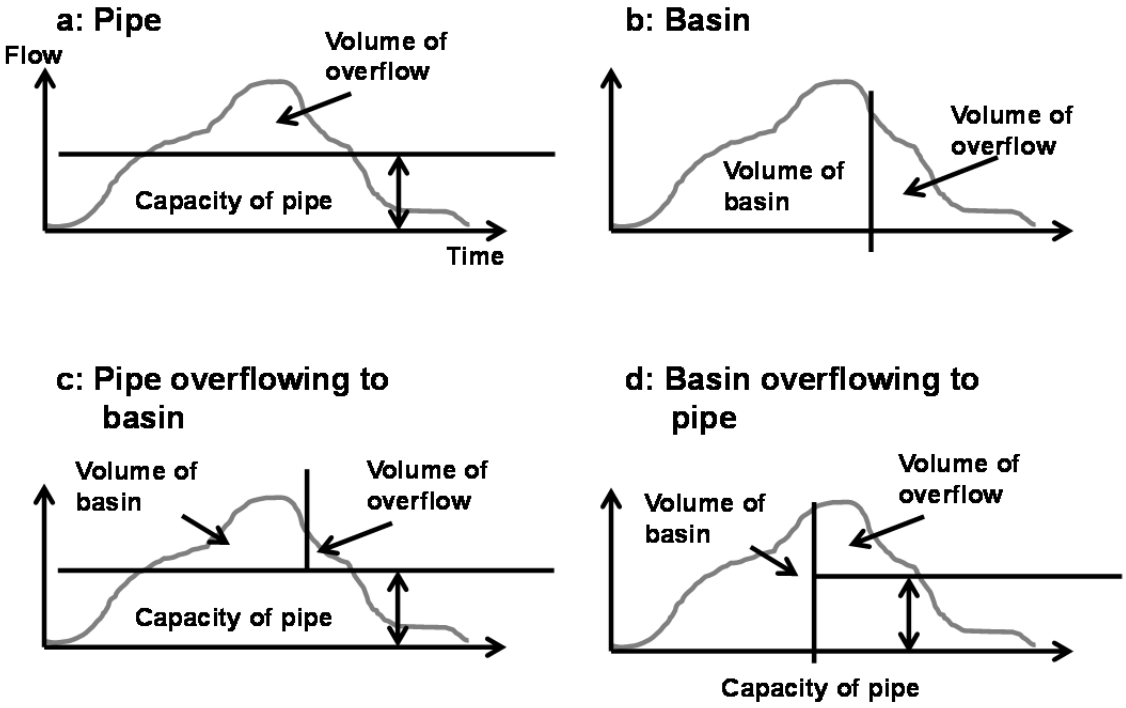

Figure 3 The fundamental difference between pipe and basin handling of water and how they can be combined.

In traditional urban drainage systems, pipes and basins are often combined as illustrated in **Figure 3**c. The pipes convey the stormwater flows that are lower than the pipe capacity and excess stormwater is diverted to a detention basin; here overflow from the system only occurs whenever the flow capacity of the pipe has been exceeded long enough to fill up the volume of the basin and only as long as the flow remains above the capacity of the pipe. If, on the other hand, a setup for typical stormwater control measures is considered; there the stormwater is handled first by local structures (e.g. rainwater harvesting tanks) with overflow to the piped sewer network. The setup will be as in **Figure 3**d; here, first the volume of the basin (the rainwater harvesting tanks acts as basins when short time frames are considered) is filled and then, when it is full, the pipe takes over and controls as much stormwater as the capacity allows for. The consequence of the latter approach is that the basin is, for a large part, filled with stormwater that could have been managed by the pipe. Thus, the volume of the basin in **Figure 3**d has less capacity for avoiding overflow than the basin in **Figure 3**c as it partially substitutes volume that would otherwise be conveyed by the pipes instead of just adding volume on top of it.

For actual design of real urban water systems, simulations with time series have to be performed to determine the effect and interactions between the different stormwater control measures. The relevant time frames that have to be considered are very much depending on the individual system. Small catchments will be very vulnerable to short term sub hourly peak rainfall and larger catchments might be more exposed during heavy rainfall spanning several days. With typical life-times of sewer systems in the order of 80-100 years design practice also has to take climate change into account (Arnbjerg-Nielsen 2012). This is very often done through climate change safety factors (Madsen et al., 2009, Arnbjerg-Nielsen 2012) which ensure an over-dimensioning of the stormwater management system to prepare it for more precipitation as a function of a changed climate. However, the relationship between precipitation event magnitude and overflow volume is not linear due to the phenomena outlined in **Figure 3**. An expected increase in precipitation of e.g. 20% due to climate change cannot be directly translated into a scenario where all events are 20% larger; even though this was sometimes done in the past (e.g Arnell and Reynard, 1996; Pilling and Jones, 1999; Eckhardt and Ulbrich, 2003). Even less likely is a scenario where the overflows increase linearly with climate change. To be able to demonstrate how actual systems work under a changed climate, simulations based on precipitation time series reflecting the changed climate are needed.

Time series from RCMs are not directly comparable to observational data from rain gauges. The intensity levels of the extremes are much lower than what is observed in point observations and the spatial extent of the modelled short term extremes is much higher in the regional climate models than what is seen in observational data (paper **IV**). Thus use of even high resolution temporal time series from these as input to stormwater management models will seriously underestimate the point scale extremes (paper **IV**; Wong et al., 2014).

Infrastructure is traditionally analysed and designed using point observations where the short term extremes is of great importance and where the relevant spatial dimensions are much smaller than what is usually provided by regional climate models. The overall aim of this study, as mentioned in Section 1, to model space-time precipitation time series under climate change, is thus also an aim to produce a data product resembling observational data more closely while adding a spatial dimension; a data product that can be used for analysis of urban infrastructure under climate change.

3 Relevant scales, data and indices

Measurements of precipitation are by no means the absolute truth (paper **II**). How the measurements are performed, which exact device is used to do the measurements and where exactly the measurements are performed all influence the measurement product (Fankhauser 1998, Jørgensen et al., 1998). Two identical rain gauges standing close together will not measure the same precipitation rates (Jensen and Pedersen, 2005).

In the present study many precipitation data products have been used for different purposes. Different data products have different spatial and temporal properties. They might be good for some purposes while bad for others. Common for all included papers is the focus on observational data relevant for urban hydrology.

3.1 Relevant scales for modelling spatio-temporal urban rainfall

The temporal scale has to be a compromise between typical response times of urban infrastructure and temporal scales where meaningful statistics can be derived from RCM output (**Figure 4**).

In relation to the 3PA and paper **I** the difference in scales between different points can be further highlighted. Fine scales in time and space are needed for modelling of fast response systems such as sewers and coarse scales can really only be used for resource calculations over longer time frames; which can be good enough for analysis that focus only on point A of the 3PA (**Figure 4** point A). For analysis and understanding of stormwater control measures and sewers under severe precipitation fine temporal scale precipitation data is needed at least at the hourly scale and ideally at the minute scale (**Figure 4** points B and C). These fine scales furthermore represent the necessary resolution to model and assess flood problems at urban scales. Data at fine time scales is essential to assess and quantify the impact of extreme events on urban hydrological infrastructure (Mikkelsen et al., 2005).

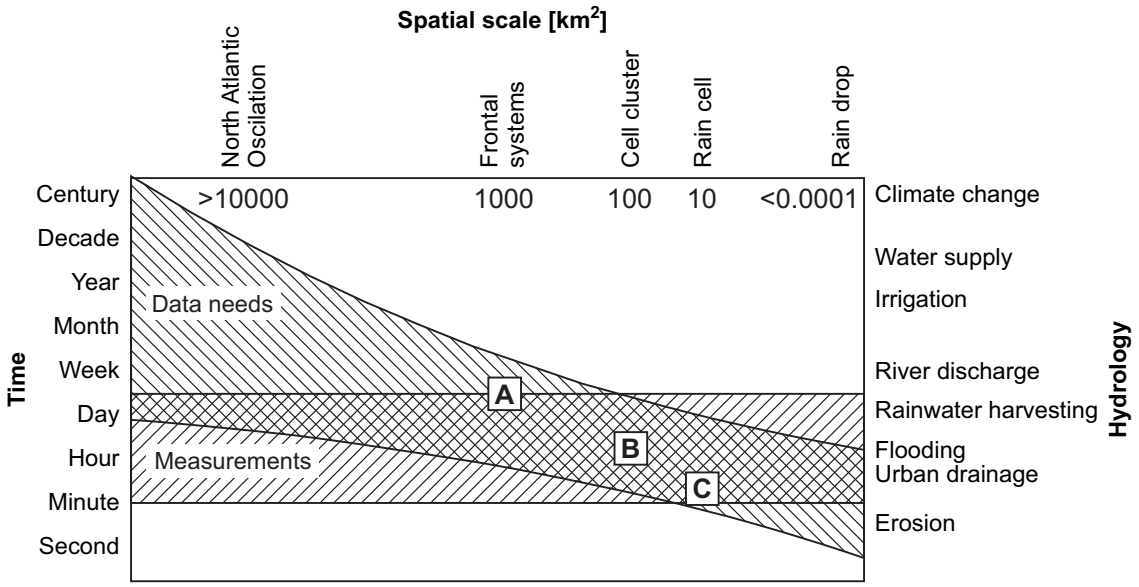

Figure 4 Spatial and temporal scales relevant for hydrology. The A, B and C's refer to the 3PA definition in paper I as shown in Figure 2. Modified from Berndtsson and Niemczynowicz (1988) and Arnbjerg-Nielsen (1996).

The relevant spatial scale is strongly related to the chosen temporal scale (**Figure 4**). Data should, ideally, be available at spatial scales finer than the size of typical urban catchments. Depending on the actual hydrological systems, this suggests a spatial scale at the kilometre level. This is also a characteristic spatial scale of present day radar rainfall products (Nielsen et al., 2012; Thorndahl and Rasmussen, 2013) and represents a relevant scale for small local precipitation events (Berndtsson and Niemczynowicz, 1988).

In paper **I** point rain gauge precipitation measurements at fine 1-minute temporal scale is used in the analysis that serves as the data basis for determining the distribution of precipitation volume as a function of return period. Paper **II** compares this rain gauge data set to three other observational data products, though only at daily scale. In paper **III** these gauge measurements are modelled at the minute-scale, but only at point level and without much success. Paper **IV** compares more rain gauge data from the same gauge network to RCM output and reanalysis data, but at the hourly scale. Paper **V** simulates spatio-temporal precipitation based on these data, also on the hourly scale. An overview of the used observational data and RCM output is given in the next two sections.

3.2 Observational data

Four different observational data products for Denmark are used in this study. Each of these data products have been created with a different purpose and thus have their individual justification. **Figure 5** shows maps of the coverage of the products and **Table 2** summarises the key statistics. The data products are:

- SVK (abbreviation for "Spildevandskomitteen", Danish for "The Water Pollution Committee", a committee under the Danish Society of Engineers) is a gauge network owned by the Danish water utility companies specifically designed for design and analysis of urban drainage systems. It has been widely used in this respect (e.g. Jørgensen et al., 1998; Mikkelsen et al., 1998; Madsen et al., 2002) and is used intensively as observational data basis for this study.
- The Climate Grid Denmark (CGD) data set was originally created for nature surveillance by the Danish Meteorological Institute (Scharling, 1999; 2000; 2012; Scharling and Kern-Hansen, 2002) and is mainly used for modelling of larger natural catchments (Seaby et al., 2013).
- The ECA&D data set (Klein Tank et al., 2002; Klok and Klein Tank, 2009) is the publicly available part of the national monitoring network maintained by the Danish Meteorological Institute. Along with a few more gauges it forms the Danish basis for the E-OBS data set.
- The E-OBS data set (Haylock et al., 2008) was created as part of the ENSEMBLES (van der Linden and Mitchell, 2009) to serve as a common European observational data basis for use in climate change studies.

To supplement the observational data, reanalysis data from an RCM run driven by ERA40 data (Uppala et al., 2005) is used in paper **IV.** Reanalysis data is model data of the state of the atmosphere based on assimilation of available historical records. It is as such to be regarded as a best fit of an atmosphere model to historical observations.

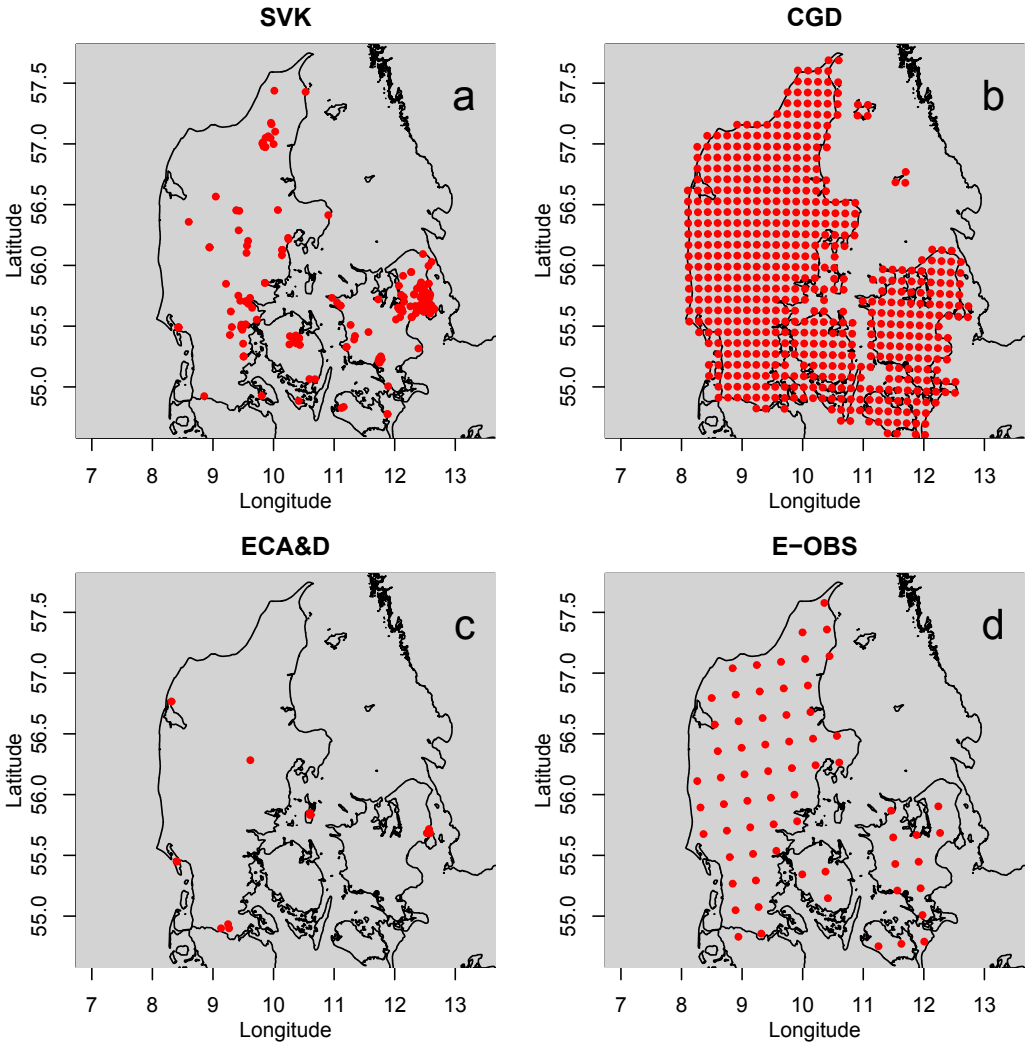

Figure 5 The localities of the four different data sets for Denmark used in paper **II**. a and c are point observations and b and d are gridded data sets. Source: paper **II**.

Table 2 Key statistics for the observational data products.

Name	Temporal resolution	Observation period	Spatial characteristics
SVK	1 minute	From 1979	Point observations, at present 145 stations in Denmark
CGD	1 day	1980 – 2010	Gridded data, 10 km resolution, 648 grid cells covering Denmark
ECA&D	1 day	From approx-imately 1850	Station data, 17 stations in Denmark
E-OBS	1 day	From 1950	Gridded data, 25 km resolution at the ENSEMBLES grid, 68 grid cells for Denmark

3.3 Regional climate model data

Besides publicly available regional climate model output from the ENSEMBLES project (van der Linden and Mitchell, 2009) at daily time step and 25 km spatial resolution, data from six climate simulations with output at hourly time step is used in the present study. Two ENSEMBLES SRES A1B scenarios have been made available for me by the corresponding modelling groups at 1-hour resolution. These are runs using the RACMO (version 2.1, Meijgaard et al., 2008) and HIRHAM (version 5, Christensen et al., 2007) RCMs; both driven by the GCM ECHAM5 (Roeckner et al., 2003). Also, four simulations carried out as part of the research project RISKCHANGE (DHI, 2014) have been available at hourly resolution for this study. These are HIRHAM RCM runs driven by the GCM EC-EARTH (Hazeleger et al., 2012) and WRF RCM runs (Skamarock et al., 2005) driven by the GCM NorESM (Bentsen et al., 2013). The four simulations use the RCP 4.5 and RCP 8.5 scenarios, respectively (van Vuuren et al., 2011). The resolution of the output of these simulations is 8 km and 1 hour (Mayer et al., in review). **Table 3** lists the characteristics of the high temporal resolution regional climate model outputs.

Table 3 Regional climate model output at hourly temporal resolution used in this study. Source: paper **V**.

Name	RCM	GCM	Spatial resolution	Present period	Future period
HIRHAM SRES A1B	HIRHAM 5	ECHAM 5	25 km	1980-2009	2070-2099
RACMO SRES A1B	RACMO 2.1	ECHAM 5	25 km	1980-2009	2070-2099
HIRHAM RCP 4.5	HIRHAM 5	EC-EARTH	8 km	1981-2010	2071-2100
HIRHAM RCP 8.5	HIRHAM 5	EC-EARTH	8 km	1981-2010	2071-2100
WRF RCP 4.5	WRF 3	NorESM	8 km	1981-2010	2071-2100
WRF RCP 8.5	WRF 3	NorESM	8 km	1981-2010	2071-2100

3.4 Comparing climate indices between observational data products

In paper **II** it is shown how the use of four different observational data products at daily level for Denmark (**Figure 5**) result in very different rankings of RCM skill for a different climate indices. The considered indices are com-

monly used indices from climate studies (based on Haylock and Goodess (2004) and Peterson (2005)).

Generally, the differences between the different data sets increase for more extreme indices, see **Figure 6**. Furthermore, gridding of observational data, to produce data products with equal data density over a spatial domain, results in smoothing of the underlying point observations with loss of knowledge of the intensities of the extremes as a consequence, see **Figure 6**e-h where the E-OBS extremes are considerably smaller in magnitude than the underlying ECA&D extremes. Also, there is a tendency for more data dense products, as in data products where there is more observational data behind the gridding algorithm, to result in more robust estimates: The gridded data set CGD, with lots of observations as the data basis for the gridding algorithm, results in extreme intensities much closer to the two point observation data sets (SVK and ECA&D) than the E-OBS data set, which only has a very limited data basis of point observations behind the gridding.

For climate indices calculated for daily rainfall data, differences between data sets and variation within data sets are pronounced. This suggests that the choice of observational data should favour data sets that represent rainfall features relevant for the study in question. For urban hydrology, good representation of extremes is the key feature. All data sets but the E-OBS seem to produce extremes of the same order of magnitude for percentiles above the 90th. This suggests that the data smoothing in E-OBS make it unattractive for studies where good representation of extremes is important. Because of this and also the daily temporal resolution it is considered less useful for urban hydrology studies.

Another important feature of precipitation is the actual dynamics of the time series, the chronology of precipitation intensity. This is important because the timing of actual weather influences flood risk and water resource management. The climate indices shown in **Figure 6** all depend on the distribution of wet day amounts and are for chronology purposes useless. They do not tell us anything about the chronology of the time series in the data set.

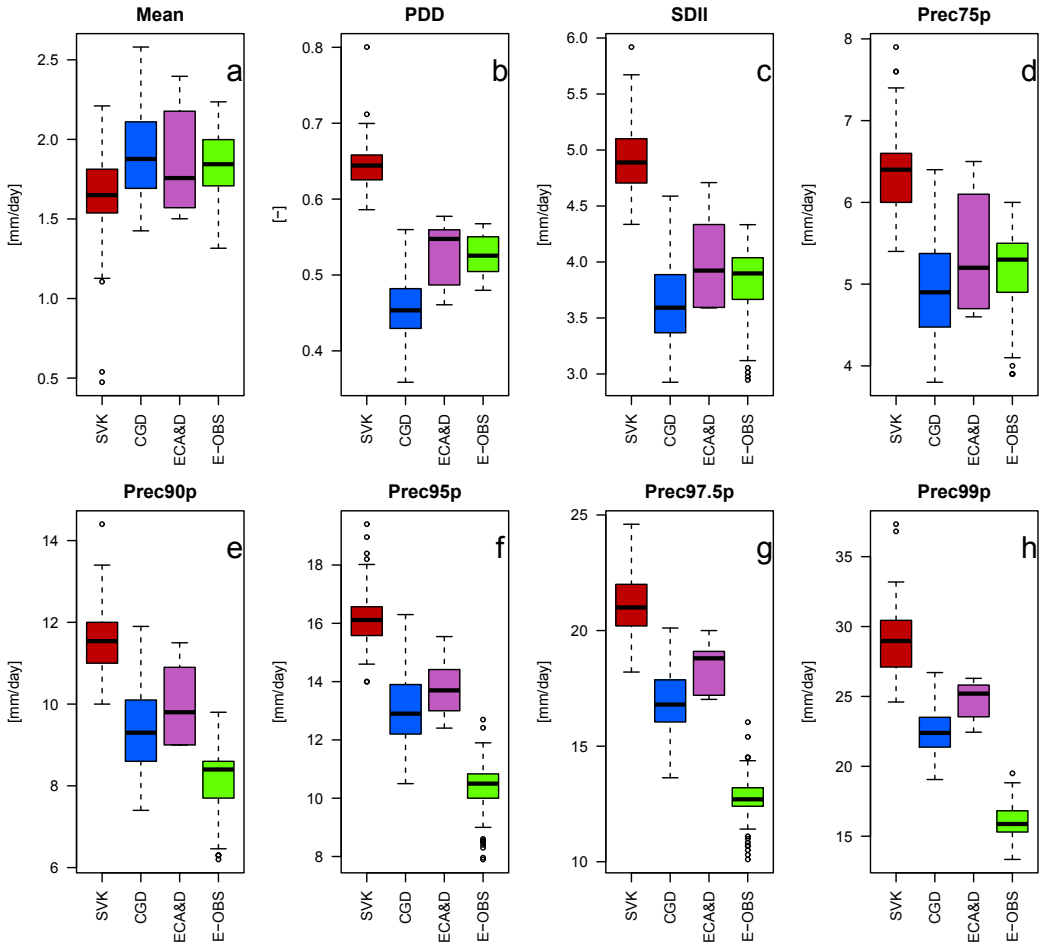

Figure 6 Considered indices for the four different data sets covering Denmark used in paper **II**. Mean: mean intensity of all days; PDD: probability of dry days; SDII: the mean intensity of wet days; PrecXp: the mean intensity of the Xth percentile of precipitation. Source: paper **II**.

3.5 Modelling precipitation time series at fine temporal scale

As climate indices do not provide the information needed for understanding the chronology of the time series, methods for time series analysis are introduced.

Point observations at high temporal resolution are traditionally used in urban hydrological analysis and application studies (Arnell et al., 1984; Jacobsen et al., 1996; Mikkelsen et al., 2005; Schaarup-Jensen et al., 2009). For small catchments this is definitely a sound approach. The point observation is probably a better representation of the catchment precipitation than a spatially

averaged precipitation product of much larger area would be (Schilling 1991; Thorndahl and Rasmussen, 2013).

Paper **III** analyses a single time series that comes from a tipping bucket rain gauge from the SVK data set. The rainfall intensity is modelled indirectly as it is inversely proportional to the waiting time between tips of the tipping bucket. The native temporal resolution of 1 minute is used and the time series is treated as a realisation of a stochastic Markov process. In literature precipitation has been described using Markov processes at daily level by several studies (Feyerherm and Bark. 1967; Haan et al., 1976; Srikantan and McMahon, 1983). Other studies have focused on minute-scale precipitation and how to describe it using Markov processes (Arnbjerg-Nielsen et al., 1998; Thyregod et al., 1998). The work in paper **III** extends the work by Arnbjerg-Nielsen et al. (1998). Common for Markov processes is that the probability distribution of outputs at any given time is a function of the state of the model at that time (potentially with links to previous time steps for higher order Markov chain models). For precipitation models this means that the probability distribution of potential near future rainfall intensities will be a function of the present intensity. This leads to models with very strong chronology in the modelled time series, but also models with no statistical links to the observations at larger time frames than the time step.

From paper **III** it is clear that the precipitation process is extremely noisy at the minute scale. The paper focuses on simplification of the Markov models by reducing the number of parameters needed to describe the precipitation process. Unfortunately, even models with 1000+ parameters, that must be considered heavily over-parameterised, are not able to capture the rainfall process well enough to produce realistic extremes over intervals ranging from minutes to hours. The Markov chain models are not able to model the peak 1-minute intensities at the right level and at the same time capture a realistic chronology over the full course of a precipitation event. Thus, the Markov chain model approach is not followed further in this thesis; besides the problems discussed above the approach is evaluated as not being suitable for spatial modelling of precipitation and inclusion of climate change.

3.6 Modelling of extreme precipitation at event scale

For papers **IV** and **V** a Peak Over Threshold (POT) approach is used, similar to the one used by Madsen et al. (2002) where extremes above a defined threshold are extracted from the data sets and modelled using a Generalised Pareto Distribution as a function of the return period:

$$z_T = z_0 + \mu \frac{1+\kappa}{\kappa}\left(1 - \left(\frac{1}{\lambda T}\right)^{\kappa}\right) \tag{1}$$

where:

- z_T is the intensity of an extreme event with return period T
- z_0 is the threshold
- μ is the mean intensity of the extreme events
- λ is the mean number of extremes per year
- κ is the curvature parameter
- T is the return period

POT analyses are often used in climate studies to model T-year events for specified return periods (Frei et al., 2006; Fowler and Ekström, 2009; Kysley and Beranova, 2009). The POT analysis used to specify the relevant extremes is usually constructed in one of two ways depending of the characteristics of the input data.

1) If all data sets have similar levels of magnitudes for extreme precipitation, static thresholds (z0's) are used across data sets. For paper V the thresholds originating from the analysis of SVK data for regional modelling of extremes in Madsen et al. (2009) is used. This approach is often referred to as type 1 censoring in literature (Madsen et al., 2002)
2) If data sets are fundamentally different in nature (if for instance point observations have to be compared to RCM output as in paper IV) another approach is adopted where the same number of extreme events (constant λ) is extracted from each data set with a specific set of thresholds for each

data set as a result. With this approach, the threshold value is a parameter of the model instead of λ. This approach is often referred to as type 2 censoring in literature (Madsen et al., 2002).

For large urban catchments, where spatially uniform rainfall is clearly a questionable assumption, other approaches are emerging where the small scale variability of weather is essential (Nielsen et al., 2012; Thorndahl and Rasmussen, 2013). Radar observations, calibrated to point observations, is being used for real-time control and predictive model control of sewer systems (Löwe et al., 2013; Goormans and Willems, 2013)

3.7 Spatial correlation of extreme precipitation events

The spatial correlation of extremes is of huge importance when the realism of a given data set is to be determined. Paper **II** uses empirical semi-variograms to correlate climate indices in space (**Figure 7**). This approach calculates correlation as a function of distance; the distance where the correlation stabilises is known as the de-correlation length. **Figure 7** highlights how different observational data products behave very differently in this respect. There is almost no correlation in the SVK data set and the E-OBS data set seem to have a de-correlation length of 150-200 km for the 95th percentile of wet days (Prec95p), which is regularly regarded as a valid measure of extremes in climate modelling. As with the indices themselves, presented in Section 3.4, gridded data (CGD and E-OBS) behave more smoothly and point observations (SVK and ECA&D) tend to present a more noisy and variable result.

For spatial correlations in actual weather the semi-variograms are not suitable. They describe overall climatic patterns in the precipitation data and as such not correlation at event level. The Markov models applied in paper **III** are not suitable for spatial application. The memory in the models is very short (between 0.2 and 0.4 mm of precipitation, corresponding to 1 or 2 tips on the rain gauge). Spatial correlation between different rain gauges requires longer correlation time frames as weather with a limited spatial extent should be allowed to move across catchments between the gauges (Niemczynowicz, 1988; 1991).

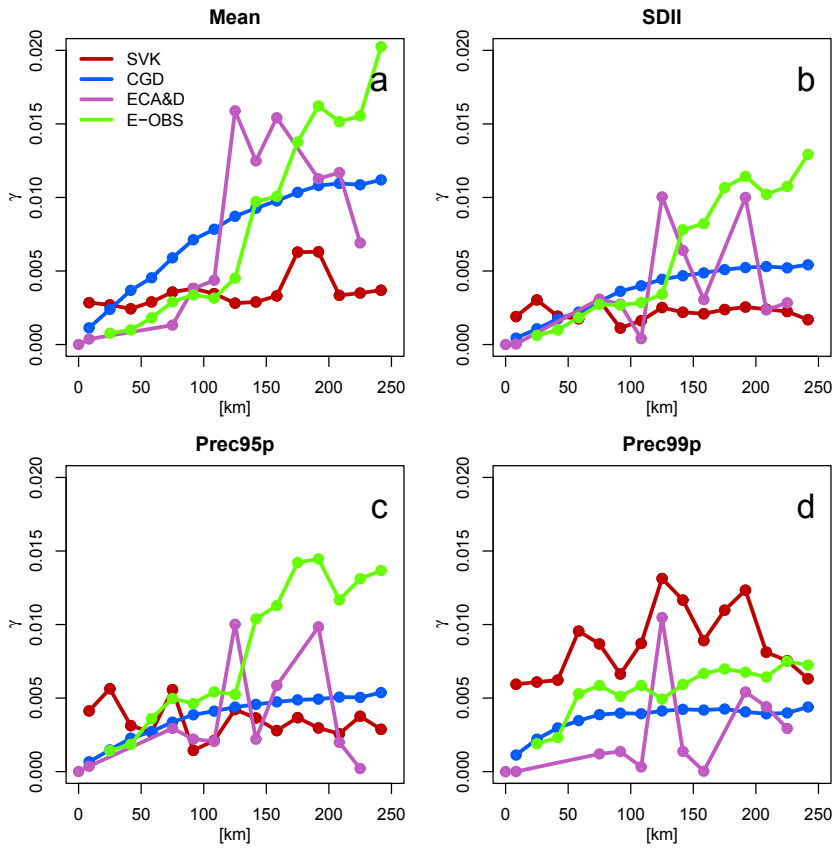

Figure 7 Empirical semi-variograms for the four different observational data sets covering Denmark used in paper **II**. Source: paper **II**.

To describe spatial correlation at event level this study uses the unconditional spatial correlation introduced by Mikkelsen et al. (1996). It describes how likely it is to observe concurrent extreme precipitation events, derived using the POT analysis described in Section 3.6, as a function of the physical distance between gauges.

The unconditional spatial correlation of extreme intensities, ρ, is a key statistical descriptor of the spatial extent of extreme precipitation events in this thesis. It is estimated through the following procedures.

For the i'th extreme event at site A, Z_{Ai}, to be concurrent with the j'th extreme event at site B, Z_{Bj}, they have to overlap in time as:

$$\{Z_{Ai}, Z_{Bj}\}: \left[t_{si} - \frac{\Delta t}{2}, t_{ei} + \frac{\Delta t}{2}\right]_A \cap \left[t_{sj} - \frac{\Delta t}{2}, t_{ej} + \frac{\Delta t}{2}\right]_B \neq \emptyset \qquad (2)$$

where t_{si} and t_{ei} are the start and end times of event Z_{Ai}, t_{sj} and t_{ej} are the start and end times of event Z_{Bj} and Δt is a lag time introduced to account for possible travelling time between the sites A and B. Δt is chosen to reflect actual realistic travel times with longer lag times for longer duration extremes and is in general set to a size in the order of the event duration (Mikkelsen et al., 1996). The unconditional covariance is then estimated between the sites by also considering the non-concurrent extremes as:

$$\mathrm{cov}\{Z_A, Z_B\} = \mathrm{cov}\big\{\mathrm{E}\{Z_A|U\}, \mathrm{E}\{Z_B|U\}\big\} + \mathrm{E}\big\{\mathrm{cov}\{Z_A, Z_B|U\}\big\} \tag{3}$$

with U being a boolean operator taking the value of 1 for concurrent events and 0 for non-concurrent ones. Finally the unconditional correlation is found by dividing the unconditional covariance by the product of the standard deviations as:

$$\rho_{AB} = \frac{\mathrm{cov}\{Z_A, Z_B\}}{\sqrt{\mathrm{var}\{Z_A\}\,\mathrm{var}\{Z_B\}}} \tag{4}$$

ρ is used intensively in this study to evaluate whether data sets exhibit realistic spatial extent of the extremes at event level and is as such a key evaluation method in papers **IV** to **V.**

Finally the e-folding distance, the distance at which the unconditional correlation falls to $1/e$, is used as index to characterize the differences between the different data products.

4 Downscaling precipitation

Downscaling of precipitation from General Circulation Models (GCMs) can be based on either physical or statistical relations. In the following the possibilities within downscaling will be discussed.

4.1 Physical downscaling

RCMs are essentially not very different from GCMs. They are both constructed to model the physical relations between the atmosphere, ocean, land surface and space. Where the GCMs model these interactions on the global scale using grids with resolutions in the order of hundreds of kilometres, RCMs generally operate at much finer spatial scale in the order of typically 25-50 km and for smaller domains; e.g. a continent (Giorgi and Mearns, 1991).

Both GCMs and RCMs are run as dynamic models. They are driven by the energy Earth receives from the Sun. The process of transforming the short wave incoming radiation to the long wave radiation Earth emits results in weather. The incoming energy evaporates water and heats the surface. This leads to pressure differences that again result in advection; movement of the air masses. As the spatial scales get finer other processes become important. The movement of air near the surface is very much dependent on the underlying orography, and the fine resolution of the RCMs result in much more realistic orographic induced precipitation. Weather on the synoptic scale, on the other hand, should be governed by the atmosphere state and should not be changed significantly by a higher spatial resolution of the RCMs. Some processes happen at scales much finer than the grid scale of the models. These processes are parameterised: Their influence on the energy budget at the grid level is computed and the contribution to relevant fluxes attributed. Convective precipitation is a phenomenon which is parameterised as it is a product of the local temperature gradient in the atmosphere and the local moisture content. These atmospheric variables can vary very much in space and e.g. thunderstorms have most often spatial coverage much less than the average grid size of an RCM (Olsson et al., 2012).

If one wants to use all the already available RCM output data archives, like the one from the ENSEMBLES (van der Linden and Mitchell, 2009) archive, for urban application, further downscaling is necessary.

High resolution local climate models or numerical weather models (NWMs) are probably the best way to model high resolution precipitation fields with realistic behaviour across spatio-temporal scales. These types of models have to be nested within existing RCM runs as even smaller local domains are modelled. Unfortunately, it is extremely computationally expensive to run such models. It is virtually impossible to run them for decades for larger domains at resolutions suitable for urban application (Larsen et al., 2013). Nonetheless, as computational power becomes less expensive this approach will be more attractive as the results seem very promising (Rasmussen et al., 2011).

Larsen et al. (2013) investigate how the grid size and choice of domain influence the results for high resolution RCMs. They use the HIRHAM RCM (Christensen et al., 2007) at 5.5 and 11 km resolution for various domain sizes ranging from 1350 * 1350 km^2 to 5500 * 5200 km^2. The main conclusion is that if a finite computational load is required, a larger domain with coarser grid cells results in better results than a smaller domain with finer grid cell resolution. The validation is done for daily values against the gridded CGD data set (at 10 km resolution) which must be expected to influence this conclusion. A higher spatio-temporal resolution of the validation data set would probably result in a different conclusion. Rasmussen et al. (2011) run the RCM WRF (Skamarock et al., 2005) at very high spatial resolution of 2 km. They highlight that at this resolution convective precipitation is modelled explicitly (and not as a sub grid parameterisation as in RCMs running at more common spatial resolutions). The study shows, how an RCM at much higher spatial resolution than normally seen, is able to capture and respond very well to the orography and produce realistic small scale rainfall fields. Unfortunately, it is also very apparent from this study that long time simulations with this setup would be extremely computationally demanding.

In Mayer et al. (in review) precipitation from two high resolution 20 year RCM runs with HIRHAM (Christensen et al., 2007) and WRF (Skamarock et al., 2005) are evaluated for ERA-Interim (Dee et al., 2011) conditions. The RCM setup is the same as used in paper **V**. One of the properties investigated is the unconditional spatial correlation of the extremes at event level following the approach presented in section 3.7. The RCM precipitation output is evaluated against both ERA Interim precipitation and the SVK data set using the POT approach described in section 3.6 with type 2 censoring. The study shows how the high resolution RCM output results in correlation distances much more comparable to the point observations in the SVK data set than the

gridded ERA Interim data set and also much more realistic than the ones observed for the ENSEMBLES RCMs output in paper **IV** (see **Figure 12** in Section 5.2). Still, the grid size in Mayer et al. (in review) is too coarse (8 km) to resolve the convective part of the precipitation process. RCM runs in even higher spatial and temporal resolution (as in e.g. Rasmussen et al. (2013) and Kendon et al. (2014)) is needed if the resulting precipitation output shall be directly usable in urban applications.

4.2 Statistical downscaling

In statistical downscaling the basic assumption is that there exists a relationship between large scale weather and/or climate and local scale weather (Wilby et al., 2004). A large number of techniques can be used to express this relationship. Common for all techniques is the assumption that identified correlation structures are valid for a changed climate. Most techniques fall within the two main groups of regression models and weather generators.

For downscaling precipitation extremes from climate models to the scale of point observations, numerous regression techniques have been demonstrated to be useful (Engen-Skaugen, 2007; Benestad, 2010; Cooley and Sain, 2010; Nguyen et al., 2010; Piani et al., 2010; Olsson et al., 2012 Schliep et al., 2010; Sunyer et al., 2012). General for all studies is the correlation of a description of the local extreme precipitation and large scale climate variables such as precipitation, pressure and cloud cover. The description of local extreme precipitation can be one of many: General Extreme Value distribution (Cooley and Sain, 2010; Schliep et al., 2010), Intensity-Duration-Frequency relationship (Nguyen et al., 2010) probability density function (Engen-Skaugen, 2007; Benestad, 2010; Olsson et al., 2012) or very simple change factor relationships (Piani et al., 2010; Sunyer et al., 2012).

When precipitation time series are of interest, rather than only a correction of the extremes from the RCM output, weather generators seem to be of use (Cowpertwait et al. 1996; Brissete et al. 2007; Kilsby et al., 2007; Sunyer et al., 2012). Also, weather generators have the advantage that they can be fitted to present day observational data. Hence, they are potentially less sensitive to biased RCM output (Cowpertwait et al. 1996). In the simplest form, weather generators generate stochastic precipitation time series where key statistics from the observational precipitation time series are reproduced; these statistics are typically mean and variance of daily precipitation intensity, probability of dry days and similar statistics on the chosen time step. Very often weather generators are operated at daily time step for single site observations

(Cowpertwait et al. 1996; 2013; Kilsby et al., 2007; Burton et al., 2008; 2010; Sunyer et al., 2012).

When the spatial correlation between observations is also considered important fewer studies are reported (Willems 1999; Burton et al., 2008; 2010; Cowpertwait et al., 2013; McRobie et al., 2013). The results are generally either of a spatio-temporal resolution considered coarse in an urban application environment, with the temporal resolution governed by daily rainfall observations and the spatial resolution governed by large river catchments (Burton et al., 2008; 2010; Cowpertwait et al., 2013), or weather generators specifically targeted at small urban catchments where small spatio-temporal scales and movement of rain storms with the wind are important (Willems 1999; McRobie et al., 2013). Both precipitation movement and convective precipitation cells are incorporated in these weather generators which produce output similar to what weather radar would if it could really measure precipitation (McRobie et al., 2013). How to link these weather generators to synoptic scale weather (and climate) is, however, not clear as the local precipitation movement is of huge importance for the final product.

Common for Burton et al. (2008; 2010) and Cowpertwait (2013) is that they use spatio-temporal rectangular pulse process models for simulation of precipitation. These models are characterised by describing precipitation at the event level. Stochastic precipitation time series are generated by aggregation of intensities from precipitation cells described as rectangular pulses. These pulses are clustered in time in precipitation storms. The distribution of cell arrival times, their intensities and the inter-arrival time between individual storms are described by statistical distributions. The parameters for these distributions are determined through analysis of historical observational data. At present, these models are generating the most reliable results for spatial precipitation downscaling at the watershed scale at daily level. The models have also been shown to generate realistic results at hourly level for point observations (O'Connell et al., 2002; Favre et al., 2004) and there is a clear potential in creating a spatial model at hourly time step that would be much more relevant for urban application. Models at even finer time step would be preferred, but as the local precipitation movement becomes more important at finer time steps it makes it more difficult to link the weather to climate indices (Willems, 1999)

Generally, weather generators, and herein the pulse process models, work by calibration to observational data with respect to relevant statistics like the

mean daily rainfall or the probability of dry days. For the *RainSim* model framework, presented by Burton et al. (2008), one can choose between a variety of statistics at both hourly and daily level and make a custom weighing scheme on a monthly basis to favour some features over others. In this way, a spatio-temporal rainfall model can be fitted to observational data, and when samples are drawn as simulated output from the model, they should behave in the same way as the input data; i.e. the output should be considered as correlated gauge measurements if that is what is used to fit the model. **Figure 8** summarises the flow in which *RainSim* is fitted. First a model for present conditions is fitted to statistics derived from analysis of observational data. This fit is a subjective task as the weighing scheme used can be modified in many ways. Climate change is introduced into the model by use of change factors (CFs) derived from the changes observed between regional climate model runs from present and future climates. All the input statistics used to fit the original model for present day conditions are also analysed for the RCM runs for calculation of change factors. Change factors are calculated for each on a monthly basis and used for perturbation of the statistics of the original model before a new model for future climate is fitted using the existing custom weighing scheme. Burton et al. (2010) present the full methodology for this.

In the following section the *RainSim* model is used to model precipitation based on 60 SVK rain gauges in the Copenhagen area. This is a completely novel context for use of *RainSim*. Also, the models ability to reproduce relevant small-scale spatio-temporal correlation structures of precipitation extremes is evaluated for the first time.

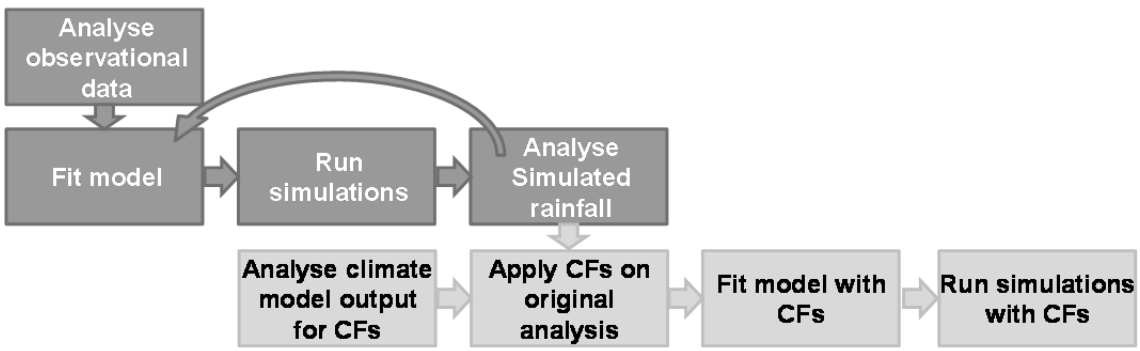

Figure 8 Flow chart for the operation of *RainSim* and the spatio-temporal Neyman-Scott rectangular pulses model.

5 Spatio-temporal weather generation at urban scales

In the following the fitting, validation and climate change perturbation of a spatio-temporal weather generator is demonstrated for urban-scale application.

5.1 Fitting the weather generator

In paper **V** the weather generator (WG) presented by Burton et al. (2008) is used in a much more urban-relevant resolution than previously. It is fitted to precipitation data from 60 high-resolution rain gauges situated in a 40 by 60 km region around Copenhagen (SVK in **Figure 9**). The original data resolution is one minute, but for paper **V** data is aggregated to hourly data. In addition, daily precipitation data from the gridded CGD data set (CGD in **Figure 9**) is included to better describe the seasonality and spatial correlation structure in the model.

The model output represents point rainfall and is generated on a regular 2 km grid (WG in **Figure 9**). Eight key statistics are used for calibration of the model to the observational data. These are:

- The mean daily precipitation intensity from the individual gauges (24 hour mean)
- The variance of the intensity of the daily and hourly observations from the individual gauges (1 hour and 24 hour variance)
- The skewness of the intensity of the daily and hourly observations from the individual gauges (1 hour and 24 hour skewness)
- The probability of dry days and of dry hours based on the observations from the individual gauges and with thresholds of 1.0 and 0.1 mm respectively as suggested by Burton et al. (2008).
- The lag-1 auto-correlation of the hourly precipitation intensity calculated from the observations at the individual gauges
- The cross-correlation between observations of hourly precipitation intensity at the individual gauges

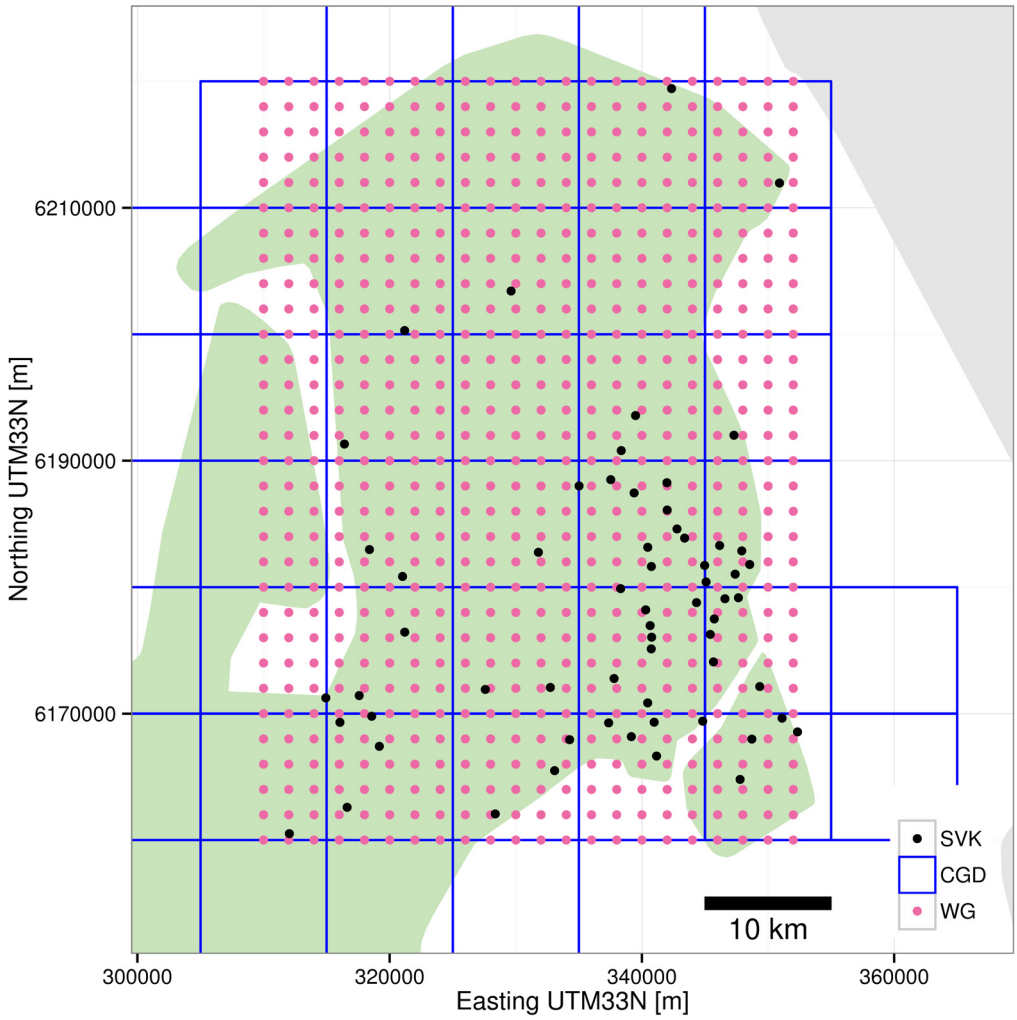

Figure 9 Model area for the spatio-temporal Neyman-Scott rectangular pulses model experiment for the North-Eastern part of Sealand (including the Copenhagen area). Source: paper **V**.

Together, these statistics characterise many urban relevant aspects of precipitation. With the weighing scheme used the model is fitted in a way where realistic performance with respect to extremes is expected. With heavy weight put on skewness, and partly on variance, at both daily and hourly level it is ensured that the extremes at both hourly and daily level are simulated with a realistic return period. Also, high weight on auto-correlation is important as this parameter ensures a realistic chronology in the time series at the event level. Furthermore, strong weight on cross-correlation is introduced to ensure that the output can be considered as realistic spatial precipitation fields where data from several grid points can be used in the same way as correlated gauge measurements.

Ten realisations with 50 years of simulation output are generated (named WG1-10). The grid points nearest to the gauge locations are evaluated against the corresponding measurements point-wise. This is done for the key statistics on a monthly basis to evaluate the fit of the model (see paper **V**). Generally the model does a very good job in reproducing the fitting statistics.

5.2 Validation of extremes in weather generator output

As extreme precipitation is of major importance for urban hydrological application, several indices related to this aspect are evaluated in the validation of the WG. A POT analysis, as described in Section 3.6, is used for each WG data set (WG1-10) and compared to the SVK data set (**Figure 10**). For both 50 and 10 years return periods the WG data sets are very close to the SVK data set and well within one standard deviation of the central estimate. Generally the WG seems to slightly overestimate the short duration 10-year extremes and underestimate the same 50-year extremes. This suggests that the curvature of the Generalised Pareto Distribution from the POT analysis is slightly different between SVK and WG. This particular parameter is very difficult to estimate accurately and it is in contrary to here often modelled as being constant between different observational points (Madsen et al., 2009).

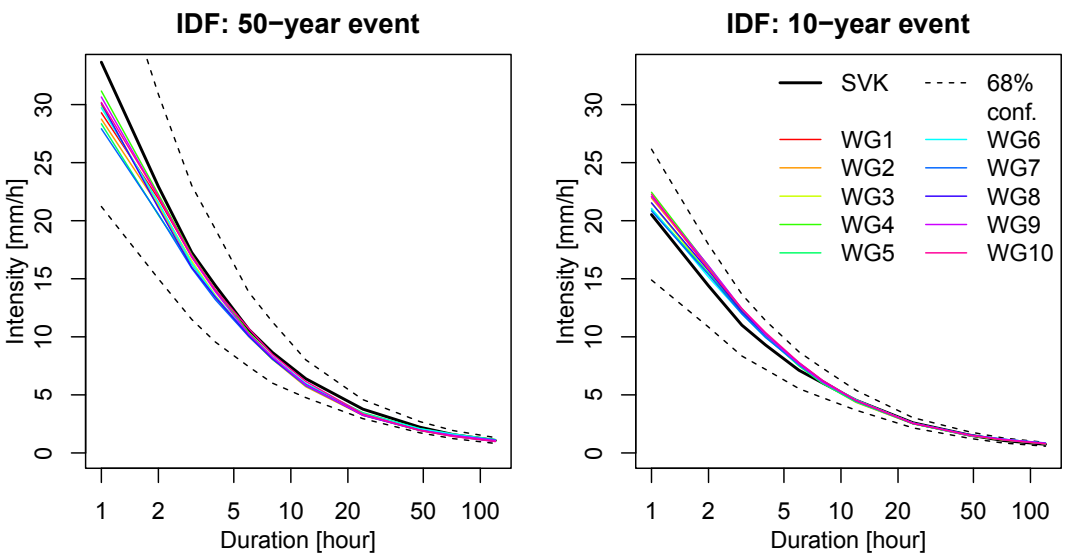

Figure 10 The intensity levels of the extreme 50 and 10-year events from the SVK data set including empirical 68% confidence interval and from the 10 WG realisations. Source: paper **V**.

The seasonal distribution of the extremes is evaluated (**Figure 11**). The seasonality of the extremes from the WG data sets seems to be very much in accordance with the SVK data set. A statistical χ^2 test in paper **V** shows that there is no significant difference between the distributions. Furthermore, as **Figure 11** shows the distribution is clearly much closer to the SVK data than to the RCM data from paper **IV**.

Paper **IV** extracts extremes from the SVK data set at event level at the hourly to daily time scale. The extremes are compared to extremes from RCM output at the same temporal scale. From the analysis in paper **IV** the key conclusions regarding comparison of observations to RCM output at high temporal scale are: Events derived using POT analysis from RCM output will not necessarily represent the same type of events as the ones derived from observations. The seasonal distribution of the events seems to be different. This suggests that short term local extremes (which are present in point observations) are smoothed beyond recognition in climate models and do not appear as extremes in the output. Also, the seasonality from hourly events to daily events observed for point observations does not follow the same pattern for RCM output (**Figure 11**).

From paper **IV** it is clear that RCM output, which might well represent realistic climate, as is expected for all the ENSEMBLES project RCM runs, does not present realistic weather at scales usable in urban hydrology.

In paper **IV** the SVK data set is used as reference for assessment of the spatial correlation of precipitation extremes. The results highlight some of the fundamental problems arising from comparing point observations to regional climate model output. In particular the studies show how the actual spatial extent of extreme precipitation at event level differs greatly at the sub-daily level between point observations and climate model output (**Figure 12**).

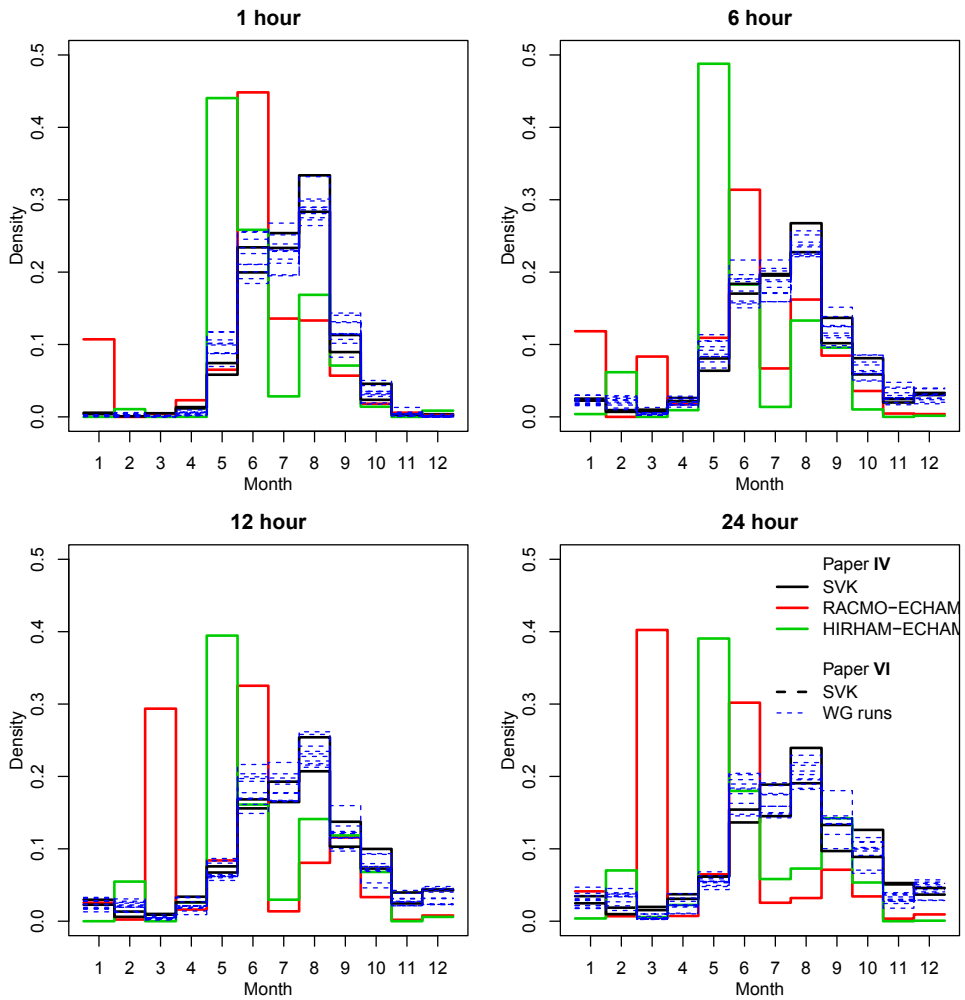

Figure 11 Seasonal distribution of the extremes from the SVK data set and the WGs in paper **V**. Data is also shown from the SVK data set and two RCMs used in paper **IV**. The time period and SVK subset is different for the two papers which creates a small deviation between the two SVK data sets. Modified from paper **IV** and **V**.

The unconditional spatial correlation, as described in Section 3.7, is calculated for the WG data sets and compared to the SVK data set (see **Figure 12**). Comparing the results shown in **Figure 12** it is visually clear that the WG output act much more like the SVK data set in this respect than both traditional 25 km RCM output (paper **IV**) and high resolution 8 km RCM output (Mayer et al., in review). The downscaled precipitation products from the weather generator, here denoted WG 2km, are similar to the one observed for the SVK data set meaning that the spatial extent of the extremes in the simulated precipitation data set is realistic.

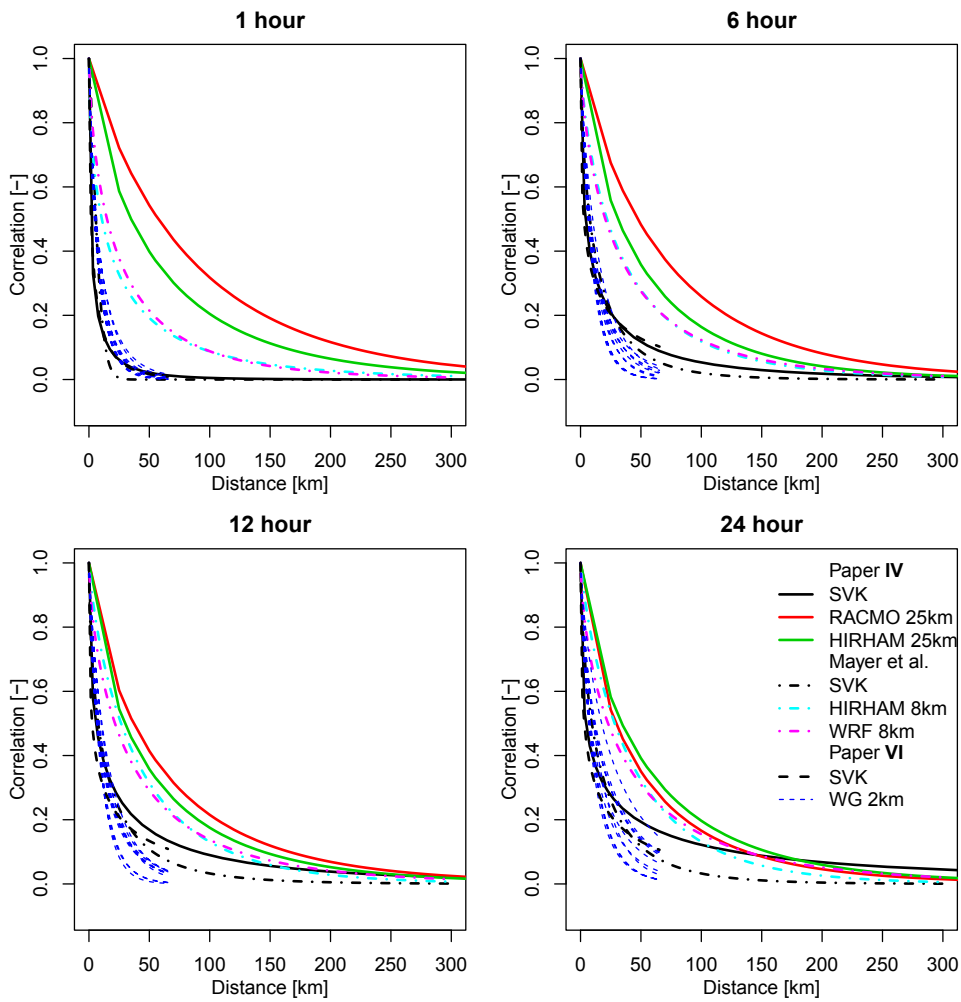

Figure 12 The unconditional spatial correlation structure of the observational SVK data set from three different papers using different sub sets and/or time periods. The observations are compared to the ENSEMBLES RCM data in 25 km resolution from paper **IV**, the 8km RCM data from Mayer et al. (in review) and the 2 km weather generator output from paper **V**. Modified from papers **IV** and **V** and Mayer et al. (in review).

5.3 Perturbation with climate change signals

In paper **V** the WG is perturbed with climate change signals from the six RCM pair runs presented in **Table 3**, Section 3.1. Change factors are derived on a monthly basis for each of the eight key statistics used to fit the model, as presented in Section 5.1. **Figure 13** shows these change factors and it is apparent that the six RCM runs together result in a very noisy picture overall. As such it results in six very different perturbation schemes for the WG. There seems to be agreement between models for some of the statistics (especially the variance and skewness statistics). But, the general picture is that there is very little structure in the perturbation schemes. Even though the

RCM runs represent 'only' three emission scenarios, three GCMs and four RCMs (see **Table 3**) the variability in the resulting perturbation schemes is pronounced. It provides a firm base for assessing the robustness of the WG towards how different realisations of the same emission scenario affect the weather simulated by the WG.

The variation of the model, as represented by the 10 realisations for present conditions, is small in comparison to the climate change signal. Thus one realisation is made for each perturbation scheme.

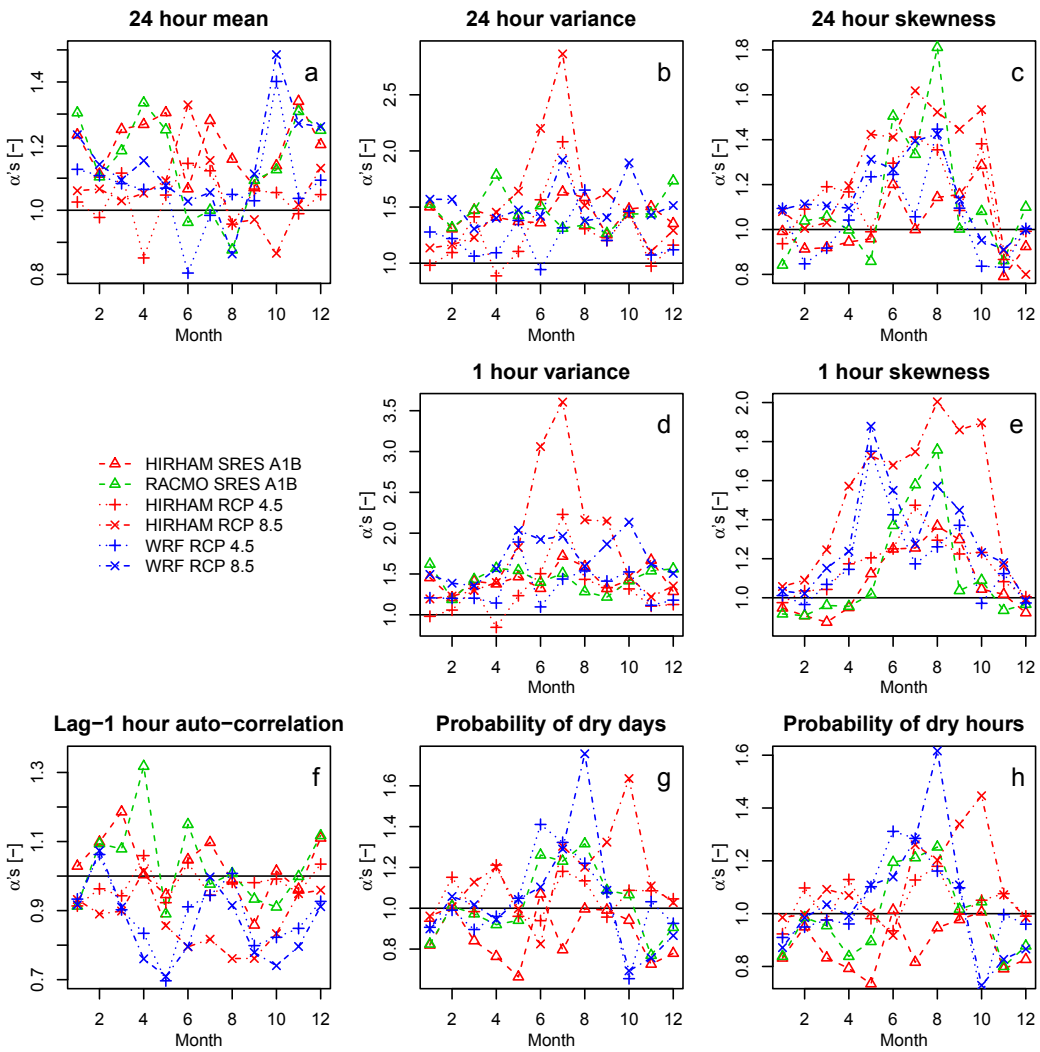

Figure 13 Change factors for the key statistics from the WG for the six RCM pair runs used for perturbation of the WG with a climate change signal. Source: paper **V**.

5.4 Evaluation of changed extremes

As expected from the results in **Figure 13** the HIRHAM RCP 8.5 perturbed WG results in a much more severe change in extreme precipitation than the other perturbation schemes (**Figure 14**). This is the case for both 10 and 100-year return periods. Calculating the change factors for precipitation T-year events from the original and perturbed WG output shows that despite the differences observed in the perturbation schemes for the input statistics (**Figure 13**), the change factors are in accordance with other studies for Denmark (**Figure 15**), such as those reported by Grum et al. (2006), Larsen et al. (2009), Onof and Arnbjerg-Nielsen (2009), Sunyer et al. (2012) and Sunyer et al. (2014) with similar forcing scenarios resulting in similar change factors and high-end scenarios resulting in higher change factors than moderate emission scenarios. This is reassuring. The results can then be regarded as representative for the expected change beyond the exact RCMs included in the study.

It is interesting to note, that the HIRHAM SRES A1B perturbed WG results in a rather high change factor. It is almost the same for both 10 and 100-year extremes and for all event durations. In comparison, the perturbed WGs based on the RACMO SRES A1B, the HIRHAM RCP 4.5 and the WRF RCP 4.5 perturbation schemes show very similar change factors. These are higher for 100-year extremes than for 10-year extremes, but not depending significantly on the event duration. From paper **V** it is clear that perturbation schemes based on RCM runs modelling comparable climate change (HIRHAM SRES A1B, RACMO SRES A1B, HIRHAM RCP 4.5 and WRF RCP 4.5) result in similar changes to extremes after downscaling with the WG (**Figure 14**).

Both the HIRHAM and WRF RCP 8.5 perturbed WG runs result in change factors that are higher for short duration precipitation extremes. This indicates that this high-end scenario is changing the climate differently than the more moderate scenarios (SRES A1B and RCP 4.5). Also, the effects are not simply linearly scalable between the different scenarios. This is in sharp contrast to what is reported in Christensen et al. (in review) where scalability is observed from low-end to extremely high-end scenarios for climate indices based on daily precipitation and temperature data from a large ensemble of RCM runs. For event durations over 48 hours the differences in change factors between the different WG runs are very limited. Surprisingly, the high-end scenario WRF RCP 8.5 perturbation scheme results in the smallest change factor for the long duration events.

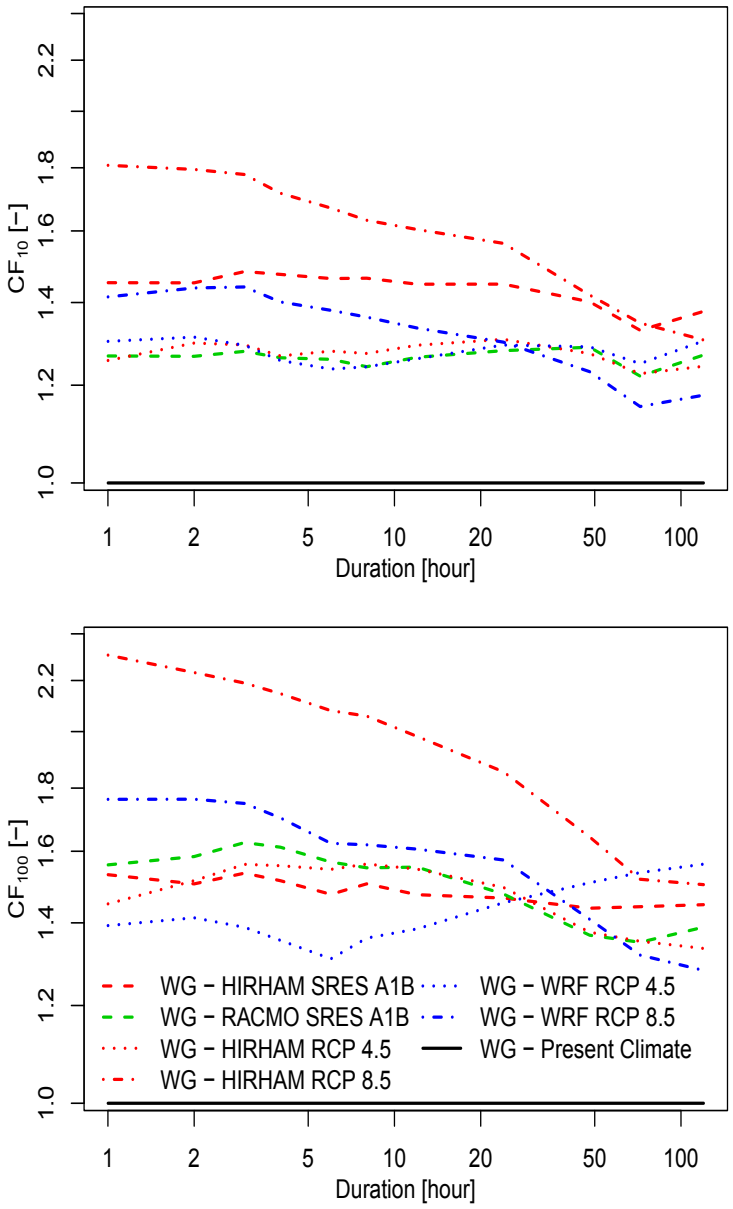

Figure 14 Change factors for the extremes with return period of 10 (top) and 100 (bottom) years derived from the simulation output from the perturbed weather generators. Source: paper **V**.

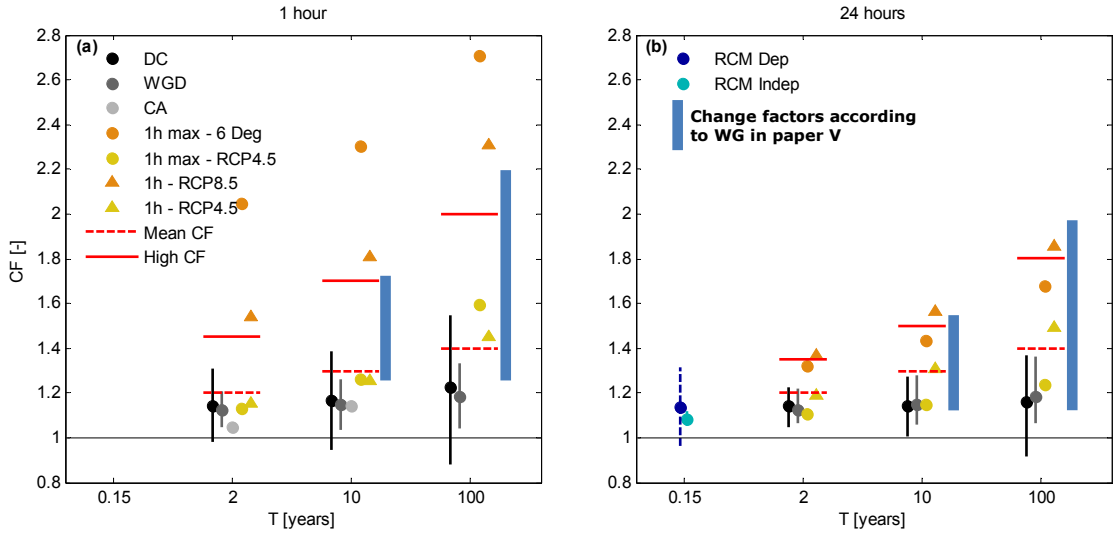

Figure 15 The change factors calculated in paper **V** relative to change factors calculated by Sunyer et al. (2014) for Denmark. The blue bars represent the span presented in **Figure 14**. Modified from Sunyer et al. (2014).

Despite the observed differences between WGs perturbed with different RCM runs and forcing scenarios, the results in **Figure 15** show that an upwards change is to be expected for all event durations. The changes seem to be more severe for rarer T-year events. Projected change factors are in the order of 1.2-1.3 for events happening every 10 years to 1.4-1.5 for events occurring every 100 years for the moderate scenarios (SRES A1B and RCP 4.5).

All the perturbed WG runs produce *T*-year precipitation events with reasonable spatial correlation structure (**Table 4**) Generally the correlation structures are much closer to SVK observations than the corresponding RCMs used as input (as shown in **Figure 12**).

The outputs from the WG represent novel data products that can be used directly in hydrological modelling. Output for present day climate can be used in cases where the observational records are not long enough for a given application and where the spatial correlation is important. The perturbed outputs representing different climate change scenarios can all be used for assessing the impact of climate change on hydrological models. If all are used they will represent a small ensemble of models that together span the recommended mean and high change factors suggested by Sunyer et al. (2014) as shown on **Figure 15**.

Table 4 The e-folding distances [km] for all aggregation periods for all climate change perturbed WG output. Source: paper **V**.

	Aggregation period			
	1 hour	**6 hour**	**12 hour**	**24 hour**
WG – Present Climate	3.9	5.0	4.9	5.0
WG – HIRHAM SRES A1B	5.2	7.4	7.7	8.1
WG – RACMO SRES A1B	7.3	9.7	9.1	8.4
WG – HIRHAM rcp 4.5	5.2	8.4	8.7	8.8
WG – HIRHAM rcp 8.5	4.6	7.7	9.3	9.0
WG – WRF rcp 4.5	5.1	9.1	9.3	11.5
WG – WRF rcp 8.5	4.9	9.4	9.9	10.2

6 Discussion

As already mentioned, the fact that the expected climate change from the assessment using the WG is in accordance with previous studies is reassuring. This supports the perception, that the WG produces realistic time series; weather, when it is used for downscaling of climate change. To use the quote by Box from the foreword:

"Essentially, all models are wrong, but some are useful."

We know that the output from the WG is not a "correct" representation of real precipitation. Useful is really all we can hope for. The wrongness of the WG is diverse and acknowledged and represents the engineering challenge of modelling highly complex systems.

The WG does not include precipitation movement. This is clearly wrong because real precipitation indeed moves in all directions including vertically. Even so, the model is useful as the exclusion of movement results in a lot less complex model that is easier coupled to climate scales, and the resulting output can still be regarded as valid if correct assumptions are considered. For small catchments where precipitation would be expected to move across within the chosen hourly time step of the model, the inclusion of precipitation movement would not result in a fundamentally different output. On the other hand, if very large catchments are considered, where it will take longer time for weather to pass, the correlation structure in the WG precipitation output could present a behaviour that is not ideal. In this case other data products might be of more use: i.e. physically downscaled RCM output. Kendon et al. (2014) run an RCM at 1.5 km resolution and validate the output against corrected radar precipitation measurements. The results are remarkably similar to the ones presented in paper **V** even though the study area is Southern Britain. The extremely fine scale RCM output shows that short term precipitation extremes are going to increase and also that the spatial extent of extremes seem to increase slightly under climate change. This behaviour is not captured by a 12 km RCM comparison run with the same model.

The accompanying material to Paper **V** includes a video of 6-hour extreme precipitation events in output from both the WG at 2 km resolution and RCMs of 8 and 25 km resolution. **Figure 16** shows one hourly time step from

each of these for comparison. The rainfall movement cannot be assessed from one time step alone, but other features can. For both RCM simulations the area where it is raining heavily during a 6-hour extreme event is rather large whereas the area is much smaller in the WG output. Also, the cell to cell changes are much more dramatic, and realistic, in the WG output compared to both RCM output. All in all the WG is considered to produce realistic correlated time series at small spatial scales; even though for urban hydrology the scales are still considered coarse. Still, the time series can be used as input to urban hydrological modelling where catchments are smaller than the resolution of typical or even high resolution RCMs. For comparison Copenhagen, the largest urban catchment in Denmark, fits within one grid cell on the 25 km ENSEMBLES grid and approximately 10 grid cells in the 8km grid.

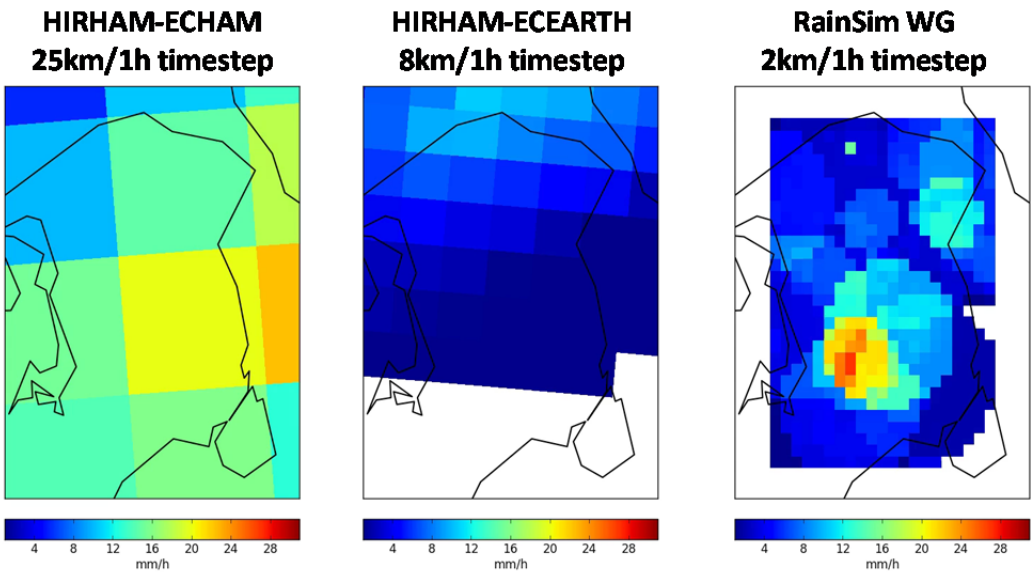

Figure 16 Simulations of precipitation 6-hour extremes from (left) HIRHAM-ECHAM at 25 km resolution, (middle) HIRHAM-ECEARTH at 8 km resolution and (left) the WG at 2 km resolution. The extremes between the models has nothing to do with one another. source: paper **V**.

For studies like the case study in paper **I**, this provides a data basis for long term simulation of structures in the urban hydrological systems and, hence, a better basis for assessing how they act and interact under different weather conditions; also in a changed climate. Furthermore, the small scale variability can be used using multiple realisations of the same weather to estimate the

variability, or uncertainty, of percentiles or POT based extreme events relevant for urban hydrology. This way, risk management can be optimized as the estimate of how wrong assumptions of T-year events, volumes or other relevant parameters relating to precipitation, can be quantified.

The spatio-temporal scales of the WG data product in paper **V** are usable for large urban catchments and for stormwater control measures as used in the examples in paper **I**. For sewer systems, especially the temporal scale is considered coarse, and scales of 5 to 10 minutes, like the one experienced for modern radar products, are desired (Bruni et al., 2014). To obtain such a product, spatio-temporal disaggregation could be considered as it has shown some skill in literature (Onof et al., 2005; Wang et al., 2010; Gires et al., 2012). But, precipitation movements would then be an even more problematic feature as its influence increases as the temporal scales decrease.

The WG presented in paper **V** is, for the available data sets, currently probably the most suitable approach for spatio-temporal downscaling of climate change. Had real distributed data been available for long periods, approaches with precipitation movement could have been introduced to enhance the performance of the model and decrease the scales even further (e.g. Willems, 1999; Peleg and Morin, 2012; 2014).

7 Conclusions

The aim of this thesis is modelling and downscaling of precipitation to spatio-temporal scales used in urban hydrology. To do so several observational data products are investigated and relevant scales where climate change and precipitation can be assessed for urban use are identified. Furthermore, precipitation is modelled at different scales using different stochastic techniques.

Identification of relevant spatial and temporal scales where climate change can be quantified with relevance for urban hydrology is difficult. What the exact relevant scales are depends of the point of view taken. The quantification of the 3PA is used to explain the importance of thorough framing and communication of needs. Also it shows the need for time series of precipitation data in urban hydrology, in addition to extreme event statistics, as model based analysis of e.g. stormwater control measures also depends on the precipitation chronology. For climate change studies this is challenging and compromises have to be made. A data product with a temporal 1-hour scale and a spatial 2 km scale is chosen as a compromise scale, which is considered to be relevant in urban hydrology and at the same time a scale where climate change impacts on precipitation can be assessed using existing regional climate model runs.

By assessing and comparing four observational precipitation data products for Denmark (SVK, CGD, ECA&D and E-OBS) it has been shown that the data quality is very important for the conclusions one can draw from studies. In this study where short term extremes and the spatial correlation structure of these is of importance, point measurements from rain gauged intended for use in analysis of urban infrastructure (the SVK data set) is the best choice.

Modelled at the finest scale available with Markov chain models the precipitation process seems very noisy. The models are not able to capture the process realistically in cases of extreme events. Also, the model framework is evaluated to be unsuitable for spatial modelling and incorporation of climate change.

The spatial de-correlation length of extreme precipitation at event level is observed to be much too large in regional climate model output compared to correlated point observations. Also, the seasonal distribution of extreme events in regional climate model output is different than for observations. Thus regional climate model output cannot just be corrected to the right intensity level and then be regarded as realistic weather input to impact models.

At the sub-daily time scale the extreme events cover way too much ground and use of adjusted regional climate model time series would potentially result in much more severe events than observed in reality.

Downscaled stochastic spatio-temporal data products with realistic spatial correlation structures can be produced by use of a stochastic Neyman-Scott rectangular pulses weather generator (*RainSim*) at relevant urban scales: The 1 hour temporal resolution on a 2 km grid used in this thesis is the finest implementation of this model to date. Good observational data, as provided by the SVK data set, are required for fitting of these models to present conditions as the correlation structures between different time series are important at the small local scale. The output from the weather generator performs well with respect to sub-daily to multi-daily precipitation extremes, their spatial correlation and their seasonality.

Climate change is incorporated into the weather generator through perturbation with change factors calculated from differences observed between regional climate model runs for present and future climate. Both high-end and moderate emission scenarios are considered. The study confirms other finding regarding expected changes in extreme precipitation for Denmark, but adds spatially correlated time series that represent these changes. Also, the study shows that there is no simple scaling relationship between moderate and high-end emission scenarios as the sub-daily extremes grows faster in magnitude than the daily ones for the high end scenarios. These data products can be used directly as input to large urban hydrological and hydraulic models where extremes are of major concern, and for models targeting stormwater control measures where water balances are mostly in focus; in both cases the hourly time scale may in many cases be acceptable.

The stochastic weather generators seem to be a good approach if the aim is to "model weather from climate". The study shows that it is possible to generate precipitation time series that are a realistic representation of weather in a changed climate using this approach. If more sophisticated models are to be implemented at finer spatio-temporal scales a shift from purely stochastic models to models including physical behaviour describing precipitation movement and links to synoptic scale weather are required.

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9 Papers

I **Sørup, H.J.D.**, Lerer, S.M., Arnbjerg-Nielsen, K., Mikkelsen, P.S. and Rygaard M. (in prep) Efficiency of alternative stormwater control measures: How the "Three Points Approach" (3PA) can guide the interpretation of strategic management approaches for rainwater harvesting, stormwater drainage and flood risk management.

II Sunyer, M.A., **Sørup, H.J.D.**, Christensen, O.B., Madsen, H., Rosbjerg, D., Mikkelsen P.S. and Arnbjerg-Nielsen K. (2013) On the importance of observational data properties when assessing regional climate model performance of extreme precipitation. Hydrological Earth System Science, 17, 4323-4337.

III **Sørup, H.J.D.**, Madsen, H. and Arnbjerg-Nielsen, K. (2012) Descriptive and predictive evaluation of high resolution Markov chain precipitation models. Environmetrics, 23(7) 623-635.

IV Gregersen, I.B., **Sørup, H.J.D.**, Madsen, H., Rosbjerg, D., Mikkelsen, P.S. and Arnbjerg-Nielsen, K. (2013) Assessing future climatic changes of rainfall extremes at small spatio-temporal scales. Climatic Change, 118(3-4), 783-797.

V **Sørup, H.J.D.**, Christensen, O.B., Arnbjerg-Nielsen, K. and Mikkelsen P.S. (in prep) Downscaling future precipitation extremes to urban scales using a spatio-temporal Neyman-Scott model.

In this online version of the thesis, the papers are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from.

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