Land surface impacts on precipitation in the Netherlands

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Abstract

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The Netherlands is a small and relatively flat coastal country with a temperate maritime climate and annual mean precipitation that varies spatially from 675 to 925 mm. Like in many regions of the world, there is ongoing urbanization. In fact, urban areas have increased from about 2% in 1900, to 13% in 2000, and are projected to increase to 24% in 2040. Other important land cover changes in the last century were the creation of new land in Lake Yssel and agricultural intensification (e.g. conversion of large heather areas into grassland). This thesis addresses the effects of historic and projected land use changes on precipitation in the Netherlands with data analyses and a mesoscale model.

The thesis first deals with the observed increase in precipitation in the last century and indicates that this is most likely attributable to an increase in sea surface temperature (**Chapter** 2). It is also found that along the West coast (the Randstad) precipitation is enhanced by urban areas (**Chapter** 3). Both chapters make use of daily gauge measurements. The observed precipitation increase from 1951 to 2009 is about 20% in the first 45 km from the coast and decreases by about 10% per 100 km thereafter progressing to the southeast/land inwards. The largest increases in precipitation are found from November through April, while the largest differences between precipitation near the coast and precipitation further inland are observed in May and June. At the same time, it is observed that precipitation amounts downwind of major urban areas are on average about 7% higher than the surrounding area. This increase was found to vary throughout the year with values of 9, 10, 3 and 8% in spring, summer, autumn and winter, respectively. The enhancement was detected over the entire distribution of precipitation, so both in the mean as well as the extremes. These results are comparable with studies from around the globe and show that the influence of relatively small fragmented urban areas, as are

present in the Netherlands, can be similar to the influence of large metropolitan areas on precipitation.

Next, the atmospheric Weather Research and Forecasting (WRF) model was used to investigate the sensitivity of precipitation to the land surface in the Netherlands in spring and summer. For a 4-day case study in spring (**Chapter 4**), a consistent positive soil moisture– precipitation feedback was found. That is, wet (dry) soils increase (decrease) the amount of precipitation. The expansion of urban areas and other projected land use changes resulted in an increase of the sensible heat flux and a deeper planetary boundary layer. Similar changes occur after reducing soil moisture. The strength of the soil moisture-precipitation feedback (measured as the ratio of evaporation to precipitation) was weaker in the urbanization experiments, because the reduction in evaporation was partly compensated by enhanced triggering of precipitation. In all, the reduction of moisture in urban areas led to a small countrywide decrease in precipitation, without a clear local response.

For summer, 19 synoptically similar days were investigated (**Chapter 5**). In WRF the change from historic to present land cover caused a decrease in precipitation. Expansion of urban areas also led to a small decrease in precipitation over the country as a whole, similar to the results in chapter 4. Over and downwind of cities precipitation increases of respectively 4 and 8% were simulated, consistent with observational evidence. In a moderate global warming scenario, here implemented as a homogeneous one degree temperature rise with constant relative humidity, increases in precipitation of about 7% are obtained. This response is larger than any of the modelled precipitation responses after land cover changes. Hence, precipitation will likely continue to increase over the coming decades, more so as a result of climate change than of land conversion. Nevertheless, in the Netherlands in summer the influence of land surface changes on precipitation is not negligible and counters the effects of climate change.

Samenvatting

De invloed van het land op regen in Nederland

Nederland is een klein en relatief vlak land met een gematigd zeeklimaat. De gemiddelde neerslag varieert over het land tussen de 675 en 925 mm per jaar. Net zoals in andere delen van de wereld, vindt in Nederland verstedelijking plaats. Het stedelijk oppervlak is uitgebreid van circa 2% in 1900, tot 13% in 2000 en, naar verwachting, tot 24% in 2040. Andere belangrijke landgebruiksveranderingen in de afgelopen eeuw zijn het afdammen van het IJsselmeer, de aanleg van Flevoland en de toename van landbouwgebieden (bijvoorbeeld de verandering van heide naar weiland) geweest. Dit proefschrift bestudeert de effecten van landgebruiksveranderingen uit het verleden en in de toekomst op neerslag in Nederland door middel van analyses van gemeten regendata en het gebruik van een weermodel.

Allereerst is in dit proefschrift de toegenomen hoeveelheid neerslag van de afgelopen eeuw onderzocht. De toename in neerslag is waarschijnlijk veroorzaakt door de stijging van de zeewatertemperatuur (**Hoofdstuk 2**). Daarnaast is gevonden dat neerslag in de Randstad (langs de westkust) versterkt wordt door stedelijk gebied (**Hoofdstuk 3**). Beide hoofdstukken maken gebruik van dagelijks gemeten regendata. De toename van neerslag tussen 1951 en 2009 bedraagt ongeveer 20% in de eerste 45 km vanaf de kust en vermindert daarna met ongeveer 10% per 100 km richting het zuidoosten/landinwaarts. De grootste toenames in neerslag hebben plaats gevonden tussen november en april, terwijl de grootste verschillen tussen neerslag langs de kust en in het binnenland plaats hebben gevonden in mei en juni. Tegelijkertijd blijkt uit het onderzoek dat neerslag benedenwinds van de grote steden (ten oosten bij westenwind) ongeveer 7% hoger is dan in de omgeving. Deze toename varieert door het jaar heen met ongeveer 9, 10, 3 en 8% in de lente, zomer, herfst en winter respectievelijk. De toename in neerslag is over de gehele verdeling van neerslag gevonden, dus zowel in het gemiddelde als in de extremen. Deze vondst is vergelijkbaar

met andere wereldwijde wetenschappelijke onderzoeken en laat zien dat de invloed van relatief klein, gefragmenteerd stedelijk gebied, zoals in Nederland, vergelijkbaar kan zijn met de invloed van grote metropolen op neerslag.

Vervolgens is in dit proefschrift het weermodel WRF (Weather Research and Forecasting) gebruikt om de gevoeligheid van neerslag voor landgebruiksveranderingen te onderzoeken in de lente en zomer. Voor een 4-daagse periode in de lente (**Hoofdstuk 4**) is een consistente positieve terugkoppeling gevonden tussen bodemvocht en neerslag. Dat wil zeggen: natte (droge) bodems laten de hoeveelheid neerslag toenemen (afnemen). De uitbreiding van steden en andere voorspelde toekomstige landgebruiksveranderingen leiden tot een toename van de voelbare warmteflux en een diepere atmosferische grenslaag. Dezelfde veranderingen treden op na een afname van bodemvocht. De sterkte van de 'bodemvocht-regen' terugkoppeling (bepaald als de ratio tussen verdamping en neerslag) was minder sterk in de experimenten waarin steden zijn uitgebreid, doordat de afname van verdamping gedeeltelijk werd gecompenseerd door een toename in het ontstaan van neerslag. Gezamenlijk leiden deze processen na het uitbreiden van steden tot een kleine afname van neerslag, zonder duidelijk ruimtelijk patroon.

De zomerperiode is onderzocht met behulp van 19 synoptisch vergelijkbare dagen (**Hoofdstuk 5**). De veranderingen van historisch naar huidig landgebruik leidden in WRF tot een afname van neerslag. Een toename van stedelijk gebied leidde, net als in hoofdstuk 4, tot een kleine afname van neerslag. In een gematigd scenario van klimaatverandering, hier geïmplementeerd door middel van een homogene temperatuurtoename van één graad, neemt neerslag met ongeveer 7% toe. Deze toename is groter dan welke neerslagverandering door landgebruiksveranderingen dan ook. Aldus is het aannemelijk dat neerslag zal blijven toenemen in de komende jaren, meer door klimaatverandering dan door veranderingen in landgebruik. Desondanks is het effect van landgebruiksveranderingen op neerslag in Nederland in de zomer niet te verwaarlozen en compenseren deze veranderingen de gevolgen van klimaatverandering op neerslag.

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Chapter 1

Introduction

Our direct surroundings influence the way we experience weather. Within a forest, for example, we are sheltered from harsh winds and from precipitation to a certain degree. But does our surrounding, the land surface, also influence the weather? This question lies at the core of the research throughout this thesis. The answer to this question is inevitably yes. Nevertheless, to which extent, under which conditions, and in which regions remains to be seen. In this thesis we study this question by analyzing observations and performing model simulations. The focus is on precipitation in the Netherlands. This chapter first describes the interactions of the land surface and precipitation, whereafter the utilized model is explained. The chapter ends with the research questions that will be answered throughout the remainder of the thesis.

1.1 The land surface

The land surface provides the lower boundary for the atmosphere, with which it exchanges energy, water and chemical compounds such as CO_2. The land surface, for example, exerts influence on the atmosphere by affecting the partitioning of incoming solar radiation. The sun's heat is partly absorbed by evaporation of water (latent heat). The remaining heat warms up the surrounding and is thereby felt by living organisms (sensible heat). As a result, on a sunny day, a well-watered grassland will remain relatively cool because a lot of the sun's heat goes into evaporation, while a dessert can become very hot, because there is little evaporation and the sensible heat flux high. This causes temperature and moisture differences between nearby and faraway areas. Weather, in turn, is driven by these temperature and moisture (i.e. pressure) differences between one place and another. On a global scale, the main driver of weather is the uneven heating of the Earth's surface by the sun.

Humans can modify the land surface and its characteristics through altered water management or changes in land use, such as expansion of urban areas, and conversion of nature into agricultural areas, or vice versa. Over the years humans have converted large natural areas across the globe. In the Netherlands, the most important land cover changes in the last century were the reclamation of new land in Lake Yssel and the conversion of large heather areas into grassland (Figure 1.1). Urban areas have increased from about 2% in 1900, to 13% in 2000, and are projected to increase to 24% in 2040 under a national scenario consistent with the SRES A2 scenario (Dekkers et al., 2012). Locally these land use changes could have an impact on weather (extremes) in addition to the changes mediated through greenhouse gases (Pielke, 2005).

The extent to which the land surface is able to modify weather or climate is often referred to as the land-atmosphere coupling strength (e.g. Koster et al., 2006). There is no single metric that can quantify this strength and, as it is often easier to calculate the land-atmosphere coupling in models than in reality, we heavily rely on models for our understanding. Different atmospheric variables can be influenced through this coupling. As such, the land-atmosphere coupling strength can be used to link observed trends to changes in the land surface. Global models are, for example, shown to be regionally sensitive to the land surface with respect to temperature (Feddema et al., 2005). However, human-induced changes have not been detected for precipitation at the global scale (Lambert et al., 2005, 2004). This is partly because changes in precipitation in different regions cancel each other out and thereby reduce the strength of the average signal (e.g. Allen and Ingram, 2002; Hegerl et al., 2004). In addition, precipitation has a high spatial and temporal variability and local events can create a diffuse pattern that is hard to formally attribute to the land surface.

1.2 Precipitation

Precipitation is an essential part of the hydrological cycle (Figure 1.2) and transfers large amounts of water from the oceans to the land. Water evaporates over bare soils, lakes,

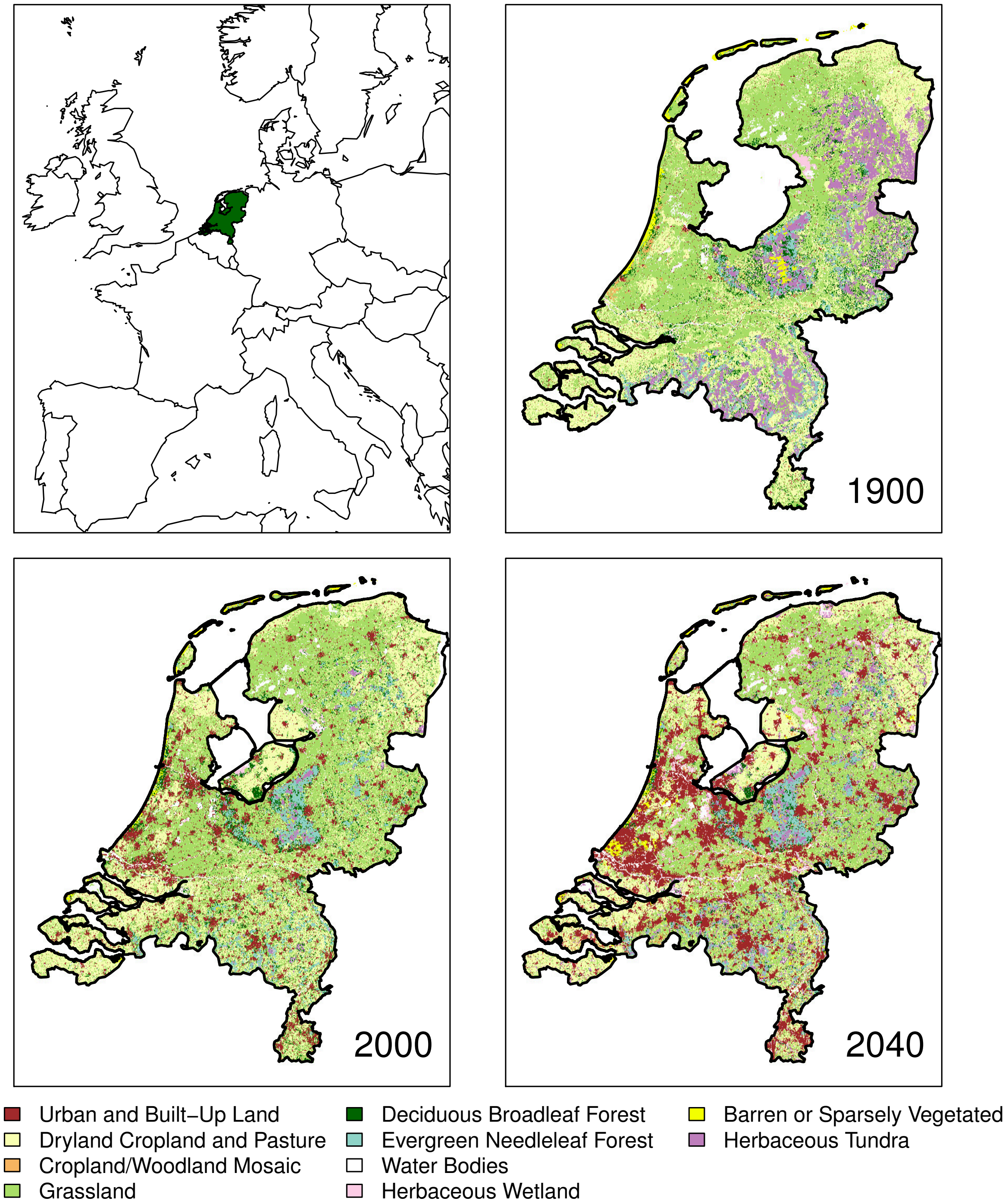

Figure 1.1 Location of the Netherlands within Europe and land use maps of the Netherlands in 1900 and 2000, and a projection for 2040.

streams and oceans and is transpired by plants in the process of photosynthesis. When air temperatures are sufficiently low (below the dew point temperature), water vapor in the air condensates onto nuclei to form cloud droplets. These droplets collide and coalesce to form larger droplets. As these larger water droplets descend, coalescence continues, so that the drops become heavy enough to fall – depending on temperature – as drizzle, rain, hail or snow.

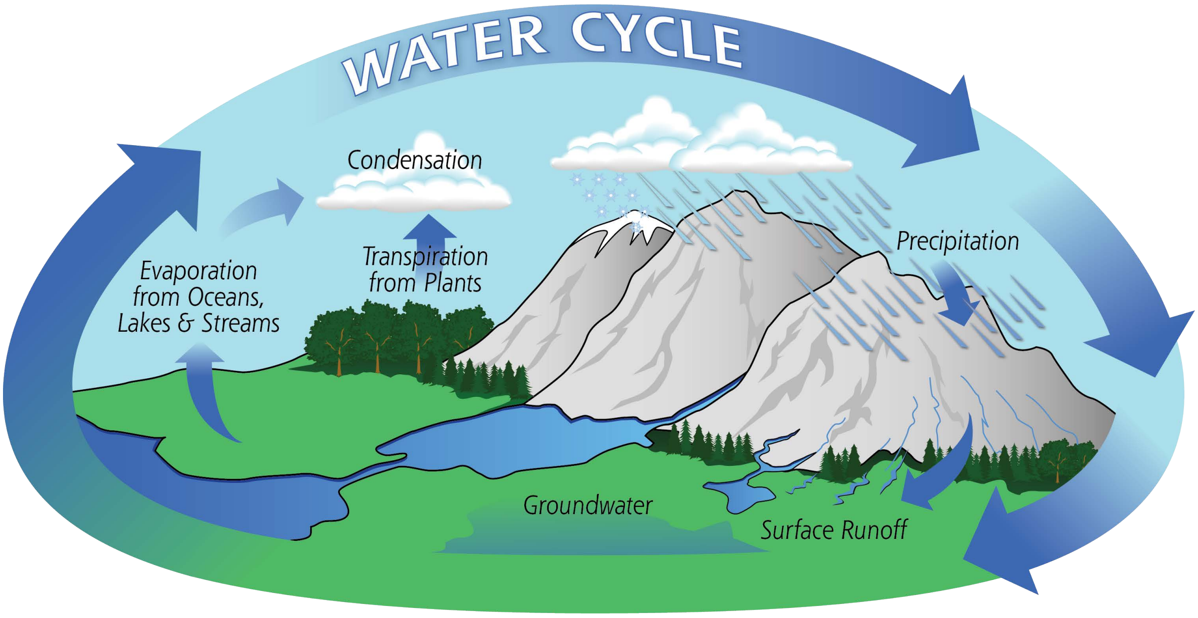

Figure 1.2 Hydrological cycle. Water vapour enters the atmosphere through evaporation or transpiration from the land surface. In the air, clouds and precipitation are formed. After precipitation falls on land, water travel back to oceans, lakes and streams through runoff or groundwater. Source: http://pmm.nasa.gov/education/water-cycle.

Evidence of the influence of the land surface on precipitation can for example be found in the relatively high precipitation amounts observed over the southernmost tip of the Netherlands, in Limburg, and over the Veluwe area (Figure 1.3). The Veluwe is a densely forested area with a maximum elevation just over 100 m located somewhat east of the middle of the country. The high precipitation amounts over the Veluwe, are the result of both topography and land cover (i.e. the abundance of forest) (ter Maat et al., 2013). In addition, the yearly cycle of precipitation shows a large, but reversed, difference between precipitation near the coast and further inland (i.e. coastal difference). The dominant wind direction in the Netherlands is (south)west, so that air entering the country from the North Sea generally provides sufficient moisture for precipitation. In spring and early summer, precipitation amounts are lowest near the coast, as the air needs to warm sufficiently before precipitation will occur. The higher surface roughness over land might also play a role (Malda et al., 2007). In autumn, precipitation amounts are highest near the coast.

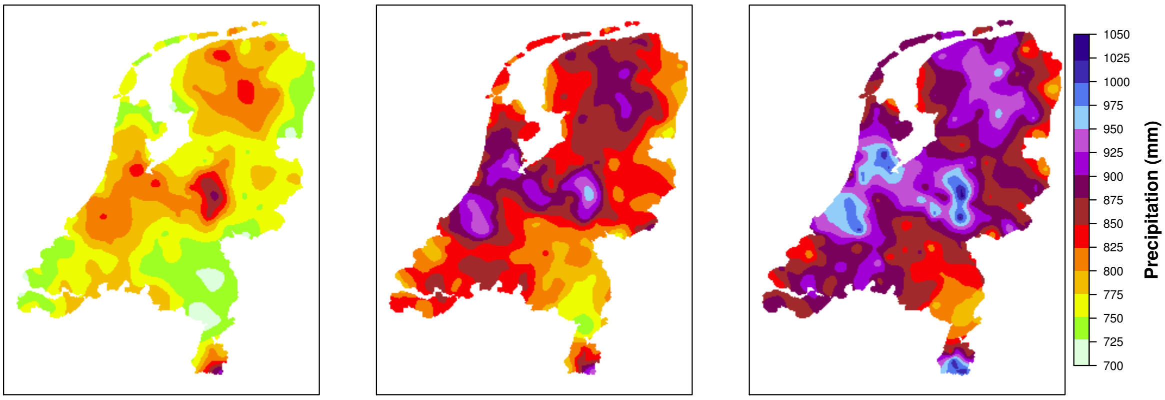

Figure 1.3 Climatological observed precipitation maps for the Netherlands for the periods 1951–1980 (left), 1980–2010 (middle), and a projection for around 2050 (right) under the KNMI'14 WH scenario.

Precipitation in the Netherlands has increased by about 25% in the last century (Buishand et al., 2013). The main reasons for this are considered to be the increasing sea surface temperatures (SST) (Attema et al., 2014) and changes in circulation (van Haren et al., 2013; van Oldenborgh and Van Ulden, 2003). Some regions (e.g. the West coast) have seen a larger increase in precipitation than others, this likely has to do with the enhanced coastal effect (Lenderink et al., 2009), but other factors like the land surface and ongoing urbanization in these areas might have contributed as well. These factors will be investigated throughout this thesis.

Climate change is expected to further alter precipitation patterns and amounts over the coming decades by enhancing temperature. The latest KNMI'14 climate scenarios for the Netherlands (van den Hurk et al., 2014) predict an increase in precipitation between 3 and 6% around 2050 depending on the scenario, compared to current (Figure 1.3). In the scenarios, the precipitation amounts are changed with a so called delta change approach. The delta change method is a transformation that scales historical precipitation time series to obtain series that are representative for a future climate. The coefficient required in the transformation is obtained from a regional climate model. The future maps of precipitation produced with this method have the same spatial distribution as the historical data, in this case the 1980–2010 period. In such a simple approach the potential influence of local land use changes on the precipitation patterns is neglected. This is debatable given the considerable changes in land use, and the indication from precipitation observations that the spatial pattern of precipitation has substantially changed over the last century.

In this thesis, gauge measurements are typically used in the chapters that investigate spatial patterns/differences and trends, because they are available for a long period of time. In the Netherlands, reliable data of over 240 stations is available since 1900 and at about 300 stations since 1950. The length of the observational record is very important for establishing the significance of results for such a variable measurement as precipitation. Radar data is more often used for the comparison with model results, because of its gridded nature and ample spatial coverage. Radar data for the Netherlands is available at a 2.4 km resolution since 1998. This radar data is used in the chapters with the model simulations. Space radars are available on some satellites, but are not used in this thesis as they have a lower quality and resolution (5 km) and sufficient ground based measurements are available in the Netherlands. Other techniques for measuring precipitation, such as satellites, microwave links, disdrometers and scintillometers are currently being explored, but the resolution, quality and/or record length is not sufficient yet to be used in this type of research. Because every type of measurement has uncertainties associated with it, a combination of measurements will likely continue to be needed in the future.

1.3 Soil moisture-precipitation feedback

The soil moisture-precipitation feedback is one of the feedbacks considered in the land-atmosphere coupling strength. This feedback is often used in investigating and explaining how the land surface influences precipitation. Key in this feedback – and more general in the connection between the surface's water and energy balances – is evapotranspiration. The term evapotranspiration (ET) is used for the combination of evaporation, from water or bare soil, and transpiration, from plants. Locally, at the plant scale, ET depends on temperature and humidity. Conditions of low humidity and high temperature are favorable for high values of ET, but ET can be limited by other atmospheric conditions, incoming solar radiation, or surface conditions, such as soil moisture and the presence of vegetation. Soil moisture is usually defined as the water contained in the unsaturated soil zone or root zone (e.g. Hillel and Hillel, 1980). However, the amount of water that a soil can hold depends on the soil type and its properties. Because ET largely depends on the availability of water at or near the surface, soil moisture is a key factor in the interactions between the land surface and atmosphere. Because of its relatively slow response, soil moisture is valuable in seasonal forecasting (The GLACE Team et al., 2004) and also an important memory component of the climate system (e.g. Seneviratne et al., 2006).

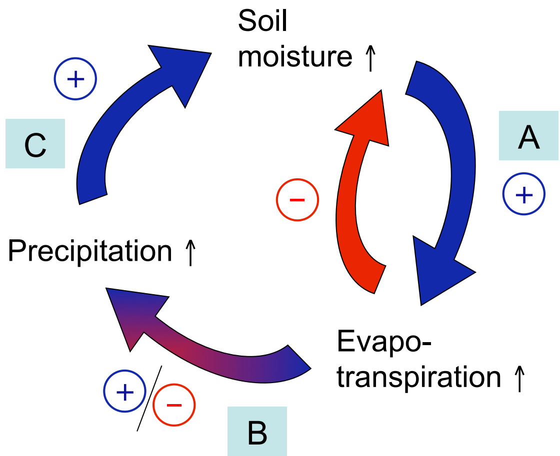

Figure 1.4 Soil moisture-precipitation feedback. Positive arrows (blue) indicate processes leading to a positive soil moisture-precipitation feedback (wetting for positive soil moisture anomaly), the negative arrow (red) indicates a potential negative feedback dampening the original soil moisture anomaly, and the red-blue arrow indicates the existence of both positive and negative feedbacks between evapotranspiration and precipitation anomalies; A, B, and C refer to different steps of the feedback loop. Source Seneviratne et al. (2010).

The soil moisture-precipitation feedback (Figure 1.4) consists of three relationships: A, B and C (Seneviratne et al., 2010). Relationship A, B and C refer to: higher soil moisture leading to higher evapotranspiration, higher evapotranspiration leading to higher precipitation, and higher precipitation leading to higher soil moisture. Relationship A and C are local, while relationship B can be regional or even global and can transport water over large areas. Relationship A is positive, though a negative feedback potentially exists, since increasing evapotranspiration decreases the available soil moisture. Thus, to sustain a positive soil moisture-precipitation feedback, the enhancement of precipitation needs to be at least as large as the enhancement of evapotranspiration, otherwise the net effect will be a reduction of soil moisture (Boé, 2013). If precipitation falls in the same region it originates from, this is called moisture or precipitation recycling (Bisselink and Dolman, 2008; van der Ent et al., 2014). Relationship B is the most uncertain and influenced by regional circulation. Though on a global scale it is commonsense and positive (van der

Ent and Savenije, 2011), locally it may be either positive or negative (e.g. Hohenegger et al., 2009; Taylor et al., 2012; Tuinenburg et al., 2011).

The sign of the soil moisture-precipitation feedback depends on precipitation being enhanced over wet or dry soils, through triggering or amplification. Dry soils have a relatively high sensible heat flux and consequently higher surface temperatures and a deeper planetary boundary layer (PBL). Because of the relatively low temperatures at the top of a deep PBL, moisture transported by uprising thermals can easily condensate and form clouds and subsequent precipitation. Wet soils, on the other hand, have a much shallower and more moist PBL in general, resulting from the high latent heat flux at the surface. This can amplify precipitation. The key for understanding soil moisture-precipitation feedbacks therefore lies in the impact of soil moisture anomalies on boundary layer stability and the formation of precipitation (e.g. Ek and Holtslag, 2004; Santanello et al., 2011; Schär et al., 1999). The soil moisture-precipitation feedback will be further explained and used in Chapter 4 of this thesis.

1.4 Effects of urban areas

Urban areas only cover 1 to 3% of the earth's surface (Balk et al., 2006; CIESIN et al., 2011), but their presence can have a large impact on the local atmosphere since the conversion of rural into urban areas alters nearly all aspects of the land surface. Vegetation is removed and soil moisture (availability) is heavily reduced by the use of impervious materials and sewers. In addition, the tall buildings change albedo and roughness. In the Netherlands, as well as in most other countries in the world, there is ongoing urbanization. More than 50% of the world population currently lives in cities and this is expected to rise to 70% by 2050 (WHO, 2014). This is important, because urban areas seem to initiate significant changes in their surroundings, despite their relatively small size. However, several specific urban challenges exist in relation to measuring, modelling and attribution.

Measurements are traditionally conducted outside of urban areas themselves to avoid influence. Gauge placement, for example, follows international guidelines (WMO, 1989) and should be at sufficient distance from nearby obstacles such as buildings and trees, in a well-watered grass field. Despite these precautionary measures, the effect of nearby urban areas has been proven to exist for temperature in the Netherlands (Brandsma et al., 2003). In the last decade the interest in the urban climate has invigorated, partly due to the adverse effects of heat stress that have become more prominent in combination with the effects of climate change. In response, more measurements are now being conducted within cities specifically. For temperature, measurements are ample, for precipitation they are still scarce.

Temperature measurements conducted in the last decade show that urban areas in the Netherlands can be up to 10 K warmer than the surrounding areas (Steeneveld et al., 2011; van der Hoeven and Wandl, 2015; Wolters and Brandsma, 2012). This phenomenon is called the Urban Heat Island (UHI). Some scientists have also used the terms Urban Precipitation Island (UPI) (Yu, 2007) or urban impact on precipitation (UIP) (Yang et al., 2014), but in contrast to UHI, these have not become recognized expressions (Figure 1.5). The reasons for this seem to be manifold. For instance, temperature is continuous in both time and space while precipitation is not. Also, the physics of heat and heat transfer are better understood than cloud physics, which need to be comprehended before accurate precipitation predictions can be made. Additionally, precipitation does not always seem to be positively enhanced by urban areas, and examples of increases as well as decreases have been given in literature (see Chapter 3). Furthermore, the location of this UPI is not located in the city itself (as is the UHI) but often occurs several tens of kilometers downwind of the city (Yu, 2007).

Shepherd (2005) state the following possible mechanisms for urban areas to impact precipitation or convection:

1. enhanced convergence due to increased surface roughness in the urban environment (e.g. Bornstein and Lin, 2000; Thielen et al., 2000);
2. destabilization due to UHI-thermal perturbation of the boundary layer and resulting downstream translation of the UHI circulation or UHI-generated convective clouds (e.g. Baik et al., 2007; Han and Baik, 2008; Shepherd and Burian, 2003; Shepherd et al., 2002);
3. enhanced aerosols in the urban environment for cloud condensation nuclei (CCN) sources (e.g. Diem and Brown, 2003; Molders and Olson, 2004);
4. bifurcating or diverting of precipitating systems by the urban canopy or related processes (e.g. Bornstein and Lin, 2000; Loose and Bornstein, 1977).

Mechanism 1, enhanced surface roughness, seems questionable, because the upward motion needs to be strong enough to initiate moist convection. The study of Thielen et al.

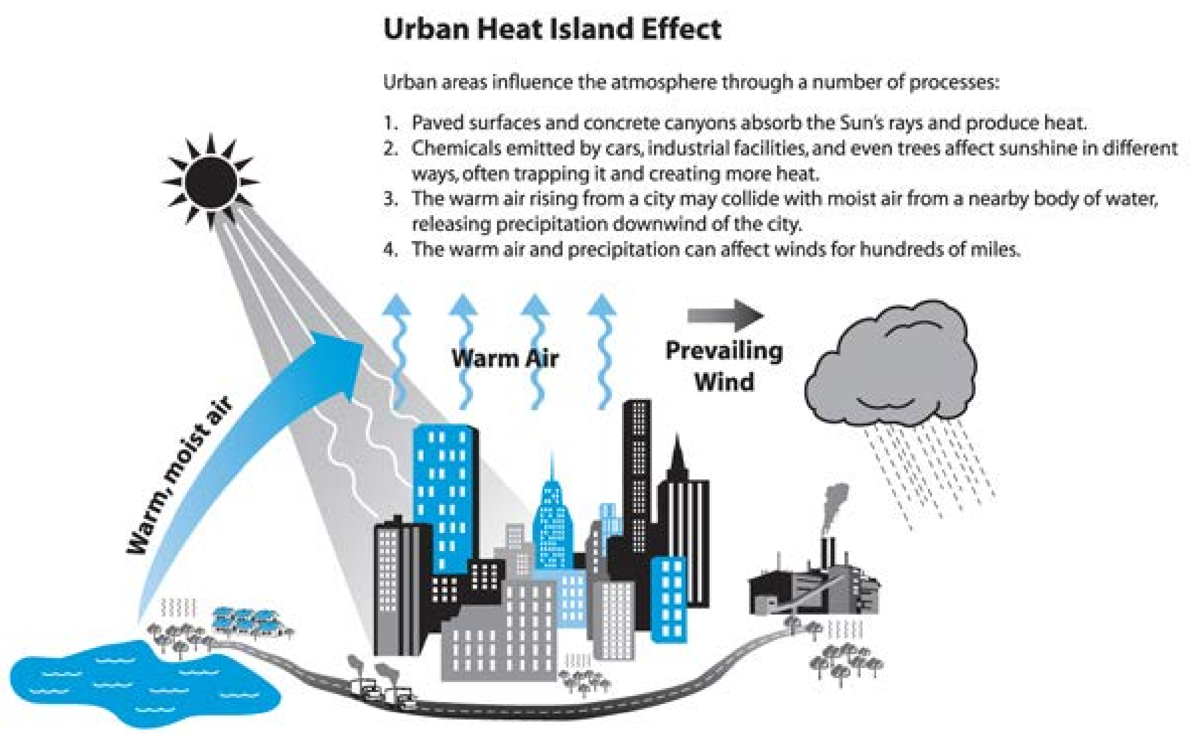

Figure 1.5 Urban heat island effect with influence on temperature and precipitation. Source: http://www.ucar.edu/communications/staffnotes/0603/cities.shtml.

(2000) was two-dimensional and more recent three-dimensional modelling efforts show that roughness alone is likely not enough to enhance precipitation (e.g. Miao et al., 2011; Rozoff et al., 2003). Mechanism 2, UHI-thermal perturbation, works particularly well when the urban sensible heat flux is large and the atmospheric boundary is almost neutral (Han et al., 2014). Hence, it plays a large role in the thunderstorms occurring downwind of cities in the afternoon or early evening in summer. Mechanism 3, enhanced aerosols, is very complex (Tao et al., 2012) and can work both ways. The large (dirty) aerosols that were emitted in the past were shown to enhance precipitation (Altaratz et al., 2014). While the small aerosols that are frequently being emitted nowadays are shown to reduce precipitation (Junkermann et al., 2011; Rosenfeld, 2000). Mechanism 4, bifurcation of the flow, has not received much attention in recent years anymore because of the inherent difficulties in separating systematic effects from the chaotic weather system.

Observational evidence of precipitation enhancements downwind of major cities can be found in many research papers. Lowry (1998); Shepherd (2005) and Han et al. (2014) give a good overview of the research conducted in the last century. Landsberg (1981) already noted the inherent difficulties of studying precipitation-related urban effects: *"A great deal of attention has been devoted to the urban effects of [sic] precipitation. These have been noted for a number of decades but were relatively hard to verify by statistical tests. The reason for this is the very high variability of rain amounts and the poor qualities of the ordinary rain gauge as a sampling device. Decades of observations are usually needed to establish differences at a reasonable level of significance."*

Attribution of urban effects on precipitation is nevertheless still challenging nowadays, even though decades of observations are available. One of the difficulties is an essential problem nicely portrayed by Lowry 1998: *"It is a certainty that the processes of urbanization and industrialization cause changes in weather and climate. But one cannot undertake a controlled experiment with and without the city present; nor can one replicate an observation, because no two cities and no two weather sequences are exactly alike. Likewise, one cannot put a city and its surroundings in a controlled experimental chamber, as could be done with a plant or an animal."*

Modelling is seen as a potential solution to overcome the measurement and attribution challenges in urban areas. With a model it is possible to simulate a controlled experiment in which a city is present or not in exactly the same weather conditions and sequence. However, such a model needs to be complex enough to be able to capture ongoing processes realistically in time and space, while being computationally efficient. For this reason small-scale processes are parameterized and simplified, and complex interactions such as aerosols are neglected.

1.5 Atmospheric modelling system

In addition to the analyses with observational data, the research in this thesis makes use of a mesoscale modelling system. A mesoscale model typically has a higher spatial (100 m – 10 km) and temporal (hourly) resolution than a global weather model. This high resolution is important for accurate prediction variability and (extreme) event statistics (e.g. Frei et al., 2006). Global models tend to have a resolution of 25 - 100 km at the least, which is insufficient to model spatial differences in the Netherlands. Specifically, this thesis makes use of the Weather Research and Forecasting (WRF) modelling system (Skamarock et al., 2008). Like all mesoscale models, WRF is usually run for a limited region and therefore needs boundary and initial conditions, such as the location of pressure systems and state of the soil (Figure 1.6). A different set of variables is needed for the initialization of the model and temporal nudging. Necessary initial conditions include: (sea) surface temperature, soil type, temperature and moisture content, terrain height, and wind, temperature and moisture fields. At the outer bounds of the model domain six hourly updates of atmospheric variables are typically given. These include: temperature, pressure and moisture at different levels of the atmosphere. The model then computes atmospheric dynamics within its domain and stores the state of the atmosphere, surface fluxes and cumulative precipitation as output.

Boundary conditions for a mesoscale model are generally obtained from a larger scale model or reanalysis product. A reanalysis product makes use of past observations and a model to obtain a synthesized estimate of the state of the weather and climate system over time. A reanalysis typically extends over several decades or longer, and covers the entire globe from the Earth's surface to well above the stratosphere. Several reanalysis products are available, such as from the USA (NOAA/NCEP) and Japan (JRA). Here the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis is used because this dataset (ERA-Interim) is easily available, compatible with WRF, and generally has a low bias compared to observations (Decker et al., 2011). The quality of the boundary conditions is important for a mesoscale model because biases are inherited (e.g. Fowler et al., 2007; Xue et al., 2007).

All atmospheric models solve the fluid- and thermodynamics equations. Global models are often hydrostatic, which means they assume a stable equilibrium and simplify the vertical motion equation. This simplification has almost no effect on the prediction of large-scale phenomena and allows the model to run faster. However, models with grid spacing of a few km or finer need to be non-hydrostatic (i.e. solve the full vertical motion equation) to get the correct answers in cases with a larger vertical depth than horizontal length, such as deep convective cells. WRF is such a non-hydrostatic model, and supplements these equations with parametrizations for clouds, short- and longwave radiation, PBL, land surface, urban surface and surface layer. Still, the model's resolution is too coarse to include individual obstacles like trees or buildings in natural and urban landscapes. Cities therefore have simplified (street canyon) geometry and bulk parameters for heat transfer and albedo among others.

The selected combination of parameterization schemes in WRF, like in other models, can have a large impact on the results. This makes investigating the sensitivity of different parameterization schemes an active area of research. Ideal settings do not seem to exist

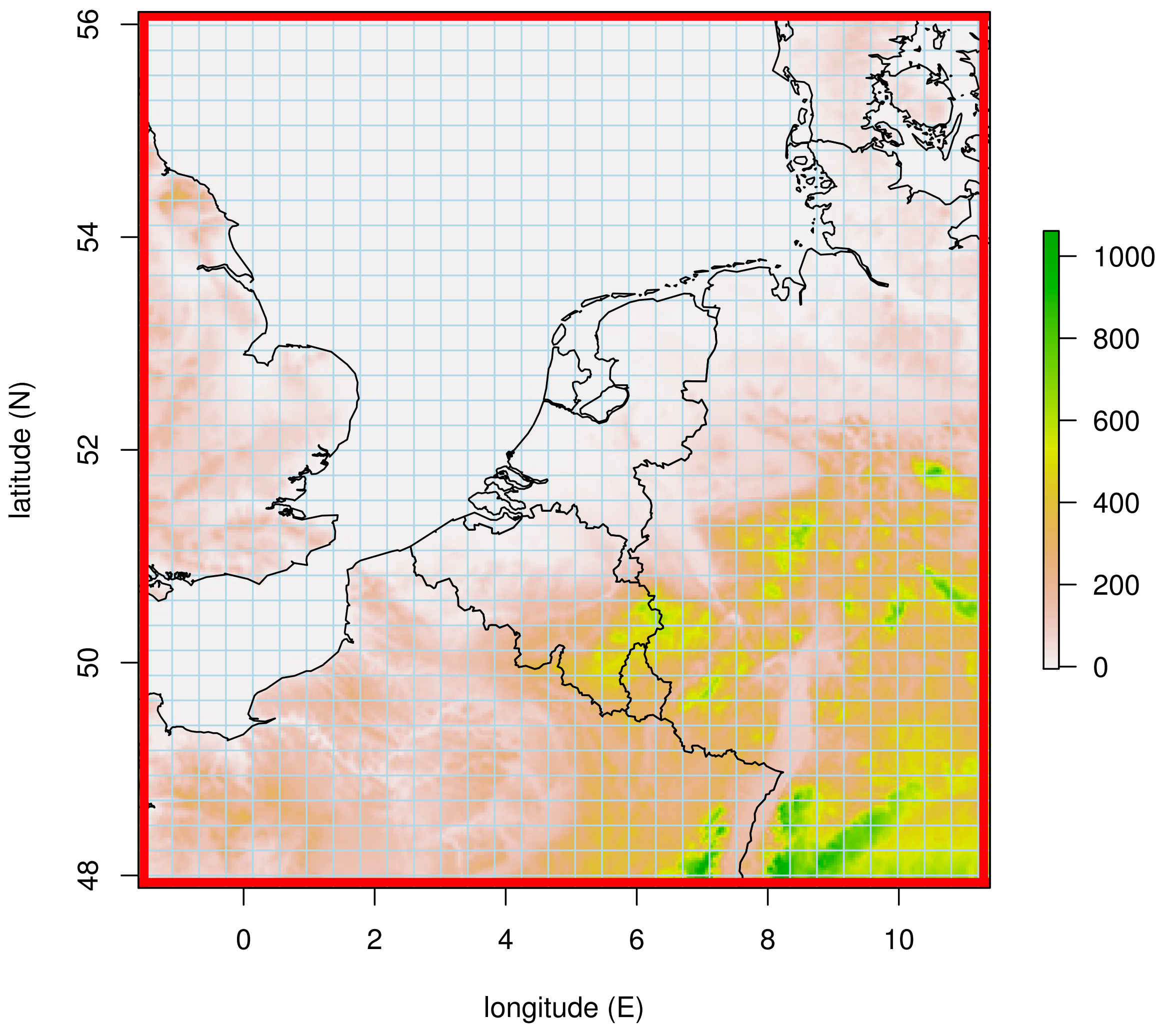

Figure 1.6 Weather Research and Forecasting (WRF) model domain (as used in Chapter 5) with the European Centre for Medium-Range Weather Forecasts (ECMWF) input data resolution, showing initial conditions (terrain height [m]) and the outer bound (red) where boundary conditions are needed.

(e.g. Jin et al., 2010; Panda and Sharan, 2012; Zeng et al., 2012). Instead, the optimal choice appears to depend on atmospheric regime and the local situation. WRF is, for example, sensitive to the PBL scheme (Jankov et al., 2005, 2011, 2007; Wang et al., 2007), that indirectly affects rainfall amounts (Argueso et al., 2012; Flaounas et al., 2011; Koo and Hong, 2010). Specifically regarding precipitation, it seems that WRF generally overestimates precipitation intensity and underestimates precipitation frequency (e.g. Caldwell et al., 2009; Dravitzki and McGregor, 2011; Gallus, 2010; Knievel et al., 2004; Kusaka et al., 2010; Molders, 2008). Accurate predictions of precipitation are difficult to make with any model, because of the variable nature of precipitation in both space and time, and the complexity of atmospheric mechanisms before the onset of precipitation.

1.6 Research objectives and questions

Overall, this thesis aims to contribute to better understanding of land-atmosphere interactions. Thorough understanding of surface and boundary layer processes, will allow for the improvement of models of weather, climate, and air quality. This might increase the predictions of the predictions of these earth system models. Adequate predictions at short to medium time scales can be used for issuing warnings. These warnings can help reduce negative effects and capitalize on opportunities for people, property, and the environment. Predictions of both weather and climate are already used in policy making and planning today and are expected to become more important in the future.

The following chapters in this thesis answer four general research questions for the Netherlands:

1. **Can observed trends in precipitation patterns be related to land surface characteristics?**

   We address this question using historical precipitation data for the period 1951-2009 and try to explain persistent spatial precipitation patterns in relation to soil type, topography, urbanization and sea surface temperature. We therefore divide the country into regions based on surface characteristics and zones at different distances to the coast and discuss the results in this context. We aim to determine the extent to which the land surface has had an influence on trends in precipitation amounts and patterns.

2. **Is there evidence of enhanced precipitation downwind of urban areas?**

   Although the question of the effect of urban areas on precipitation is touched upon in Chapter 2, we provide a more detailed analysis in Chapter 3. Now, we categorize days with the synoptic circulation classification and specifically look at precipitation downwind of urban areas (i.e. to the east of a city, under westerly winds). The growth of urban areas and consequently increased downwind area are taken into account by redoing the analysis every 10 years throughout the 1951-2010 period. Traditionally, research compares precipitation in the area upwind to that in the area downwind of a major city. Our approach differs from these methods to account for the many relatively small cities in the Netherlands that lie in close proximity.

3. **How does the land surface influence springtime precipitation?**

   To address this question, in Chapter 4 we use the atmospheric modelling system and alter the land surface conditions, by simulating wet and dry soil conditions and different extents of urban areas. We simulate a 4-day period in spring where we expect that triggering of convection above land plays an important role. We investigate the potential for cloud formation, triggering of precipitation and explore changes in the precipitation distribution in the simulations. In addition, we quantify the ratio of evapotranspiration to precipitation, which can be seen as a measure of the soil moisture-precipitation feedback. In this way, we are able to quantify the influence of land-atmosphere interactions on precipitation.

4. **What is the influence of historic and future land use changes on summertime precipitation?**

   For Chapter 5 we incorporated high resolution land cover maps of the Netherlands into WRF and simulate summer precipitation with land cover of 1900, 2000 and 2040. In addition, we conduct a simple climate change experiment in which temperature is increased by 1 K. We investigate this for 19 synoptically similar days that are selected with a clustering procedure. With this, we are able to investigate the relative contributions of historical and future land cover changes and climate change on summer precipitation in the Netherlands.

Finally, in Chapter 6, we give an overview of additional work on urban effects, and present an analysis of precipitation as simulated within and downwind of urban areas by WRF. Next, we try to put our work in the perspective of ongoing climate change and show the results of a 'composite event'. Lastly, we reflect on the methods utilized in this thesis and discuss the implications for future research.

Chapter 2

Spatial precipitation patterns and trends during 1951-2009*

Significant increases in precipitation have been observed in the Netherlands over the last century. At the same time persistent spatial variations are apparent. The objective of the present study is to analyse and explain these spatial patterns, focussing on changes in means and extremes for the period 1951-2009. To investigate different possibilities for the causes of spatial variations, a distinction was made between six regions based on mean precipitation, soil type and elevation, and four zones at different distances to the coast.

Spatial maxima in mean precipitation inland and over elevated areas are mainly formed in winter and spring, while maxima along the coast are generated in autumn. Daily precipitation maxima are found in the central West coast and over elevated areas. Upward trends in daily precipitation are highest from February to April and lowest from July to September. The strongest and most significant increases are found along the coast. For several seasonal and climatological periods diverging behaviour between coastal and inland zones is observed. We find that distance to the coast gives a more consistent picture for the seasonal precipitation changes than a classification based on surface characteristics. Therefore, from the investigated surface factors, we consider sea surface temperature to have the largest influence on precipitation in the Netherlands.

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2.1 Introduction

Assessment and estimation of weather and climate extremes contributes to our understanding of the changing climate (e.g. Klein Tank et al., 2009) and studies analyzing trends and especially extremes are numerous. For precipitation some recent European studies find opposing trends in extreme precipitation (Anagnostopoulou and Tolika, 2012; Burauskaite Harju et al., 2012; Karagiannidis et al., 2012). This is no surprise because, trends can be even of opposing direction for different regions within a country (del Rio et al., 2011; Lupikasza et al., 2011) and obviously within Europe as a whole (e.g. Klein Tank and Konnen, 2003). Furthermore, trends are often dependent on the time period examined (Brunetti et al., 2012; Turco and Llasat, 2011) and care has to be taken when results based on different periods are compared.

The most recent precipitation trend analysis for the Netherlands has been performed by Buishand et al. (2013). They determined annual precipitation amounts, precipitation amounts in winter and summer halves of the year, number of days per year with a precipitation amount greater than 20 mm and 30 mm, and the 5-day annual maximum precipitation. All six indices show increasing trends, the strongest of which were found in winter precipitation and the number of days with more than 20 and 30 mm rain. The mean exceedance frequency of the 30 mm threshold for the wettest parts of the country was found to be about twice as large as that for the driest part and shows a relatively strong increase from the beginning of the 1980s. Overall, the largest changes were found in the coastal area.

Especially for extremes, the achieved results are strongly dependent on the chosen index (Ustrnul et al., 2012). Ustrnul et al. (2012) show the advantages and disadvantages of different methods used to identify extremes in temperature and precipitation and their influence on long-term variability and trends. They found the method of percentiles to be the most suitable for spatial analysis. Percentiles split a set of ordered data into hundredths, so 90% of the data should fall below the 90th percentile. Percentile values are site-specific because they sample the same part of the distribution at each station while the value over threshold approach can favour sites at specific locations where events with high precipitation amounts occur more frequently.

This study will extend the work of Buishand et al. (2013), who investigated threshold exceedance frequencies, with an analysis of percentiles and focus on regional differences in precipitation changes for the Netherlands. Our objective is to analyse and explain persistent spatial patterns in relation to several factors, which will be described in more detail below. Investigated are soil type, sea surface temperature (SST), topography and urbanization. We choose these, because (1) soil moisture has a large impact on the energy partitioning between latent (moisture) and sensible heat fluxes at the land surface (Seneviratne et al., 2010) and therefore has the potential to influence precipitation; (2) a large fraction of the Netherlands is located along the relatively shallow North Sea and the influence of SST on precipitation has been investigated and proven for the Netherlands (Lenderink et al., 2009); (3) even though elevation differences in the Netherlands are small, they have been shown to affect local precipitation (ter Maat et al., 2013); and (4) the influence of urbanization on precipitation is receiving more and more attention (Shepherd, 2005; Trusilova et al., 2009) and might be significant.

Soil type and soil moisture are directly related to each other through the differences in water holding capacity and pore size. Although soil moisture-precipitation feedbacks are usually found at large (i.e. continental or global) scales, the influence on smaller scales should not be dismissed. Even within the Netherlands large differences in Bowen ratio or evaporative fraction can occur. This is shown by a quick comparison of two Fluxnet sites: Loobos, a pine forest on sand in the East region (see Figure 2.2 for the location of the regions), and Cabauw, a grass field on a peat/clay soil in the West region. Observed mean Bowen ratios computed from Fluxnet towers (available online: www.fluxdata.org) are 2.0 for Loobos and 0.6 for Cabauw in spring (MAM) and are 1.3 for Loobos and 0.4 for Cabauw in summer (JJA).

Seneviratne et al. (2010) have written an extensive review on large scale soil moisture-climate interactions that also focusses on soil moisture-precipitation feedbacks. They conclude that because of the direct impact of precipitation on soil moisture, links of causality between soil moisture and precipitation are difficult to establish. Two opposing feedback mechanisms that enhance convective activity and increase precipitation have been proposed (Findell and Eltahir, 2003). On the one hand, dry soils could trigger convection because the higher sensible heat flux increases the strength of the updraft, this combined with high moisture availability at the top of the atmospheric boundary layer enhances cloud formation (Westra et al., 2012). On the other hand, wet soils could increase convection through the build-up of a comparatively shallow and moist boundary layer and a large(r) net radiative energy flux (Schär et al., 1999) so convective updraft saturates at relatively low levels. The feedback mechanism over wet soils is mainly found in modelling studies and might be an artefact of model parameterizations at low resolutions. Hohenegger et al. (2009) for example found significant differences between simulated soil moisture-precipitation feedback at 25 and 2.2 km resolution. A recent global observational analysis showed afternoon precipitation falls preferentially over dry soils, in contrast with the precipitation simulated by global climate models (GCMs) (Taylor et al., 2012). In addition, Orlowsky and Seneviratne (2010) warned that apparent soil moisture-precipitation feedbacks for GCM simulations can often as well or even better be attributed to the influence of global SST fields.

There are several studies on influence of SST on large scale precipitation (e.g. Benestad and Melsom, 2002; Kjellström and Ruosteenoja, 2007) and a few at smaller scales (Jung et al., 2010; Messager et al., 2004; Persson et al., 2005). For the Netherlands the influence of SST on precipitation has been found significant and particularly strong in the coastal area less than 30-50 km from the coastline (Lenderink et al., 2009). The adjacent North Sea is a shallow coastal sea (20–200 m deep) and therefore cools or warms relatively fast (on time scales of weeks to months) dependent on the atmospheric conditions and shortwave radiation. van Oldenborgh et al. (2009) found that the North Sea temperatures follow the temperature rise of the Netherlands, which is higher than the global mean trend. Some of the observed increases in precipitation along the coast are likely related to the land-sea temperature contrast. Temperatures over sea are higher from August onward and enhance coastal precipitation until December when the atmosphere is on average too stable for frequent convective showers to occur (Attema et al., 2014). From April to July coastal precipitation is suppressed by relatively cold sea water temperatures.

Topography plays an important role in the distribution of precipitation, even in Northwestern Europe where gradients are relatively small (Gilles et al., 2006; Osborn et al., 2000). The Netherlands is a very flat country with maximum elevation of about 325 m in the South of the country and just over 100 m on the Veluwe. The Veluwe is a densely forested and elevated area located somewhat east of the middle of the country. Nonetheless even the limited topography of the Veluwe has been shown to influence the local precipitation climate (ter Maat et al., 2013). ter Maat et al. (2013) showed that the difference in precipitation between the Veluwe and its surroundings, with a maximum of 14.5%, is highest in winter. Their analyses suggest that the precipitation maximum can only be explained by a combination of topography and land-use.

Both modelling and observational studies show increases in precipitation downwind of or near large urban areas (Comarazamy et al., 2010; Li et al., 2011; Mitra et al., 2012;

Shepherd et al., 2010). These increases seem to be caused by a combination of physical and chemical processes. Urban areas have a larger heat-storage capacity, Bowen ratio and an increased surface roughness in comparison with rural areas (Oke, 1982). These differences affect the surface energy budget and planetary boundary layer, which in turn impact the regional climate in and around urban areas. Furthermore, Russell and Hughes (2012) find increases in precipitation are significantly and negatively correlated with NO_x emissions. Other simulations with a microphysics cloud model show that heightened urban aerosol concentration in combination with the low-level updraft induced by the urban heat island leads to enhanced precipitation (Han et al., 2012). Urbanization in the Netherlands has strongly increased in the last century and its influence on observed precipitation increases cannot be ruled out. Therefore we integrate urbanization into some of the analyses in this study.

Our objective is to analyse and explain persistent spatial patterns and changes herein in relation to surface forcings. To achieve this, we divide the country into regions based on surface characteristics and zones at different distances to the coast. Topography is taken into account in the regions based on surface characteristics. The regions and zones will be introduced in Section 2.2. Section 2.3 identifies persistent spatial patterns and adds percentiles to the analyses of Buishand et al. (2013). In this section we also analyse mean and extreme annual and seasonal precipitation amounts and annual trends. The regional differences in monthly mean and extreme precipitation changes are compared in Section 2.4 where we also compare annual precipitation differences over two climatological periods. The paper will conclude with a discussion and summary of results in Sections 2.5 and 2.6 respectively.

2.2 Data and methods

Daily precipitation data for the period 1951-2009 are obtained from the KNMI manual rain gauge network. The data used in this study has been homogenized as part of the study by Buishand et al. (2013) with the automated homogenization procedure of Menne and Williams (2005). About 37% of the initial 377 precipitation series were designated as inhomogeneous and were corrected with the homogenization procedure. We use the same dataset as Buishand et al. (2013) for consistency, therefore the years 2010-2012 are not included. Only stations that had no more than 2% of daily precipitation observations missing are used. Missing data were supplemented with data from the nearest station at a maximum distance of 50 km.

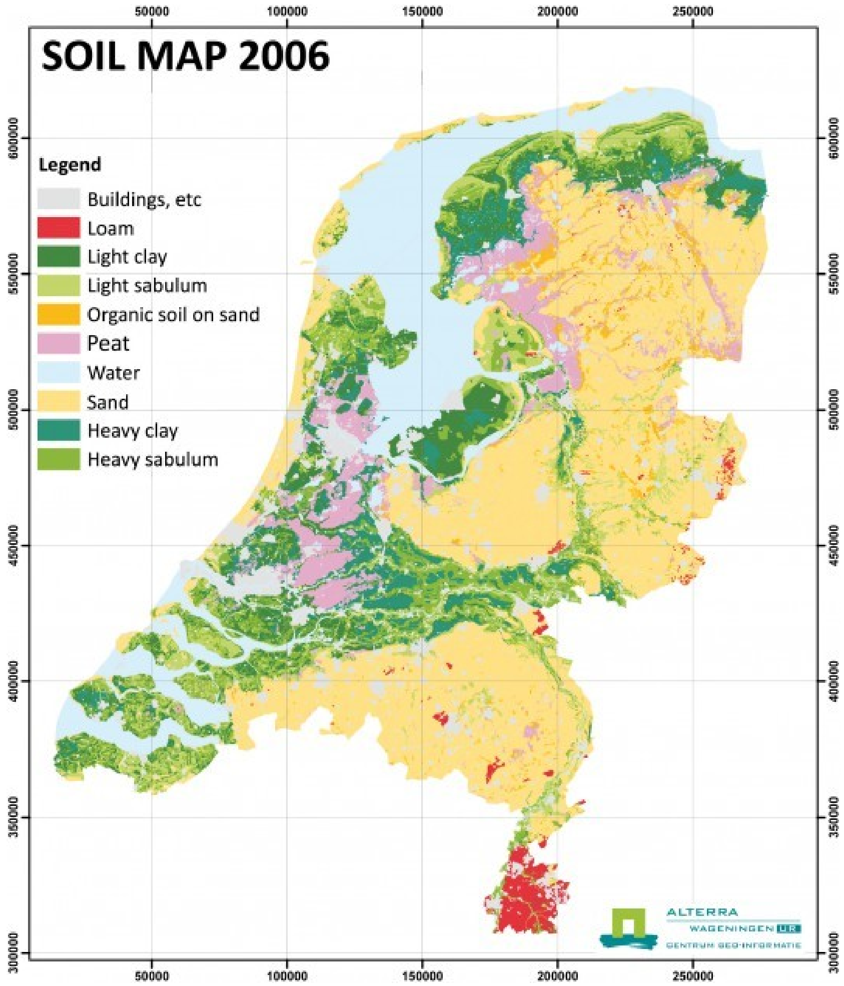

Figure 2.1 Simplified soil map of the Netherlands.

Spatial differences for the precipitation changes presented in Section 2.4 are computed for regions based on mean precipitation, elevation and soil type, and zones at different distances to the coast. The Netherlands has four major soil types, sand, clay, loam and peat (Figure 2.1). Clay and loam are mainly present along the seacoast and the (former) courses of the major rivers, Rhine and Meuse. Peat has been excavated in major parts of the country, but is still present in the North and West, while sandy soils dominate the east and south of the country. Combining the soil characteristics with average precipitation data led to the creation of five different regions. The sixth "region", referred to as "high", is based on topography and encompasses the Veluwe area and five stations in the southeast of the Netherlands that lie above an elevation of 80 m. The main characteristics of these

Table 2.1 Characteristics of the 6 regions that were investigated in this study. Mean precipitation is calculated over the entire investigated 59 year period.

Region	Main soil type	Number of stations	Mean precipitation (mm)	Mean height (m)
High	Sand and loam	15	870	60
South-West	Clay	40	791	2
West	Clay and peat	53	831	0
South-East	Sand	36	776	15
East	Sand	36	813	12
North	Sand and peat	60	814	4

regions are given in Table 2.1 and their spatial extend is given in Figure 2.2. The use of soil characteristics as such was not possible in the regression analysis with mean precipitation trends (Section 2.4), therefore we used soil moisture capacities for each of the different soil classes based on Wösten et al. (2001).

The degree of urbanization is calculated as the fraction of urban area within a 5 km radius around each station using the European Corine land cover database (EEA, 2002) for the year 2000. Land cover categories classified as urban are: discontinuous urban fabric, industrial and commercial units, road and rail network, port areas, airports, mineral extraction sites, dump sites, construction sites, green urban areas, and sport and leisure facilities.

To create the coastal distance zones, the shortest distance to a coastline enclosing the northern islands and south-western peninsula is calculated for each station. The zones are defined such that each contains about a quarter of the total number of precipitation stations available in this study. This results in four zones at 0-25 km, 25-50 km, 50-100 km and 100-200 km from the coast. The distance zones are depicted in Figure 2.3.

Percentile values in this study are calculated by sorting the precipitation measurements over wet days (>1 mm) and taking the respective value. Trends are based on a simple linear regression on time and their degree of significance is assessed using the related P-values computed with ordinary least squares fitting. We take a 0.05 significance level. The results are determined statistically significant if the P-value is less than the significance level. Percentual changes are calculated by subtracting the last value of the linear trend analysis from the first and dividing by the first, i.e. the difference between 1951 and 2009 expressed as percentage. For the regions and zones the data of all the

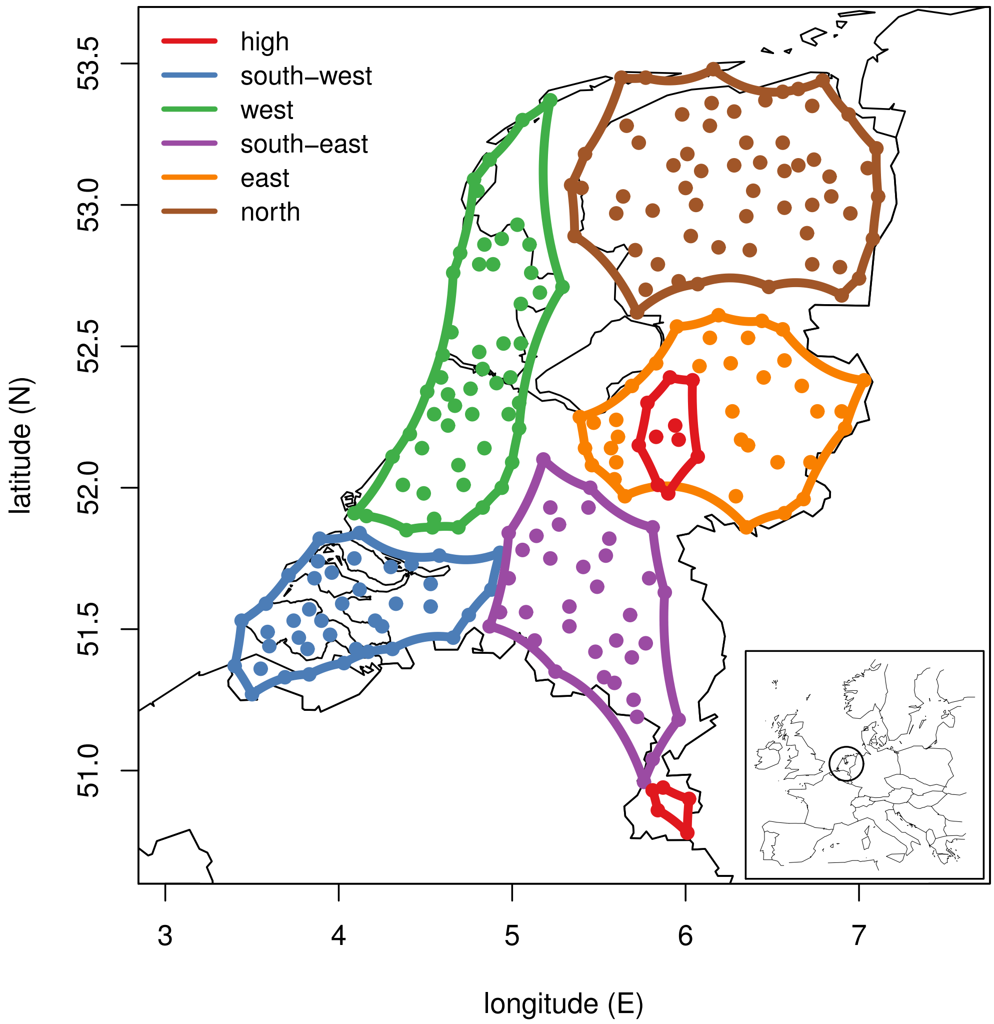

Figure 2.2 Map of the Netherlands with coloured polygons indicating the six different soil characteristic regions and encompassed KNMI precipitation stations.

encompassed stations is combined before the percentile values and trends are computed. A similar approach was taken for the countrywide changes of percentile values given in Table 2.2.

Determining whether surface characteristics exert significant influence on precipitation is more complicated however. As introduced before, we define a set of regions based on surface characteristics and coastal distance zones. The changes in these regions and

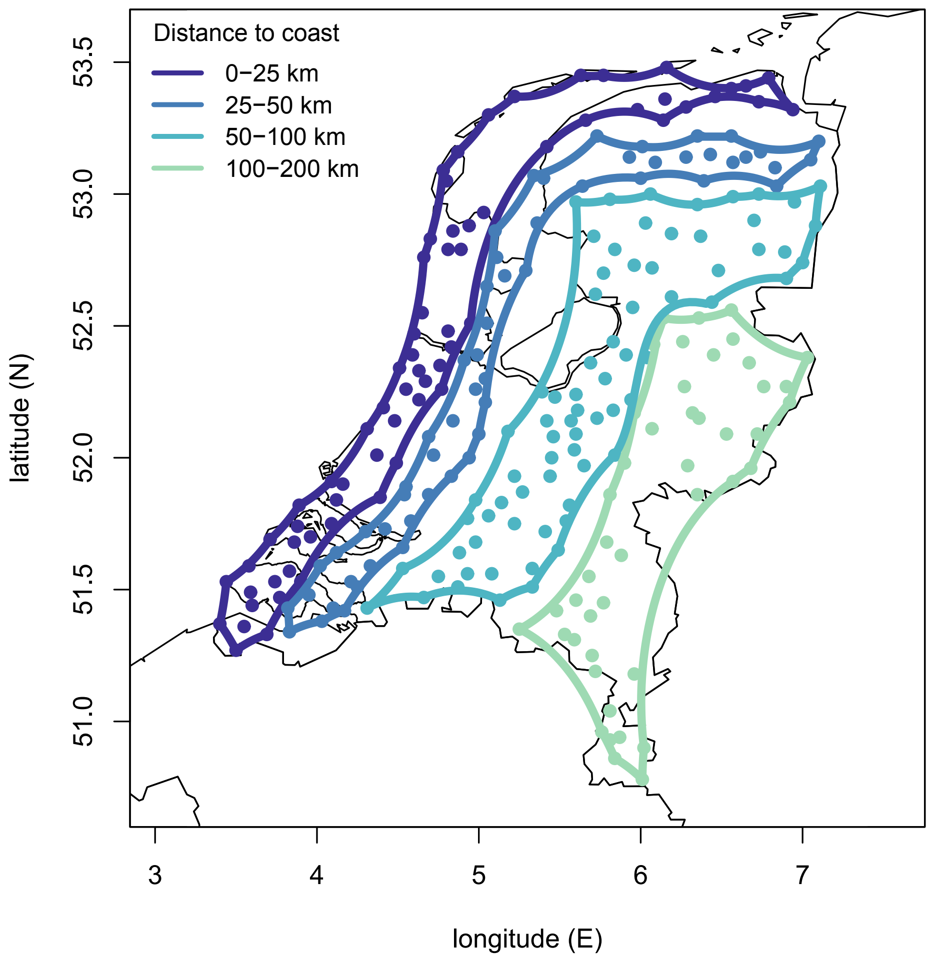

Figure 2.3 Map of the Netherlands with coloured polygons indicating the four coastal distance zones and encompassed KNMI precipitation stations.

zones are compared with a random sample of stations to give an indication of the local variability. For the number of stations we use 50, which is about the average number of stations in the regions. Accordingly we resample 50 stations randomly out of all stations available and compute the same statistics from this set of stations as was done for the regions and zones. We repeat this bootstrap procedure 1000 times, and the 5th and 95th percentiles are presented. Thus we compare the statistics results of the regions and zones to random regions assuming spatially uncorrelated data (in short, random region). For most statistics, however, spatial correlation exists. This can be either due to the scale of the weather systems that are involved, or due to surface forcing. We are interested in the role of the surface, but this cannot be separated statistically from the role of the implicit scale of the weather systems. As a complication, the regions and zones defined have

Table 2.2 Results of the trend analysis for the period 1951-2009. Changes in mean precipitation and the 90th, 95th and 99th percentiles. Columns 3-6 give the changes relative to the 1951-1980 period.

Indices	Change (%)	1961-1990	1971-2000	1981-2009
mean	15.63	1.02	1.03	1.06
p90	16.02	1.03	1.04	1.10
p95	15.11	1.03	1.04	1.09
p99	12.68	1.03	1.03	1.09

different shapes, with more circular shapes for the regions based on soil type and more elongated shapes for the coastal distance zones. As a result spatial correlation due to the scale of the weather systems is not necessarily the same in both sets and is likely larger in the regions based on soil type as these are generally spatially more confined areas. This effect is very difficult to incorporate in the bootstrap resampling and therefore we only compare to the random regions. This is by no means an absolute measure of significance, but merely a rough measure of the spread which would be expected if there is no spatial correlation in the data. Finally, we note that bootstrap procedures have been used with spatially correlated data (e.g. Douglas et al., 2000) by, for example, resampling fields at the same time. However, such a procedure answers a different question (significance of trends) than the one we aim to answer: how different trends in regions are from each other.

2.3 Spatial differences and trends

Here we discuss the main features of precipitation in the Netherlands from 1951-2009. In general the Netherlands has seen an increase in both mean and extreme precipitation. Despite the fact that precipitation has a large inter annual variability, mean annual precipitation has increased almost 16% over the 59 years investigated. Figure 2.4 shows the annual mean precipitation and the climatological means for the standard WMO 30-year periods (WMO, 1989). The 1980-2009 climatological values for mean precipitation are strikingly different from the others. This is consistent for all of the investigated indices of extremes, such as the annual number of days with precipitation greater than 20 and 30 mm and the 90th, 95th and 99th percentiles.

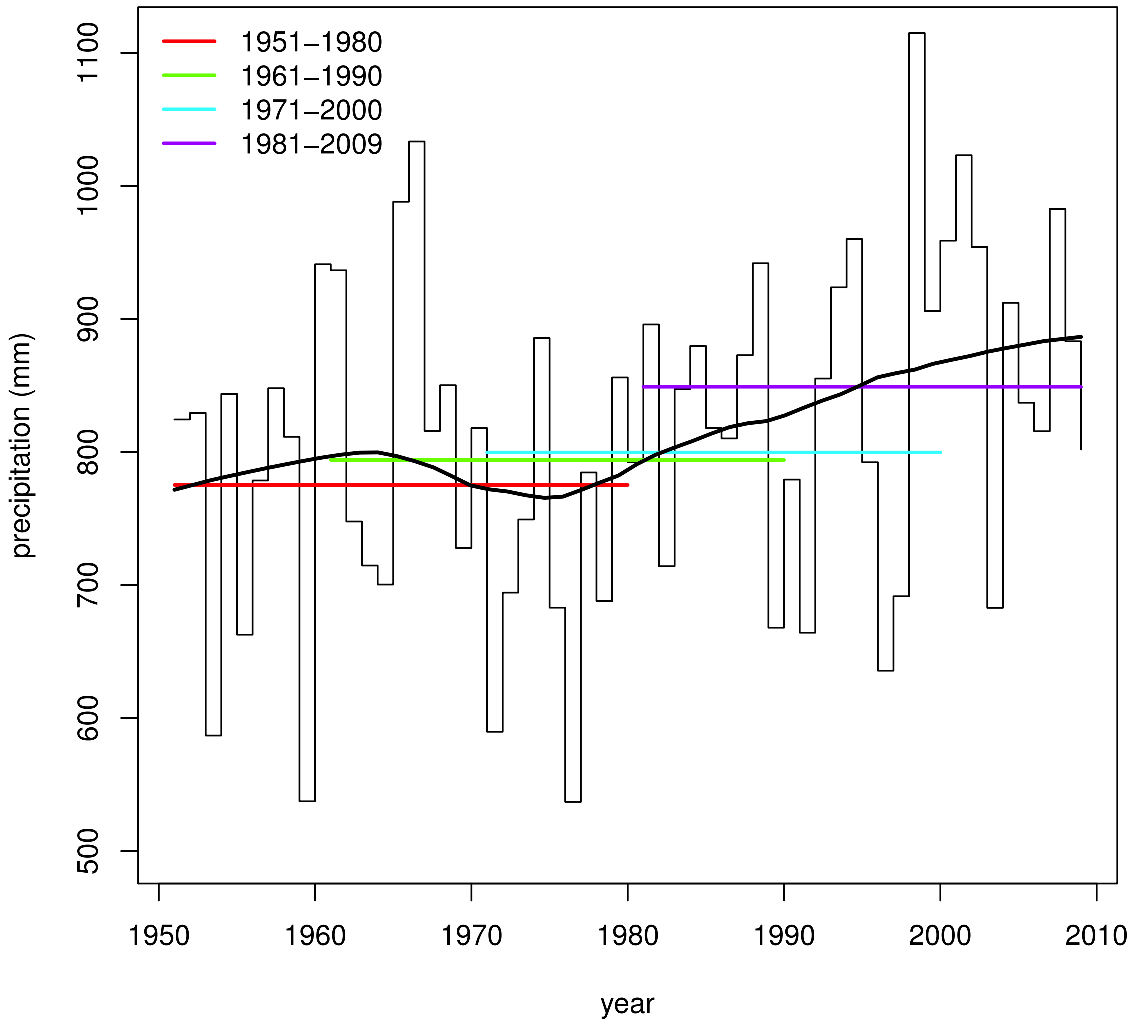

Figure 2.4 Average mean annual precipitation amounts (mm) in the Netherlands for the period 1951-2009. The black line is based on a loess smoother with span 0.45. Climatological means for different periods are indicated.

Despite the small size of the Netherlands, persistent spatial variations in precipitation can be observed. The whole country ranges 312 km in the North-South direction and 264 km in the East-West direction. Relatively wet areas are present in the middle of the West coast, over the Veluwe area and at a few stations in the South. These areas receive the largest mean precipitation, around 900 mm in contrast to the country average of 800 mm, as well as the highest daily amounts. The values of the 95th and 99th percentile for these areas are on average 16 and 28 mm respectively which is about 20% more than the countrywide values of roughly 13 and 24 mm. We will first focus on extreme events and compare the spatial distribution of the number of days on which a specific threshold is exceeded to the spatial distribution of percentile values for extreme events (see Figure 2.5). The 20 mm threshold (panel A) is approximately exceeded five times per year over the Veluwe as well as over the West coast. However, on average the amount of precipitation is higher along the West coast, which is reflected in higher values of the 99th percentile (panel B).

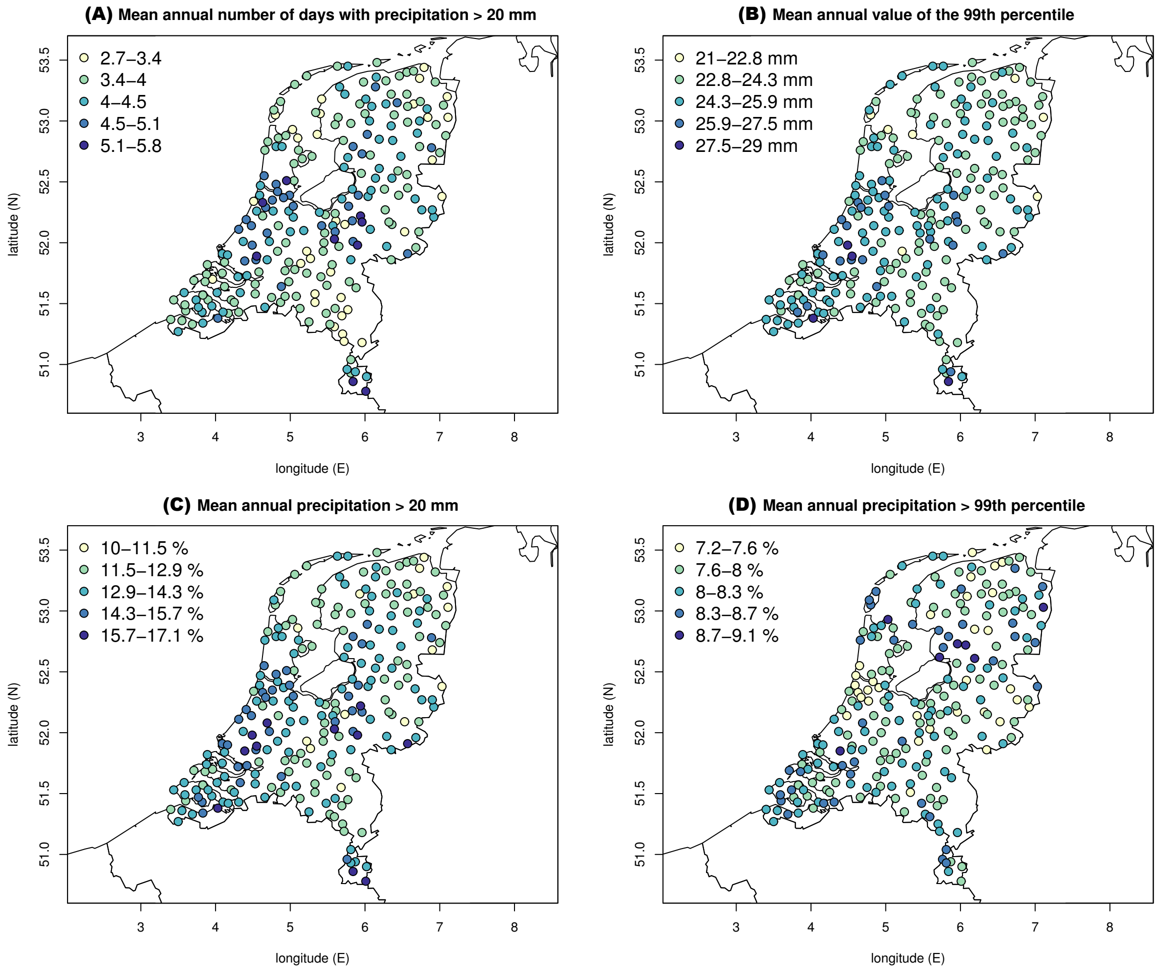

Figure 2.5 (A) Mean annual number of days with precipitation greater than 20 mm, (B) Mean annual value of the 99th percentile (mm), (C) Mean annual percentage of precipitation that has fallen in daily amounts greater than 20 mm, (D) Mean annual percentage of precipitation that has fallen above the 99th percentile. Given over the Netherlands for the period 1951-2009

We also investigated the percentage of precipitation that falls above a number of fixed thresholds and above different percentiles, the results can be seen in panel C (a threshold of 20 mm) and D (the 95th percentile) of Figure 2.5. The highest values for the percentage of precipitation above the percentile thresholds (of approximately 45%, 30% and 10% for the 90th, 95th and 99th percentile respectively) are found at a few stations in the north(-east) of the country. The percentage of precipitation over the 20 and 30 mm thresholds in contrary shows maxima over the Veluwe area and near the southwest coast. Taking an average, we can say that more than 10% of whole year precipitation falls on days with extreme precipitation, i.e. days with more than 20 mm rain and/or above the 90th percentile.

The number of days with precipitation varies throughout the year from around 50% in spring and summer to 60% in autumn and winter in the Netherlands, but the maximum daily totals are much higher in summer when precipitation has a more convective character. In spring and winter daily maxima are on average 25 mm, while summer and autumn daily totals can be more than twice as high. The seasonal variations in mean precipitation are quite large as well (see Figure 2.6). Spring (MAM) is the driest season with little spatial variation because of typical (high pressure) circulation patterns (Buishand and Velds, 1980). Generally the Veluwe area receives somewhat more and the coast somewhat less precipitation than the rest of the country. Summer (JJA) precipitation has a similar gradient along the coast, this is likely caused by a suppression of precipitation by the relatively cold sea water temperature in spring and early summer. Precipitation in autumn (SON) is the highest and has a clear opposing coastal gradient with highest amounts along the coast and minima further inland. The contrast between coastal and inland precipitation has become larger in recent times presumably because the increasing SST feeds convective systems. In winter (DJF) amounts are generally low again and the most outstanding feature is the maximum over the Veluwe area. Annual mean precipitation is consequently dominated by summer and autumn.

A simple trend analysis through station wise linear regression of daily precipitation shows a positive change over all stations in the Netherlands (Figure 2.7). The increases are largest near the coast and smallest in the Southeast. Station wise assessment of the related P-values shows that over the entire country nearly 90% of the observed changes are significant at the 0.05 level. Nearly all changes in daily precipitation at stations along the coast are significant, while some inland stations are not. We note that we do not take spatial correlation between neighbouring stations into account in estimating the

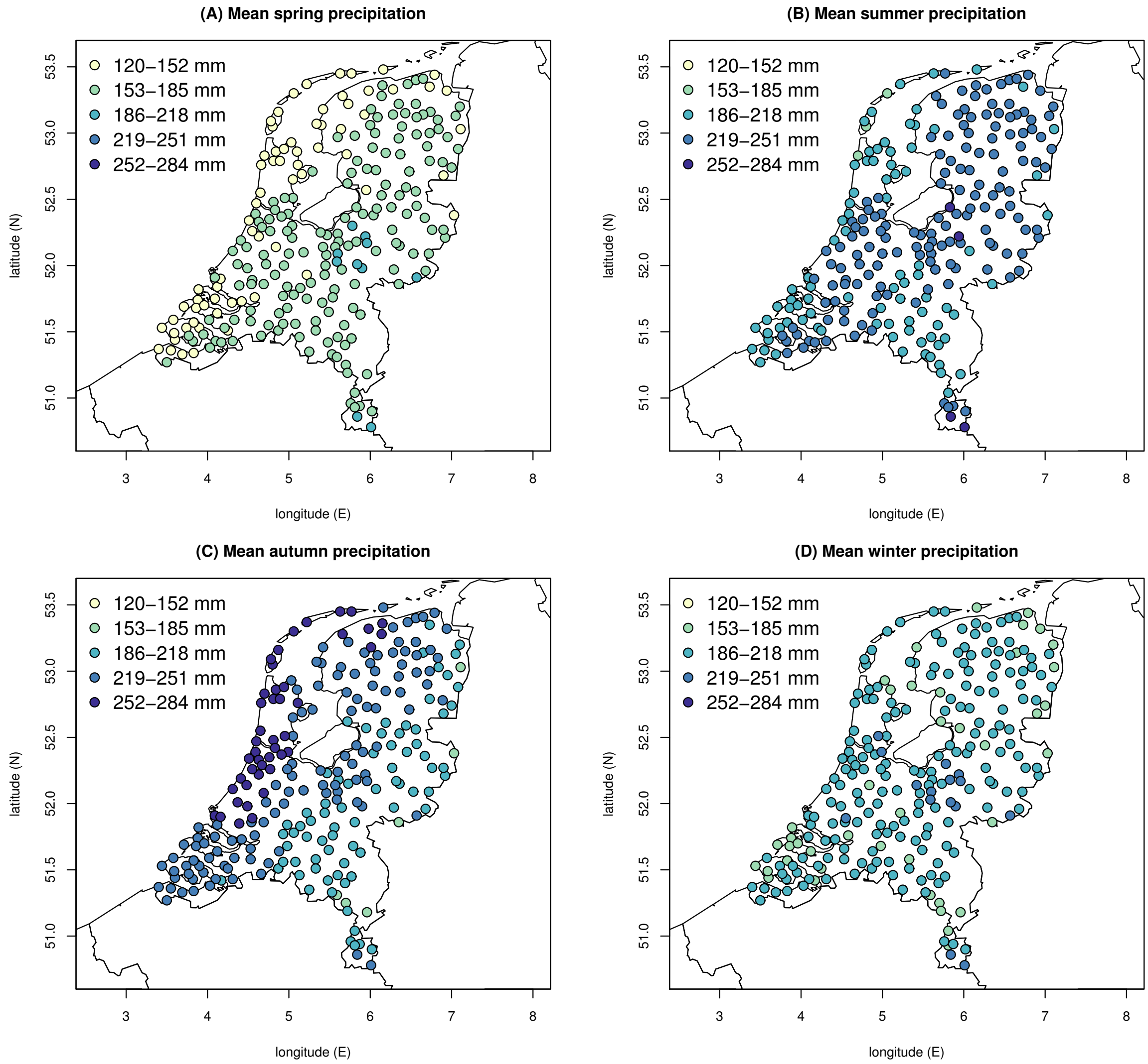

Figure 2.6 Mean seasonal precipitation (mm) in the Netherlands for the period 1951-2009 in (A) spring (MAM), (B) summer (JJA), (C) autumn (SON) and (D) winter (DJF).

significance. The changes are largest in spring and winter (can be seen in Figure 2.9 which will be discussed in the next section) and smallest in summer on average, although the difference between coastal and inland changes are largest in summer. The largest increases, on average up to 35%, are found in the months February to April. The changes in the following months are successively smaller until hardly any change can be detected in July. After September the changes increase again up to 20% from October to January. Although early spring and winter changes are the largest, the spatial distribution in these seasons does not change. Hence the overall spatial pattern in precipitation changes is dominated by early summer and late autumn.

Urban stations, i.e. stations with an urban fraction greater than or equal to 25%, are indicated in Figure 2.7 with diamonds. Almost half the cities designated as urban lie in the central West coast, where the percentile values and threshold exceedances are higher than in the rest of the country. Mean precipitation changes in these stations are relatively high, however, urban stations in the rest of the country have similar changes as nearby non-urban stations.

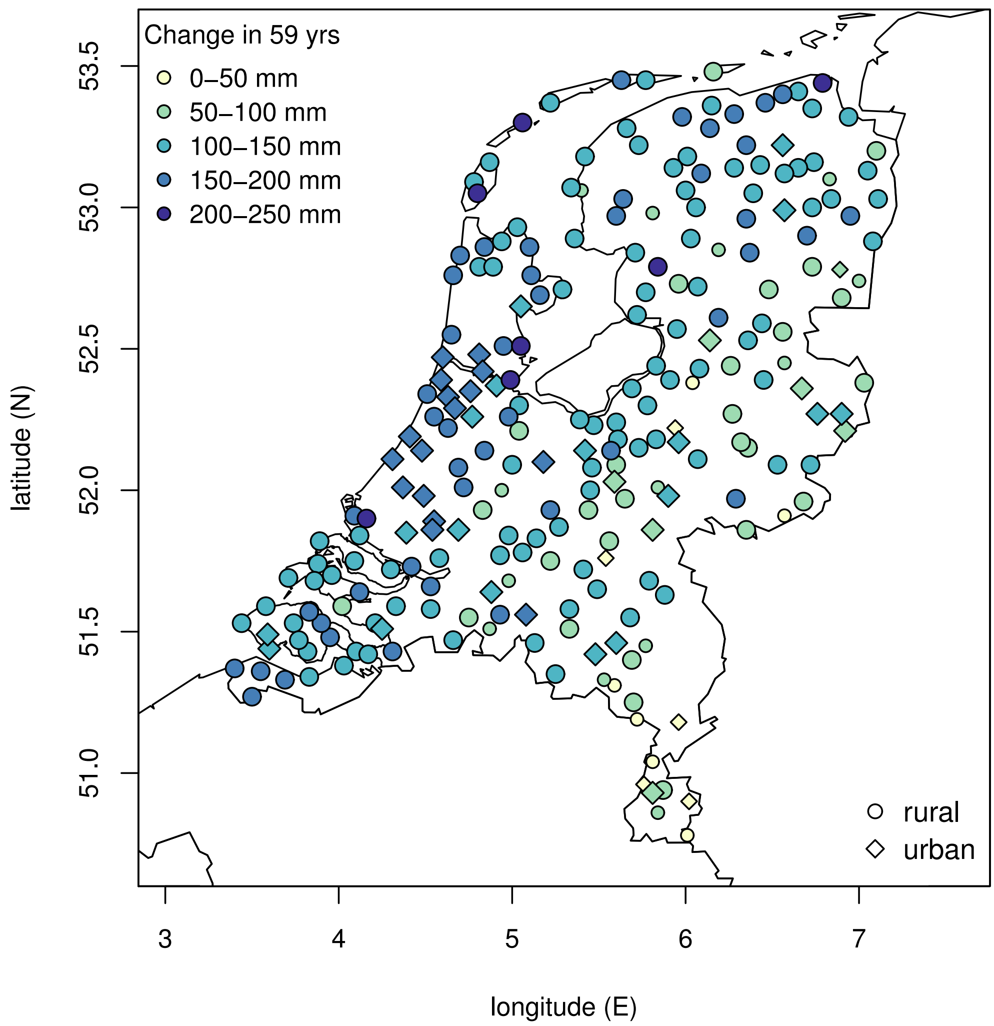

Figure 2.7 Station-wise mean annual precipitation changes in the Netherlands for the period 1951–2009 (mm in 59 years). Stations with changes that are not significant have smaller symbols.

Last we explore the changes in percentile values. On average these changes are close to the change in mean precipitation (see Table 2.2, column 2, all significant at the 0.05 level). This is an indication that the shape of the distribution of precipitation has not altered much throughout time, as extreme events still occur in about the same proportions. Columns 3 to 5 of Table 2.2 give the changes in percentile values relative to the 1951-1980 period. It shows that all indices increase throughout time, but the largest changes are found in the 1980-2009 period. The overall picture is that of increasing mean precipitation as well as percentile values and the percentage of precipitation above the percentile values.

2.4 Regional trend analysis

We now investigate spatial precipitation trends and how differences between the regions and coastal zones can be explained. Simple linear regression analyses between the change in mean precipitation and the investigated factors: soil moisture, distance to the coast, elevation and degree of urbanization show little correlation for soil moisture (capacity) and urbanization. Both topography and distance to the coast have a negative relation with the observed precipitation changes, although the relation for distance to the coast is stronger. Topography and distance to the coast themselves are also correlated as stations with low elevation lie close to the coast and elevated stations mainly lie in the southeast and on the Veluwe.

Figure 2.8 shows the negative relation between the station wise increase in precipitation (i.e. the difference between 1951 and 2009 expressed as percentage) and distance to the coast. The regression between precipitation change and distance to the coast is approximately 8% per 100 km in the 59 years that were investigated. The changes are given in percentages rather than mm to be able to compare stations with different annual precipitation amounts equally. The correlation coefficient (R^2) is about 0.4. On average, precipitation increases are greatest near the coast and decrease further inland. For stations that change less than 9%, the changes turn out not to be significant. Urban stations are present throughout the entire scatter and there is no coherent clustering, which, if present, would suggest the influence of the degree of urbanization on precipitation amounts and as a result on trends.

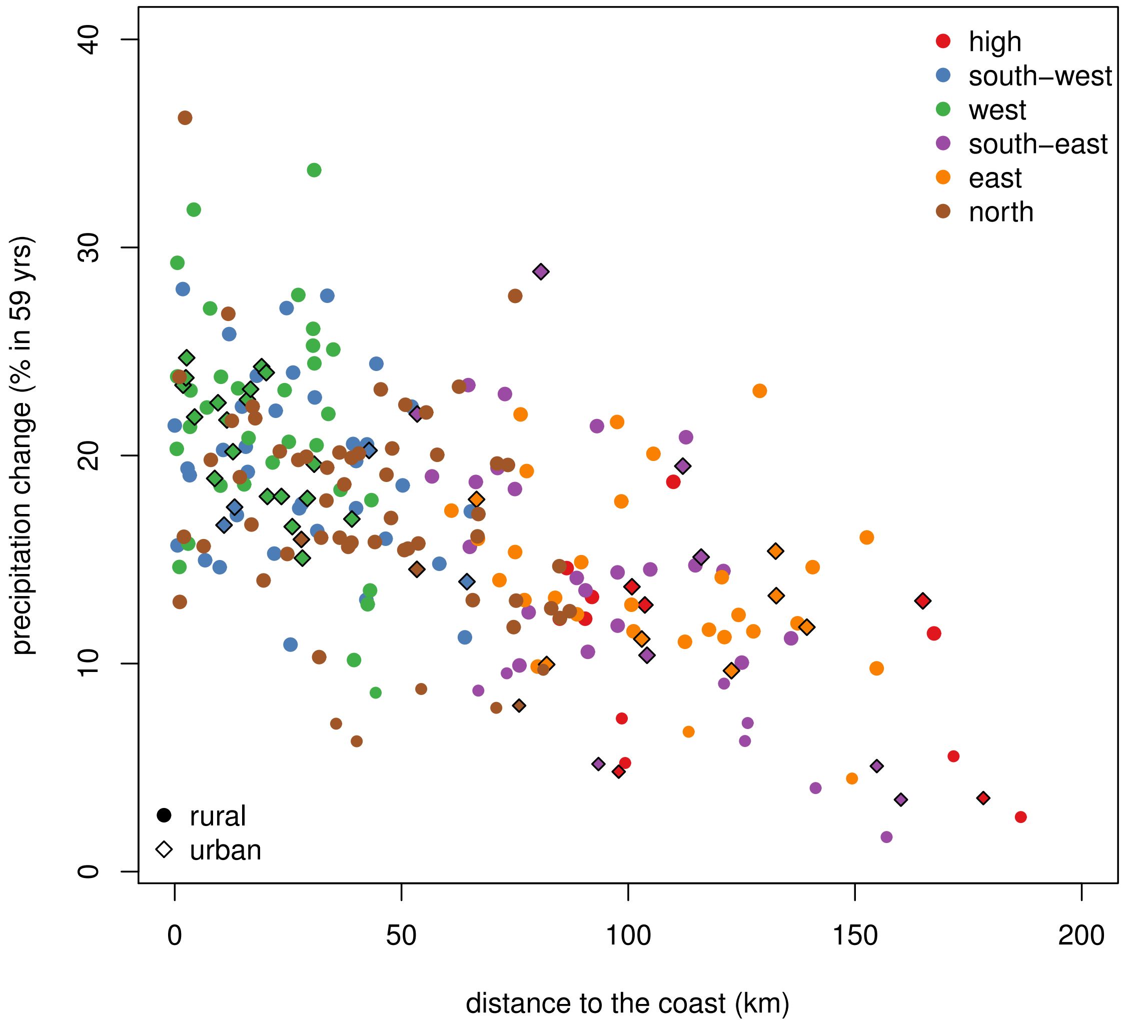

Figure 2.8 Scatterplot of the station-wise daily precipitation change (%) in the Netherlands in the period 1951-2009 against distance to the coast. Stations with changes that are not significant have smaller symbols.

As mentioned in the previous sections, we defined a set of regions based on surface characteristics and zones at different distances to the coast (see Figure 2.2 and Figure 2.3). The remainder of this paper will focus on the differences when comparing these with each other. Figure 2.9 provides two panels for each statistic, the left gives the changes for regions based on surface characteristics, the right for coastal distance zones. Panel A and B give the change in mean precipitation for each month of the year. The most distinctive feature is the order of the regions from April to June and its near reversal from July to September. In panel B it is easy to see that the strongest increases in these months are along the coast and the lowest further inland. The largest differences between the regions can be found from April to June, when the change in mean precipitation is about 20% higher along the coast than further inland.

Extreme precipitation follows roughly the same pattern throughout the year as mean precipitation. Panels C and D give the change in the 95th percentile value. It is hard to find a coherent picture in panel C and not easy in panel D either, because both the most inland and the coastal zones behave differently from the rest. Sometimes the coastal zone has the largest (smallest) trend and sometimes the most inland zone. From August to November the change in the most inland zone is up to 15% higher than the coastal zones.

Panel E and F show the change in the value of the 99th percentile calculated over all days, thus not only over wet days as before. The regions and zones are somewhat easier to distinguish in these graphs than in the last. Panel E shows a very large spread, of about 30%, between the regions in the months December and January. This feature cannot be seen in panel F where the changes differ only about 10%. The months June, July and August show contrasting behaviour for the most coastal zone, with changes up to 15% higher than the others. Conversely, the trend of most inland zone is also larger than the two in between zones in the months June and July.

Last, the differences between the regions are investigated for two different climatological periods that split the dataset in half. So Figure 2.10 shows the differences in yearly mean precipitation between the 1980-2009 and 1951-1980 periods. The difference for each of the regions is plotted against the percentile, given as a fraction between 0 and 1. Thus the most extreme values recorded have a cumulative probability of 1 and the x-axis gives the probability that x or lower occurs. Every station in a region is individually averaged for each year in the two periods. For every region the yearly precipitation sums of each station and each year in the considered 30 year period are then ordered to get their corresponding percentiles and compared to the other period.

On average precipitation has increased about 10% when the earlier period is compared to the latter. For probabilities higher than 0.8 and lower than 0.1 contrasting behaviour for the coastal and inland zones can be seen. For high probability values, the coastal zones, up to 50 km from the coast, increased up to 5% more than average, while precipitation in some inland zones even decreased. For low probability values however, inland zones

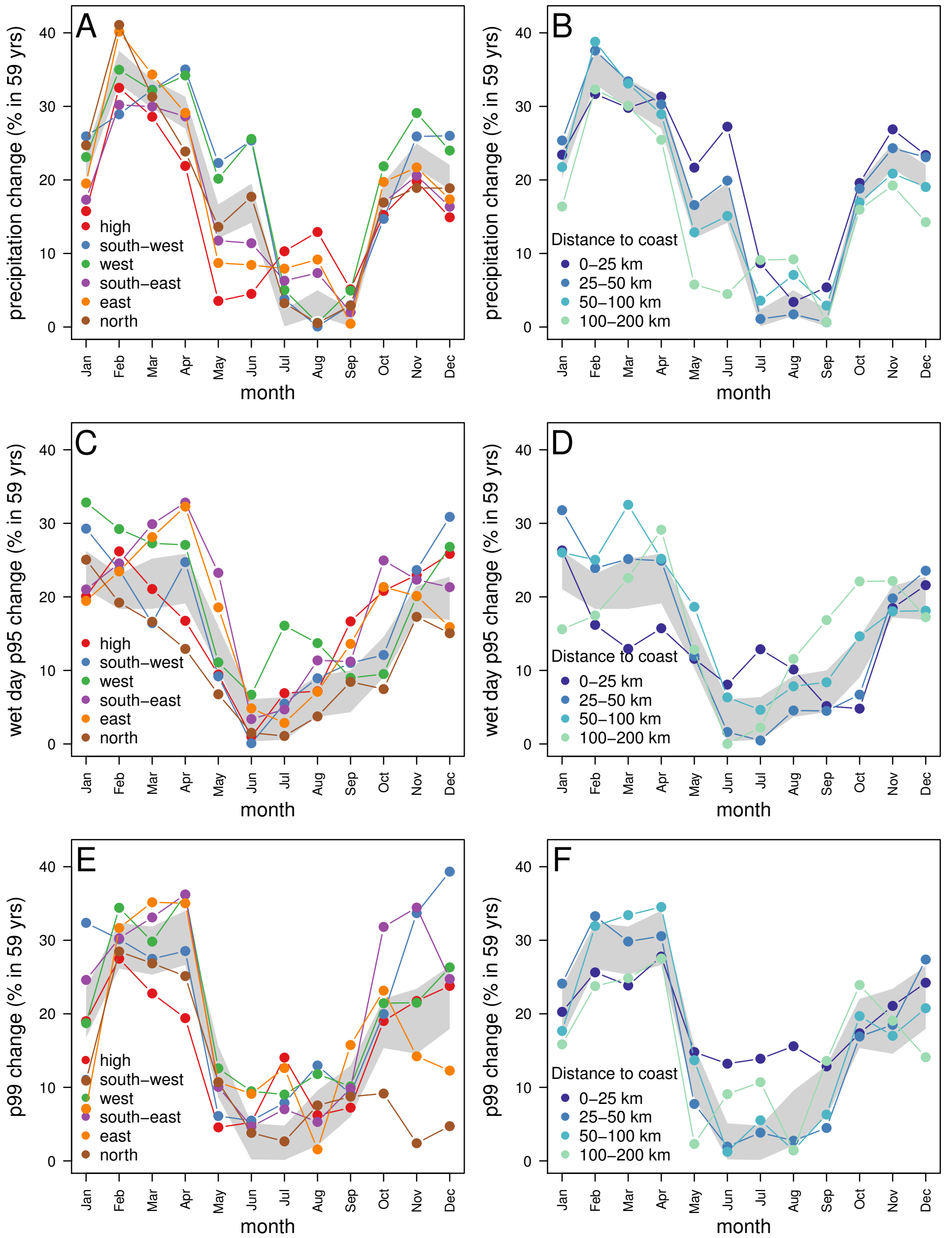

Figure 2.9 (A) Mean daily precipitation change (%) in the Netherlands for the surface characteristics regions for each month of the year in the period 1951-2009. (B) Same as A, but for coastal distance zones. (C) Change of the 95th percentile calculated over wet days for the surface characteristics regions for each month of the year in the period 1951-2009. (D) Same as C, but for coastal distance zones. (E) Change of the 99th percentile calculated over all days for the surface characteristics regions for each month of the year in the period 1951-2009. (F) Same as E, but for coastal distance zones. The grey shading gives the 5–95% bootstrap confidence range. All plots are based on overlapping 3-month periods, e.g., Jul refers to the average of June, July and August.

have become wetter than the regions near the coast. Especially for low probabilities the differences are more distinct when comparing coastal distance zones to one another than comparing the regions based on surface characteristics.

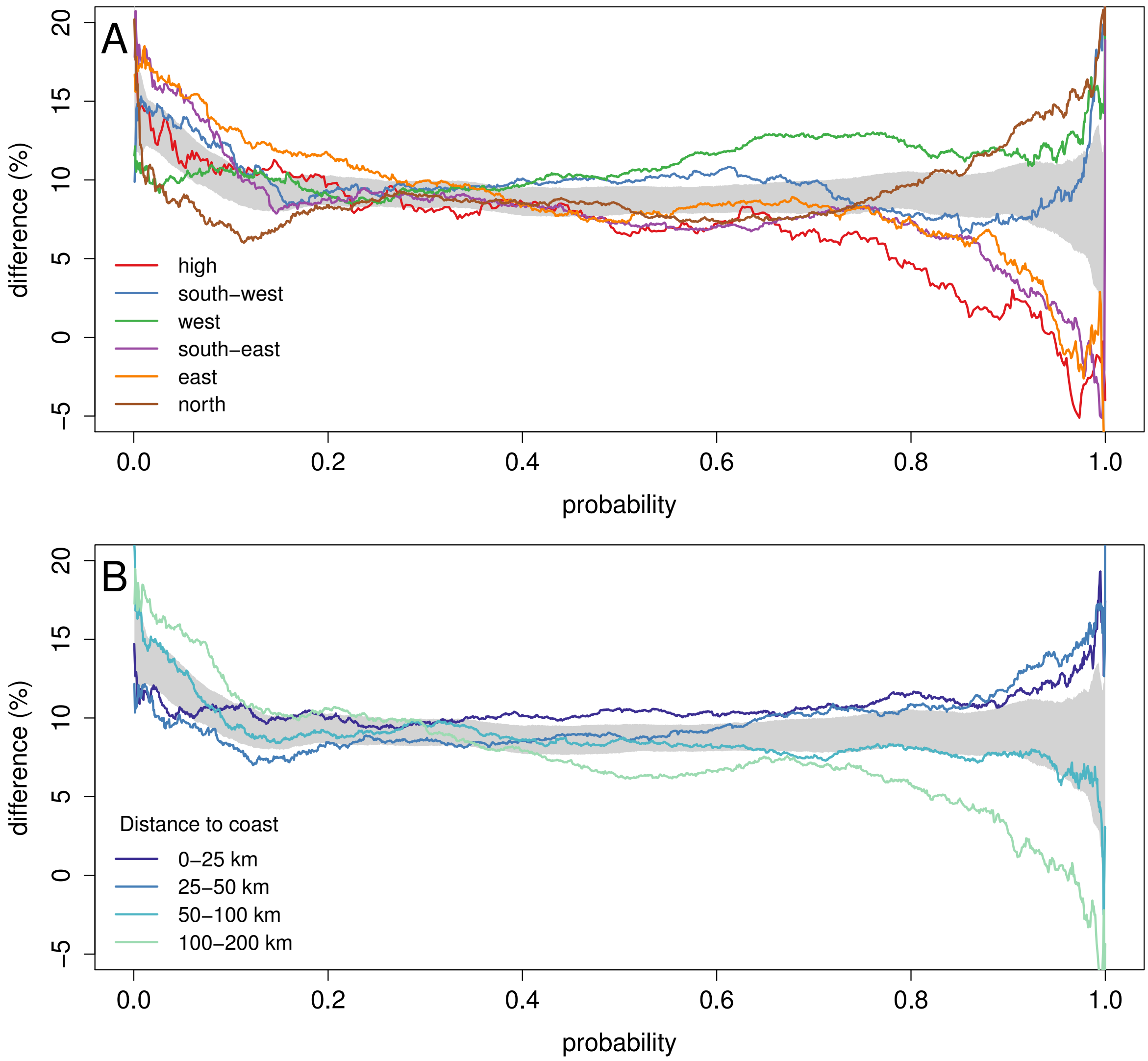

Figure 2.10 (A) Quantile differences in yearly mean precipitation (%) in the Netherlands between the period 1980-2009 and 1951-1980 for each of the surface characteristics regions against probability. (B) Same as A, but for coastal distance zones. The grey shading indicates the 5–95% bootstrap confidence range.

2.5 Discussion

In comparing the two sets of surface characteristic regions and coastal distance zones we showed bootstrap confidence intervals. Although we find a lot of consistency in trends and between zones, a large proportion of the data points lie outside the bootstrap confidence intervals in Figure 2.9 and Figure 2.10. Some differences probably arise because the bootstrap sample is based on 50 random stations, while the regions range in amount of stations from 36 to 66 with exception of the high region which has only 15 stations. However, the shape of the regions and spatial correlation between the stations likely plays a much larger role. Spatial correlation decreases the effective sample size in a dataset and not taking it into account results in an overestimation of trend significance. Several studies report significant impact on trends if spatial correlation would not have been taken into account (e.g Adamowski and Bougadis, 2003; Douglas et al., 2000). Our station wise trend assessment of the significance of mean precipitation is for this reason much higher than the significance reported by Buishand et al. (2013) who assessed the entire field significance. In other situations correlation has been dealt with by using a regional or seasonal Kendall trend test (Helsel and Frans, 2006). For our regional trend analyses these methods are less appropriate because we are not so much interested in the field significance of a trend, but more in how trends are affected by the surface. The bootstrap confidence intervals currently plotted in the figures should give a lower boundary of the expected spread assuming spatially uncorrelated data.

Increases in both mean and extreme precipitation indices were found. Both yearly and seasonal precipitation have increased over the investigated 59 year period, but the largest changes are generally found in the last 30 year climatological period. This is because the increase in precipitation is not gradual and consistent, but dry and wet periods can be distinguished and the inclusion of the dry period peaking in 1976 into all of the other climatological periods cause the later period to be strikingly different. The North Atlantic Oscillation (NAO) has important links with precipitation over Europe (Hurrell, 1995) and most of the temporal changes between wet and dryer periods in the Netherlands are strongly influenced by changes in the atmospheric circulation (Lenderink et al., 2009; van Haren et al., 2013). The overall rise in precipitation causes the thresholds for the annual number of days with precipitation greater than 20 and 30 mm to be exceeded more frequently. Although similar spatial results are found for the analyses of exceedance frequencies and intensity changes (i.e. percentile values), the changes of respectively 44 and 53% for the annual number of days with precipitation greater than 20 and 30 mm reported by Buishand et al. (2013) appear much higher than our changes in percentiles. The results are comparable however, because a 10% increase in intensity decreases the return time by roughly a factor two on average.

Trends in precipitation patterns were analyzed with respect to soil type, distance to the coast, topography and urbanization. Urban stations were found to have similar changes as nearby non-urban stations, so no distinctive influence was found. The fact that especially modelling studies do find an impact of urban areas could be due to the short timespan that they look at or the location of the urban effect. The effect of urban areas is expected downwind which is not defined in this study as we look at yearly or seasonal averages. Topography has been found influential before, for example over the Veluwe (ter Maat et al., 2013) where average yearly precipitation sums of up to 100 mm higher than the rest of the country have been observed. We find the increases in this region however are among the smallest during the period investigated, both for mean and extreme precipitation. So, over time the higher precipitation amounts over the Veluwe area have become less distinct. For soil type and precipitation changes no direct relation was found and regions based on soil type show less consistent behavior than the coastal distance zones.

Coastal precipitation increases reported here are consistent with the results of Lenderink et al. (2009), who investigated the influence of SST on precipitation. They showed that, apart from the spring months, the coastal area has consistently become wetter compared to the inland area since the 1950s. This wetting of the coastal area compared to the inland is confirmed by the present study. Some inconsistent behavior was found for the months July and August when the increase in mean precipitation is higher for both inland regions compared to the coastal area. Lenderink et al. (2009) found that the influence of SST is particularly strong less than 30–50 km from the coastline. This finding is strengthened by this study, although we show that for extreme summer precipitation the influence seems to be confined to the first 25 km. The differences between the first and second halve of the investigated period show further diverging behaviour between the stations less than 50 km from the coast and those further away. The influence of SST on coastal precipitation in the Netherlands might be larger than in other countries because the temperature of the relatively shallow North Sea has increased more than the global mean trend.

The consistent increases in precipitation in the Netherlands are quite unusual in comparison to other European trends which are highly variable, sometimes giving opposing trends for different regions and/or time periods (e.g. del Rio et al., 2011; Karagiannidis et al., 2012; Lupikasza et al., 2011). A common conclusion from other studies is that precipitation amounts have large interannual variability, on both annual and seasonal scales. Our study confirms this and also find the period examined can have a large effect on the results. For example, the standard 30 year climatologies are not appropriate to compare with each other either, as in- or exclusion of a relatively wet or dry period can cause large differences between the periods. A running trend analysis, such as the one utilized by Brunetti et al. (2012) and Turco and Llasat (2011) might be the most appropriate to investigate changes throughout time. For extreme precipitation analysis several other techniques are available, such as those referred to and used in Ntegeka and Willems (2008).

We have shown that the spatial patterns found in the Netherlands, though persistent, are not time invariant. Future precipitation patterns in the Dutch climate scenarios (van den Hurk et al., 2006) are the same as in the present day climate. We suspect this assumption is not valid, because regional differences in past trends are apparent. Future modelling work at higher temporal and/or spatial resolution might be able to find local influence of urbanization and the land surface that we have not because of our relatively coarse approach.

2.6 Conclusions

In this study spatial patterns and seasonal precipitation trends were investigated with homogenized daily precipitation data from 240 stations in the Netherlands for the period 1951-2009. Homogenization of the data and a first analysis was conducted by Buishand et al. (2013). This study has extended their results regarding persistent (seasonal) spatial patterns and regional differences in precipitation changes.

Overall, both mean and extreme precipitation have increased on seasonal and annual scales over the last 59 years and especially in the last 30 years. Persistent patterns in mean annual precipitation are related to a combination of seasonal variations and the spatial distribution of extreme precipitation. Linear regression shows a positive change in daily precipitation for the entire country with the largest changes along the West coast. Both annual and seasonal changes show increases in precipitation, but the observed spatial patterns are sensitive to seasonality and the investigated time frame. Observed changes are largest in spring and winter, while absolute amounts peak in summer and autumn.

We find that distance to the coast explains more of the variance of precipitation in the dataset than the other investigated factors, being soil type, topography and urbanization. Zones based on distance to the coast give a more consistent picture for precipitation changes over time than regions based on surface characteristics do. The zones up to 50 km from the coast show a number of different characteristics than the inland zones, especially regarding extreme precipitation on both seasonal and climatological timescales.

Chapter 3

Observed urban effects on precipitation along the Dutch West coast*

Expansion of urban areas has profound effects on land surface characteristics. As such the land surface can exert influence on atmospheric parameters that might alter precipitation amounts or patterns. In this study, precipitation observations near urban areas along the West coast of the Netherlands are investigated throughout the 1951-2010 period. An innovative analysis methodology is used to deal with the small and fragmented urban areas in the Netherlands. The results show that daily precipitation totals downwind of urban areas are, on average, about 7% higher than precipitation in the rest of the Dutch West coast. Precipitation enhancements up to 20% are found depending on wind direction and time period. These results are comparable with studies from around the globe and show that the influence of relatively small fragmented urban areas, as are present in the Netherlands, can be similar to the influence of large metropolitan areas on precipitation.

3.1 Introduction

The influence of urbanization and land-use changes on different climate aspects has become a thoroughly investigated issue (e.g. Mahmood et al., 2014). While the effects of urban areas on temperature are well understood (Arnfield, 2003; Oke, 1982), the effects

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on precipitation are not as straightforward. On one hand, cloud microphysical processes in response to increased (ultrafine) urban aerosols may reduce rainfall (e.g. Givati and Rosenfeld, 2004; Junkermann et al., 2011). On the other hand, local dynamics and thermodynamics associated with an urban heat island (UHI)-induced convergence zone and more convective boundary layer may enhance urban rainfall (e.g. Han and Baik, 2008; Shepherd et al., 2002). During the 60s and 70s the topic of urban effects on precipitation received ample attention in the USA after the discovery of the La Porte weather anomaly (Changnon, 1968) and the extensive field observation programme METROMEX was initiated (Ackerman et al., 1987; Changnon et al., 1977). Both observational studies and modelling work have been conducted meanwhile, and recommendations for future research have been made (see e.g. Han et al., 2014; Lowry, 1998; Shepherd, 2005, and references therein).

Taking heed of these recommendations, this paper investigates urban effects on precipitation in the Netherlands. Days are stratified with a circulation type classification, according to month/season, and occurrence in an early or later stage of urbanization. The Netherlands is a relatively small and flat country with a marine climate located in the northwest of Europe. Individual cities are not larger than 20 km in diameter and lie in close proximity to each other. Our study area is therefore not comparable to the metropolitan areas where previous studies have been conducted. Despte their relatively small size Dutch cities do influence the atmosphere and UHIs over 5°C have been measured (Steeneveld et al., 2011; van der Hoeven and Wandl, 2015; Wolters and Brandsma, 2012). The effects on precipitation have not been investigated however. Although extensive knowledge on UHI and urban effects on precipitation exists elsewhere, extrapolations to the Dutch situation are difficult to make due every location's unique setting (Schluenzen et al., 2010).

Dutch annual mean precipitation varies spatially from 675 to 925 mm (Overeem et al., 2009). In spring and autumn, a distinct but reversed difference between precipitation near the coast and precipitation further inland exists. In spring (autumn) rainfall is more abundant inland (along the coast). This seasonal cycle in coastal precipitation is well linked to the land-sea temperature contrast (Lenderink et al., 2009), but other effects (like atmospheric stability) are likely to be important as well (Attema et al., 2014), and urbanization might be one of them. The objective of the present study is to quantify the influence of Dutch urban areas on precipitation by the development and use of an innovative methodology that addresses the cities small size and mutual proximity.

Investigating urban effects in the whole of the Netherlands is inappropriate, because most of the major cities lie along the West coast. When sampling precipitation near urban areas one would inadvertently sample coastal precipitation gradients too. So we face the persistent challenge in urban meteorological research of disentangling the effect of urban areas from the effect of open water sources (Landsberg, 1981). This challenge is dealt with by investigating urban effects up to 45 km from the shoreline, where the coast-inland precipitation gradient is minor (Daniels et al., 2014). This region is of additional interest because it has experienced a larger increase in precipitation than the rest of the country in the last century (Buishand et al., 2013). The investigated region hosts approximately 6 million inhabitants (CBS and PBL, 2011) and is about 5300 km^2.

The utilized data are presented in the next section, while Section 3.3 presents the novel methodology designed to deal with the fragmented urban areas in the Netherlands. Subsequent results for the time period 1951-2010 are shown in Section 3.4. The results are positioned into a broader context in Section 3.5 and conclusions follow in Section 3.6.

3.2 Data

3.2.1 Urbanization trend

Historical land cover maps (HGN) for the Netherlands are available for 1960, 1970, 1980 and 1990 (Kramer et al., 2010). Having these detailed maps available for different time periods is important because the Netherlands, like many countries in Europe, has substantially rebuild and expanded its urban areas after World War II (Diefendorf, 1989). The 1951-2010 period is therefore divided into six periods of 10 years for the analysis. For each 10-year period, the urban extent is determined based on the land-use map at the end of the period. For the years 2000 and 2010 the national land cover maps (LGN) version 4 (Hazeu et al., 2011; Wit, 2003) and 6 (Hazeu et al., 2010) respectively are used. All maps are available at a 25 m resolution. The legends of the HGN and LGN maps differ and the urban classes given in the HGN maps are split into several classes in the LGN maps. To avoid discontinuities in the urban extent over time, a selection of urban related classes is made (Table 3.1).

Table 3.1 Historical/National land use map classes included in the urban extent.

HGN	LGN4	LGN6
5: Buildings and roads	8: Greenhouses	8: Greenhouses
9: Built up	18: Urban built-up	18: Primary built-up
10: Greenhouses	19: Buildings in rural areas	19: Secondary built-up
11: Baarlenassau	22: Forest in densely built-up	20: Forest in primary built-up
	25: Major roads and railways	23: Grass in primary built-up
	26: Buildings in agricultural areas	25: Major road and railways
		26: Buildings in rural areas

3.2.2 Circulation type classification

Individual days are stratified using a circulation type classification, computed with the "cost733class" software (Philipp et al., 2010, 2014). Mean sea level pressure (MSLP) data from ERA-20C at 12 UTC are used as input for the area 47.25- 57.75°N and 3-12.75°E. We use the ERA-20C reanalysis dataset, instead of the more commonly known ERA-Interim for example, because it is available over the entire investigated 1951-2010 period. The Jenkinson-Collison types classification scheme (Jenkinson and Collison, 1977), that provides an objective reproduction of the Lamb weather types (Jones et al., 1993; Lamb, 1950), is used. This scheme determines geostrophic wind flow characteristics using MSLP data from 16 points in the area of interest. The resulting classification has eigth weather types (WTs) representative of the prevailing geostrhophic wind direction (W, NW, N, NE, E, SE, S, and SW, where W = 1, ..., SW = 8) and one with light flow.

3.2.3 Precipitation

Precipitation measurements are available from the national meteorological institute (KNMI). Measurements are taken every morning at 8:00 UTC at about 320 stations. Approximately 60 of these stations lie in the West coast and their altitude ranges from 6 m below to 18 m above mean sea level. For analysis in each 10-year period, those stations with more than 80% data availability are selected.

3.3 Method

Examples of typical methods for evaluating urban effects on precipitation have been schematically depicted by Shepherd et al. (2002) and Huff and Changnon (1972). Positioned in relation to the mean wind vector they encompass the upwind control area, central urban area, and downwind area (with the maximum impact area), or simple geometric buffer constructions (e.g. Ashley et al., 2012). While these sorts of analyses are feasible for large (American) cities with relatively unpopulated surroundings, they are unsuitable in the heterogeneous urban landscape of the Netherlands with its many relatively small cities in close proximity. As such it is difficult to investigate a single city and predefine the up- and downwind area in the Netherlands, because the up- and downwind area would interfere with other cities or would be located in the North Sea.

Table 3.2 Total number of stations and number of stations classified as urban for each weather type (geostrophic wind direction) in each of the 10-year periods ending with the year indicated.

Year	# of stations	WT1	WT2	WT3	WT4	WT5	WT6	WT7	WT8	WT9
1960	57	5	7	2	5	2	2	4	4	0
1970	57	10	10	6	9	7	5	10	9	2
1980	60	11	16	11	13	8	10	12	14	5
1990	62	13	15	12	13	10	12	14	15	5
2000	57	13	17	17	18	21	17	19	20	13
2010	59	20	17	21	25	25	22	22	24	24

In this study, we select stations downwind of urban areas and compare with all other stations in the selected region on a daily basis. This is done separately for each weather type (WT) so whether a station is selected as urban or rural depends on geostrophic wind direction. For each station the urban fraction in the upwind area is determined based on a one-eight circle with a 20 km radius (Figure 3.1). For WT 9 (light flow) the urban fraction is determined in the whole of the circle. Stations with more than 0.25 urban fraction in the upwind area are considered “urban”. Setting a threshold like this increases the number of urban stations throughout time (Table 3.2). Consequently, in the 1950-1960 only four out of 57 stations are selected as urban, while 22 out of 59 stations are selected in 2000-2010. The remaining stations (i.e. all stations with an urban fraction equal to or lower than 0.25) are classified as “rural”. A sensitivity analysis for the number of stations and radius size, for both a quarter and one-eight circle, is given in the discussion section.

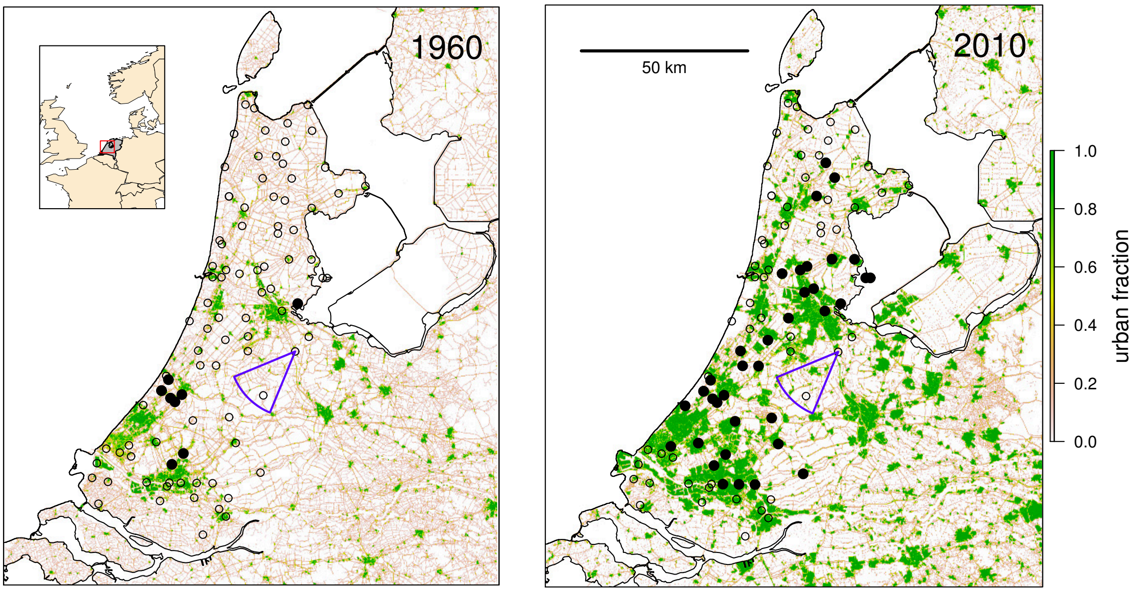

Figure 3.1 Urban fraction in the northwest of the Netherlands in 1960 (left) and 2010 (right) showing precipitation stations classified as “urban” (closed circles) and “rural” (open circles) based on their upwind urban fraction in the one-eight circle with a 20 km radius in the prevailing geostrophic wind direction (here weather type 8, implying southwesterly winds).

Mean precipitation is calculated separately for each month and each WT. Where possible, a bootstrap interval is computed to get an estimate of the associated uncertainty. Bootstrapping is done by randomly sampling (with replacement) from the appropriate number of stations (Table 3.2) and redoing the calculations. This procedure is repeated 1000 times for both urban and rural stations and the 5 and 95th percentile are shown as confidence bands in the appropriate figures. Extreme precipitation is investigated by pooling all data from urban or rural stations together and taking the 95th percentile.

3.4 Results

This paper will mostly show mean values, while the underlying data have a large spread, because of the variable nature of precipitation. In an example of this spread (Figure 3.2) the most extreme (> 12 mm) values lie well above the 1:1 line. While this is not a generality, extreme precipitation is on average more enhanced than mean precipitation downwind of urban areas (Section 3.4.2). In Figure 3.2, urban precipitation is about 11% higher than rural precipitation, this is on the high end of the outcomes (Section 3.4.1). The next section will focus on mean precipitation amounts like these, thereafter a few examples of other precipitation metrics like the distribution and rate are provided. Detailed results for the period 2001-2010 are shown while other periods are summarised because they are similar.

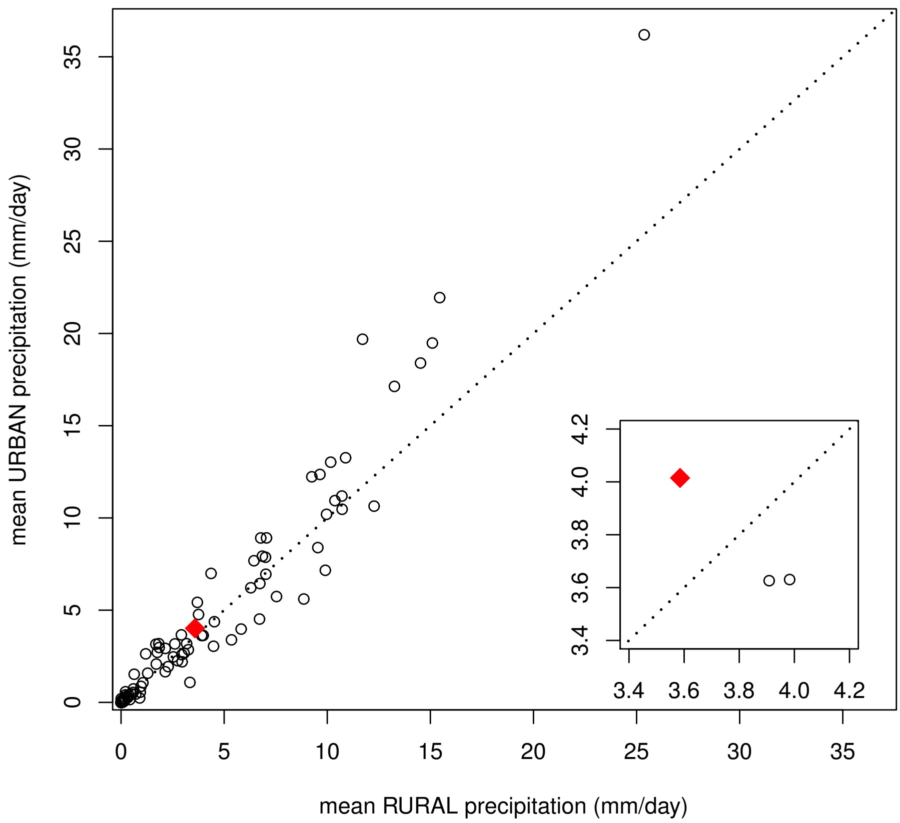

Figure 3.2 Scatterplot of daily mean summer (JJA) precipitation (mm/day), averaged over all urban and rural stations respectively, for weather type 8 (SW wind) in the period 2001-2010. The average is given as a diamond and zoomed into in the inset.

3.4.1 Mean precipitation

Mean precipitation is on average higher at urban stations than at rural stations in eight of the nine WTs (Figure 3.3). The only exception is for northeasterly winds (WT 4), when precipitation at rural stations is about 2% higher. This relative difference (given in the top left of each figure panel) is calculated from the frequency weighted yearly means of urban and rural precipitation. The occurrence frequency of the combination WT-month is given by the grey bars. This makes it easy to see westerly (SW, W, NW) winds are much more frequent than easterly (NE, E, SE) winds and have higher precipitation on average. Out of the total 108 WT-month combinations urban precipitation is higher in 92, and rural precipitation in 16. So although there is some variation, urban precipitation is higher in the vast majority of cases.

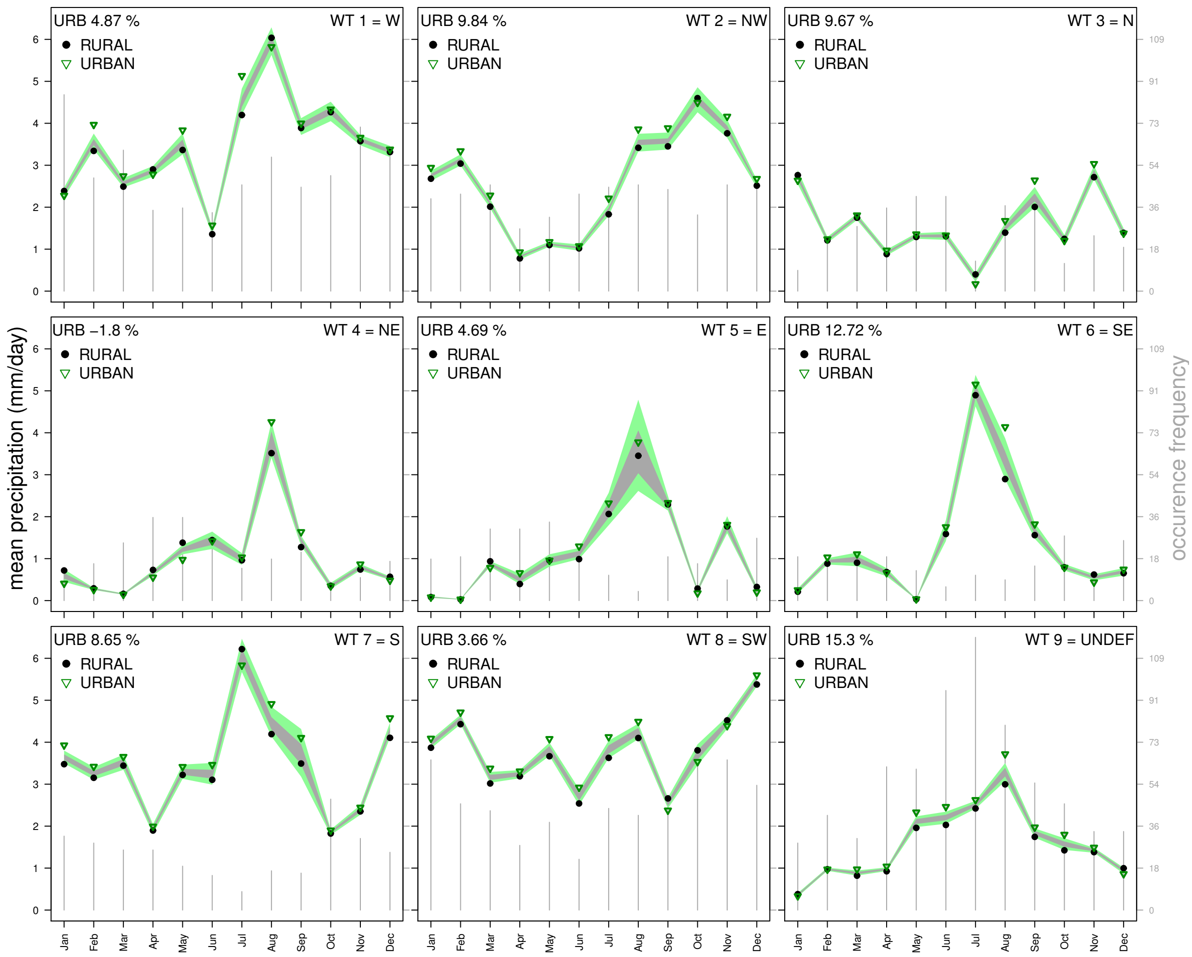

Figure 3.3 Mean daily precipitation (mm/day) at urban and rural stations for each geostrophic wind direction (determined by weather type) throughout the year over the period 2001-2010. Light green and dark grey bands show the 90% confidence intervals for urban and rural precipitation respectively. The grey bars show the frequency of occurrence of each WT-month combination.

The yearly cycle of urban and rural precipitation aggregated over all WTs is given in Figure 3.4. Urban (green) triangles lying above the light green band indicate confidence in the results that urban precipitation is enhanced, while rural (black) dots lying under the dark grey band give confidence that rural precipitation is lower than expected by chance. Over the 2001-2010 period (Figure 3.4, left) the difference between urban and rural precipitation is rarely significant, but urban precipitation is rather consistently higher. This enhancement is largest in the summer period (12% in JJA), and about 4, 8 and 6% higher in autumn, winter and spring respectively. Similar results are obtained for the other 10-year periods and the entire period (1951-2010, Figure 3.4, right), indicating these are robust results, not dependent on the investigated time period. When analysing the entire 1951-2010 time period, bootstrap intervals cannot be easily computed because the number of stations varies over time.

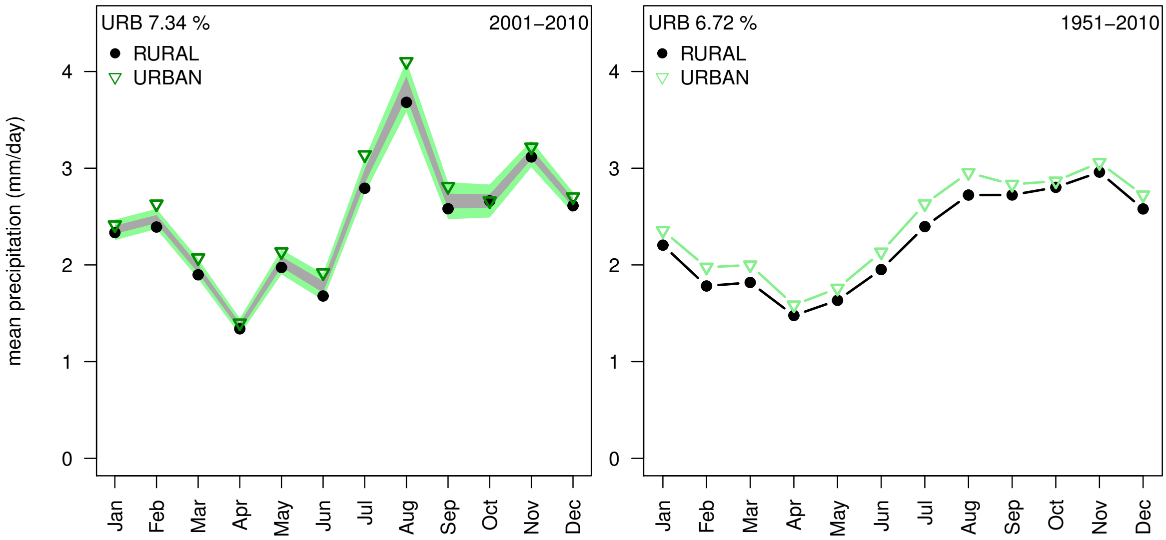

Figure 3.4 Mean daily precipitation (mm/day) at urban and rural stations throughout the year over the period 2001-2010 (left) and 1951-2010 (right). Light green and dark grey bands (left) show the 90% confidence intervals, based on a bootstrapping procedure, for urban and rural precipitation respectively, that cannot be estimated for the period 1951-2010 (right).

The average urban enhancement throughout the entire period is about 6% when WT 9 is not taken into consideration and 7% when it is. WT 9 cannot be taken into account in the 1951-1960 period because no stations are classified as urban since the urban fraction is always below the 0.25 threshold. Urban precipitation in WT 4 (NE) and 5 (E) can be up to 10% lower than rural in some 10-year time periods (Figure 3.5). These instances when urban precipitation is lower generally happen in the less frequently occurring easterly WTs and, therefore, have limited influence on the mean. The largest positive urban effects are found under light flow (WT 9). We hypothesize this is because more convective precipitation occurs in this WT and this type of precipitation is more susceptible to triggering by the land surface.

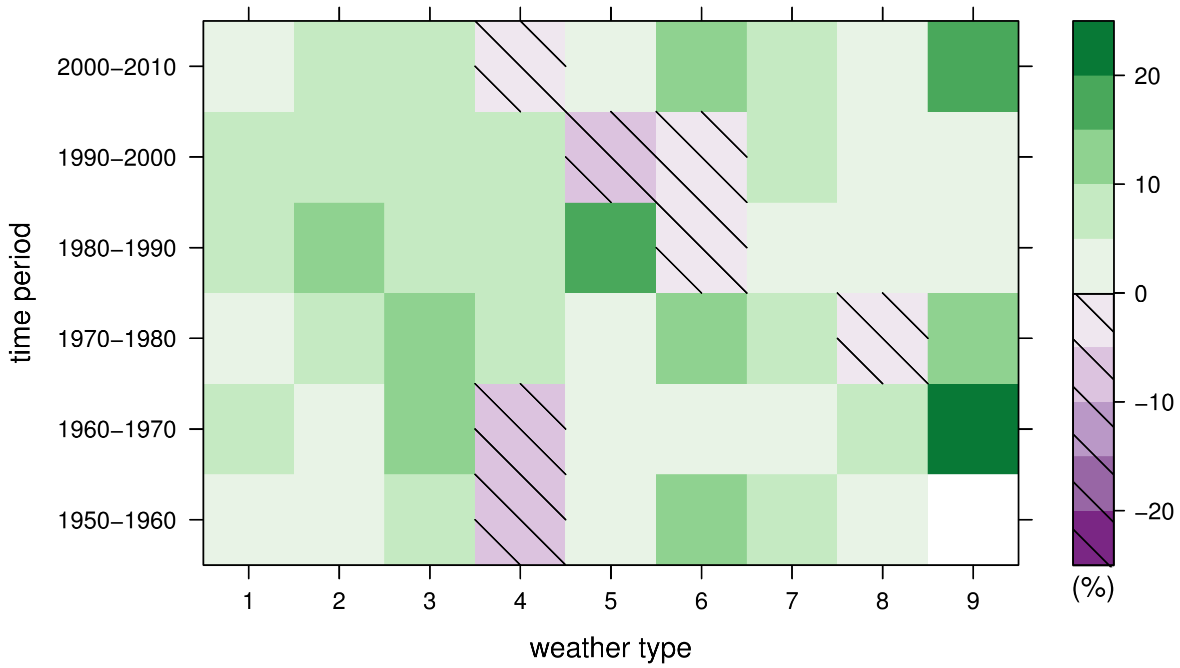

Figure 3.5 Relative difference between mean precipitation at urban and rural stations (%) for each weather type (wind direction) and 10-year period ending with the year indicated. Hatching marks negative values.

In addition, the strength of the urban enhancement of precipitation is larger at low wind speeds (Figure 3.6). To investigate this, we use average 10 m wind speed from ERA-Interim over the central Netherlands (i.e. a 0.5x1 degree area centered around 52.5°N and 3.5°E). Average precipitation is much higher at high wind speeds (> 7.2 m/s), but the relative urban enhancement is larger (13.8%) at low wind speeds (< 3 m/s). The enhancement at low wind speeds is only seen in the summer half year (May-September). At high wind speeds the urban enhancement is seen throughout the entire year, but it is relatively small in summer. The 20 km distance that is used to determine urban stations might be too small for use under high wind speeds as clouds could cover this distance, or more, within the time that precipitation forms and as such limit the urban enhancement calculated here. Moreover, at low wind speeds the air mass overlying urban surfaces stays in place for a longer period of time and hence can be influenced more. Consequently, the relatively high sensible heat flux and updrafts over urban areas could provide the trigger for the formation of precipitation. Additionally, the high levels aerosols associated with urban areas are more likely to impact nearby precipitation at low wind speeds.

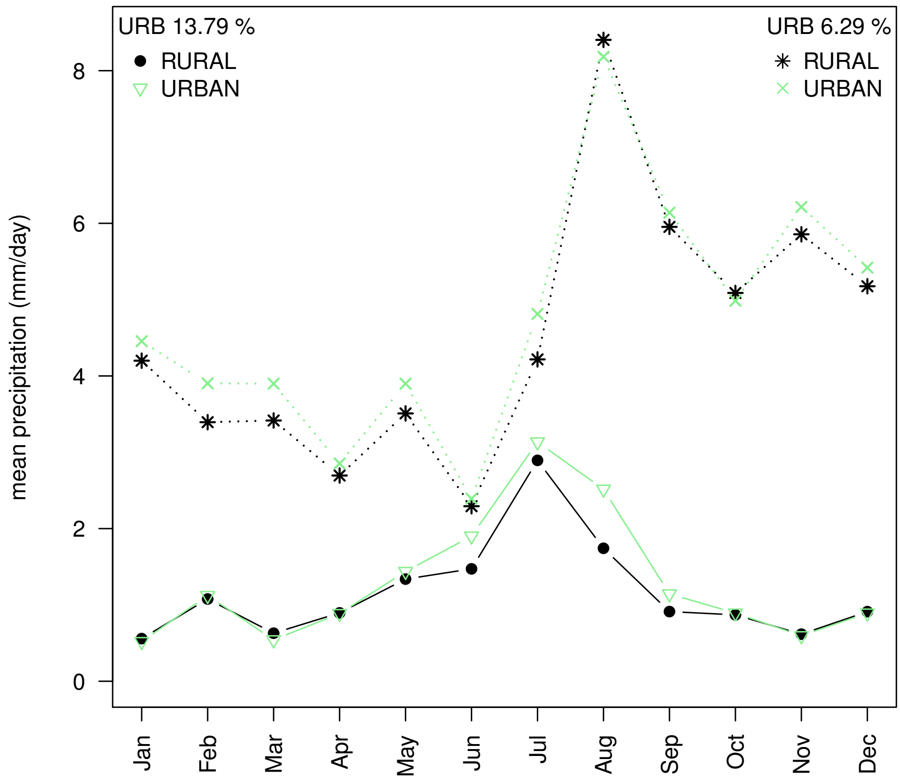

Figure 3.6 Mean daily precipitation (mm/day) at urban and rural stations throughout the year over the period 2001-2010 for days with the 20% lowest wind speeds (symbols and solid lines) and 20% highest wind speeds (crosses and dashed lines).

3.4.2 Other indices

A similar enhancement to that found in mean precipitation is also found in other precipitation indices. The figures for extreme precipitation (95th percentile of the pooled urban and rural data) are remarkably similar to those for mean precipitation in all time periods. The urban enhancement is somewhat lower (6%) in the latter 2001-2010 period, than over the entire 60 year period (11%) (Figure 3.7). Similar to mean precipitation, the differences are largest (10%) in summer and smallest (3%) in autumn.

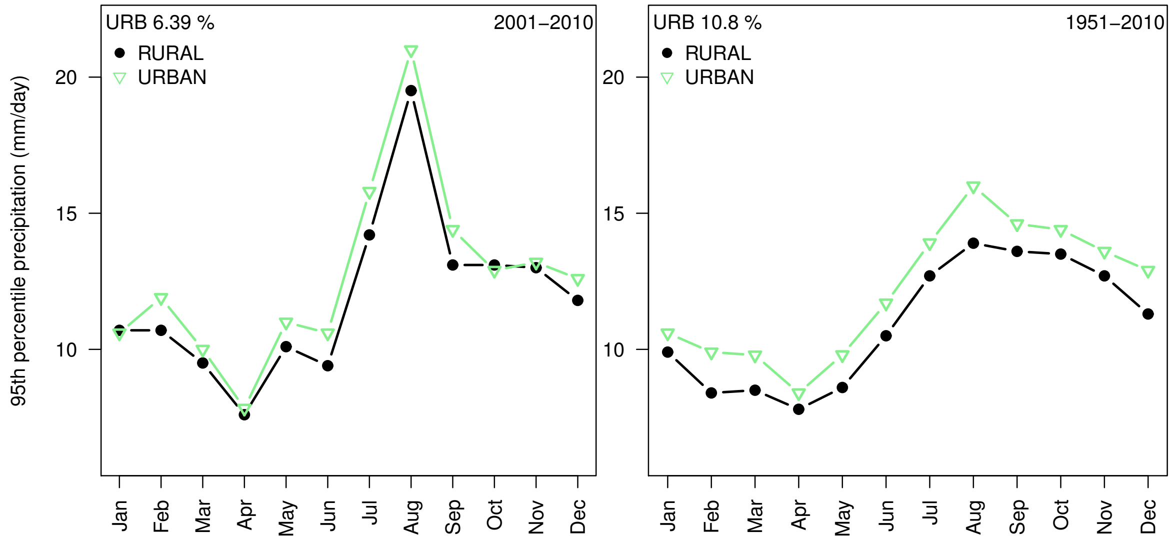

Figure 3.7 Mean 95th percentile of precipitation (mm/day) at urban and rural stations throughout the year over the period 2001-2010 (left) and 1951-2010 (right).

We also investigate the distribution of precipitation for urban and rural stations (Figure 3.8). This can be done without any averaging because the data are simply pooled together. The difference in distribution between the seasons is caused by the more convective character of precipitation and higher moisture content of the atmosphere in summer, and more frontal character and lower moisture content in winter. For both winter and summer, urban precipitation consistently lies above rural precipitation throughout the entire distribution except for the very tails. The tails however consist of little data (the ten most extreme data points are indicated by dots) and are therefore uncertain.

Finally, to examine whether enhanced aerosol loading due to urban areas played a role, the weekly cycle of precipitation was investigated. The existence of a weekly cycle has more often been used as evidence of human activities on climate (e.g. Arnfield, 2003; Kanda, 2007; Rosenfeld and Bell, 2011; Stallins et al., 2013). However, following the methodology of Stjern (2011), we could not find any evidence of a weekly cycle in precipitation along the Dutch West coast or the Netherlands as a whole.

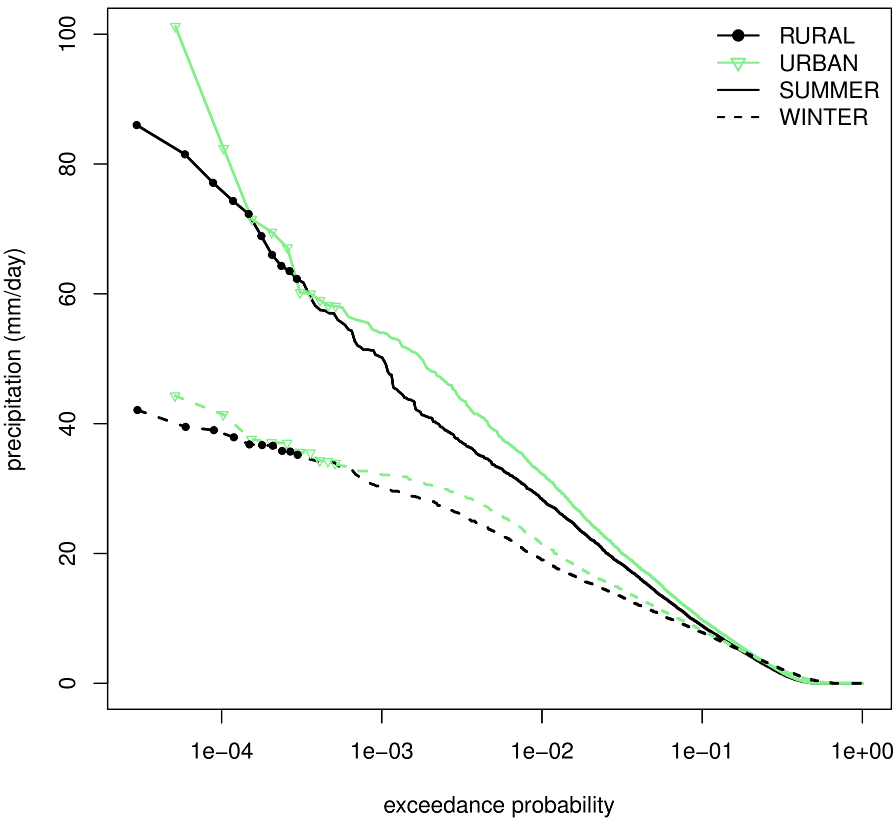

Figure 3.8 Rainfall (mm/day) exceedance probability at urban and rural stations in summer (JJA) and winter (DJF) over the period 2001-2010.

3.5 Discussion

The selection of urban and rural stations in this study is a crucial step in the methodology of this paper. Nevertheless, a sensitivity analysis shows that using different criteria for selecting urban stations, a smaller or larger influence radius or a different angle (90° instead of 45°) for the selection area, only influences the strength and not the sign of the observed urban effect (Figure 3.9). The number of “urban” stations varies here from 5 to 35, always selecting those stations with the highest urban fraction. Note that the 0.25 urban fraction criterion that is used throughout the rest of the paper does not apply here and a fixed number of stations is used. Ultimately, it seems the enhancement of precipitation downwind of urban areas is robust (i.e. always positive), but it could be biased by the selection method because some stations are classified as urban more often. The reason these stations have higher precipitation amounts could be due to the nearby urban areas or other factors (e.g. the influence of the North Sea). To test this, the calculations for the 2001-2010 period are repeated 1000 times, but now with a random WT for each day. The resulting distribution indicates an average urban effect of 4.5% (σ=0.5%), that the actual calculated urban effect of 7.3% falls well outside of. Therefore, there is a small, but significant precipitation enhancement at the stations downwind of cities, that we can certainly attribute to urban influence.

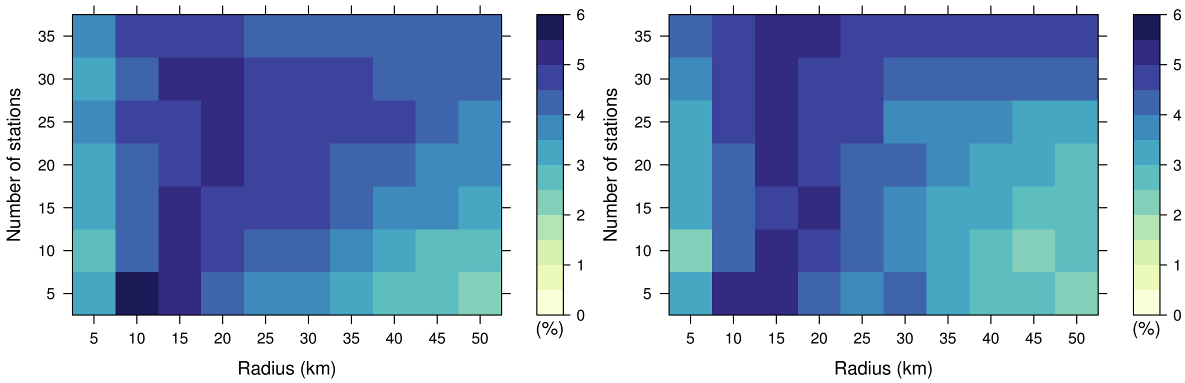

Figure 3.9 Relative difference between mean precipitation at urban and rural stations (%) averaged over the period 1951-2010 for a fixed number of stations with the highest urban fraction, using different radius sizes (km) of a one-eight circle (left) and a one-quarter circle (right) used to determine the upwind urban fraction.

Other studies show that the chosen method can have substantial impact on the calculated size of urban effects. For example, average precipitation downwind of St Louis in spring (autumn) was found to be 14% (7%) enhanced using regional pattern analysis (Huff and Changnon, 1986), while using a quadrant method total precipitation in spring (autumn) was found to be 4% (17%) enhanced (Changnon et al., 1991). The mean urban precipitation enhancements we find for the Dutch West coast over the entire 1951-2010 period are 9, 10, 3 and 8% respectively for spring, summer, autumn and winter. These magnitudes are comparable to the aforementioned enhancements at St Louis and other large metropolitan regions (e.g. Ashley et al., 2012; Huff and Changnon, 1973; Jauregui and Romales, 1996). In our study we find the lowest enhancement in autumn (3%), this is quite dissimilar to other studies and is probably related to the coastal effects of the North Sea. Another Dutch study has compared radar data of precipitation within urban areas to that in the rest of the country. For the period 2009-2012 it seems that high intensity events (> 25 mm in 15 min, > 60 mm in 60 min) occur somewhat more often within urban areas (Overeem, 2014). Although this is a very different methodology, these results seem to be in agreement with the observed difference in precipitation distribution at urban and rural stations in this study.

All the same, mean precipitation has increased by about 25% near the Dutch West coast in the period 1951-2009 (Buishand et al., 2011). Urban areas might have contributed to this increase, but they are unlikely to be the major cause since we only find an enhancement of 7% along the most populated West Coast. Therefore, other factors like the enhancement of sea surface temperature (Attema et al., 2014) or changes in circulation (van Haren et al., 2013) must also be responsible for the observed trend. In addition, the increase of coastal precipitation is smallest in July-September, while the enhancement downwind of urban areas is strongest in these months. Nevertheless, the area that is influenced by urban areas is presently much larger than in the past. Where cities made up approximately 14% of our investigated region in 1960, they covered almost 33% of the region in 2010, and the affected region must have non-linearly expanded in the meantime as well.

3.6 Conclusions

In this paper, precipitation near urban areas in the densely populated coastal region in the West of the Netherlands is investigated with a novel methodology over the time period 1951-2010. Individual Dutch cities are not larger than 20 km in diameter, but many of them lie in close proximity. To deal with this fragmented urban area, different stations were determined "urban" or "rural" for every weather type (geostrophic wind direction). Stations were classified as urban if the fraction of urban area in the upwind region was above 0.25, the amount of urban stations therefore increases through time.

Based on daily station observations for the 1951-2010 period we find a consistent year-round precipitation enhancement of about 7% downwind of urban areas along the Dutch West coast compared to the rural surroundings. This enhancement is seen throughout the entire distribution of precipitation, so in extreme precipitation as well as the mean. The effects are seen for nearly every weather type and the relative difference between urban and rural stations remains moderately constant throughout time. The largest urban-rural differences are found under light flow (WT 9) and low wind speeds, suggesting that enhancement of precipitation is favoured under convective conditions. In all we find our methodology deals well with the fragmented urban areas in the Netherlands and the influence of such type of urbanisation can be similar to that of a large metropolitan region.

Chapter 4

Land surface feedbacks on spring precipitation*

In this paper the Weather Research and Forecasting (WRF) model is used to investigate the sensitivity of precipitation to soil moisture and urban areas in the Netherlands. We analyze the average output of a four day event from 10-13 May 1999 for which the individual days had similar synoptical forcing. Four simulations are conducted to test the impact of soil moisture changes on precipitation. We find a positive soil moisture-precipitation feedback, i.e. wet (dry) soils increase (decrease) the amount of precipitation. We execute two additional experiments in which urban areas in the Netherlands are expanded and one in which urban areas are completely removed. Expansion of urban areas results in an increase of the sensible heat flux and a deeper planetary boundary layer, similar to reducing soil moisture. Expanding urban areas reduces precipitation over the Netherlands as a whole, but the local response is not clear. Within existing urban areas, mean and maximum temperature increases of respectively 0.4 and 2 K are found under an urban coverage scenario for 2040. The ratio of evaporation to precipitation (a measure of the soil moisture-precipitation feedback) in the urbanization experiments is only about one third (23%) of that in the soil moisture experiments (67%). Triggering of precipitation, on the other hand, is relatively high in the urban expansion experiments. The effects of reduced moisture availability and enhanced triggering in the urban expansion experiments compensate each other, leading to the moderate reduction in precipitation.

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4.1 Introduction

The land surface directly affects the surface energy budget and corresponding surface energy fluxes through the partitioning of incoming solar radiation at the surface. The land surface, in this context, refers to both the (water content of the) underlying soil and the surface properties implied by land use and land cover. Urban areas, for example, have a high albedo, surface roughness and large heat-storage capacity compared to rural areas (Oke, 1982). In addition, the large impervious fraction in urban areas reduces moisture available for evaporation. The influence of large urban areas has been investigated and proven for temperature (e.g. Kalnay and Cai, 2003; Oke, 1982) as well as precipitation. Both the onset and timing of precipitation can be influenced (e.g. Niyogi et al., 2010; Schmid and Niyogi, 2013) as well as the amount of precipitation and area where precipitation occurs (e.g. Daniels et al., 2016; Rozoff et al., 2003; Shem and Shepherd, 2009; Shepherd et al., 2010). However, to our knowledge there is only one study that has simulated the effect of urban areas on precipitation in Europe as a whole and there are no modelling studies for the Netherlands. Trusilova et al. (2008) compared simulations with current urban cover to simulations in which all urban areas were removed. They found that inclusion of urban areas resulted in a small decrease of total precipitation in Europe. Expanding urban cover, by 40% compared to the current situation, reduced total precipitation further in January while no clear signal was found in July (Trusilova et al., 2009). In general, the impacts of land use and land cover changes are likely to become more significant in the coming decades (Pielke et al., 2007).

In addition, variations in land surface properties - a combindation of land use, land cover and top-soil characteristics - can feed back on themselves through the changes they impose on the near-surface climate. These feedbacks are mainly controlled by the surface albedo, soil moisture content and consequent energy partitioning of latent and sensible heat. For example: a reduction in soil moisture and consequent decrease in evapotranspiration (latent heat flux) leads to increases in sensible heat flux and near-surface air temperature. Higher temperatures, in turn, increase the evaporative demand and latent heat flux which subsequently reduces soil moisture. This constitutes a positive soil moisture-temperature feedback.

Seneviratne et al. (2010) have written an extensive review on how soil moisture feedbacks affect both near-surface air temperature and precipitation. In earlier work the soil moisture-precipitation feedback was attributed to a direct contribution of regional evapotranspiration to precipitation enhancement in the same region (e.g. Brubaker et al., 1993; Eltahir and Bras, 1996). More recently however, the role of indirect interactions in the formation of precipitation and the stability of the boundary layer have received more attention (e.g. Ek and Holtslag, 2004; Findell and Eltahir, 2003; Hohenegger et al., 2009; Santanello et al., 2009; Schär et al., 1999). A prerequisite for the formation of clouds and subsequent precipitation, is high relative humidity at the top of the planetary boundary layer (PBL). Dry soils have a relatively high sensible heat flux and consequently higher surface temperatures and deeper PBLs. Because of the relatively low temperatures at the top of deep PBLs, moisture transported by uprising thermals can easily condensate and form clouds. Wet soils, on the other hand, have a much shallower PBL in general. However, over wet soils, cloud formation can occur because of a more moist PBL resulting from the high latent heat flux at the surface. In both cases the lifting condensation level can be reached below the top of the PBL, thus allowing cloud formation. The feedback arising from this mechanism can be of either sign, because precipitation can be triggered over both dry and wet soils. Indeed, both positive and negative soil moisture-precipitation feedbacks have been found in observational and modelling studies (e.g. Boé, 2013; Hohenegger et al., 2009; Santanello et al., 2009; Taylor et al., 2012; Tuinenburg et al., 2011).

Urban areas in the Netherlands have strongly expanded in the last century, a trend that is likely to continue in the (near) future. Urban areas made up around 8% of the total area in the Netherlands in 2000 and are projected to increase to 12% in 2040 (Dekkers et al., 2012) under the Global Economy scenario (CPB et al., 2006). This national scenario is consistent with the SRES A2 scenario. Urbanization has mostly taken place in the Randstad, a conurbation consisting of the four largest Dutch cities mainly located along the west coast of the Netherlands. At the same time, precipitation has gradually increased over the last half century by almost 16%, especially along the west coast (Buishand et al., 2013). The impact of sea surface temperature (SST) changes on precipitation in the Netherlands has recently been investigated (Attema et al., 2014; Lenderink et al., 2009) and appears to have played a major role. In this study however, we will use a model to investigate the impact of urbanization and soil moisture conditions on precipitation in the Netherlands, in isolation of other climatological conditions like SST and circulation.

We will first introduce the selection of the case study period, the model setup and experiments. Hereafter, the model results from the reference run are compared to observations. Next, the outcome of the sensitivity analysis, the resulting soil moisture-precipitation feedback and the effects of urban areas are evaluated, followed by a general discussion and the conclusions.

4.2 Methods

4.2.1 Study area

Our study area, the Netherlands, is located in northwest Europe along the North Sea and the Atlantic Ocean (Figure 4.1). The vicinity to these water bodies has great influence on weather in the Netherlands and causes the typical mild winters and wet summers associated with a sea climate. The spatial distribution of precipitation varies strongly between different seasons. In winter and summer, precipitation is relatively uniform, whereas a strong coastal gradient exists in spring and autumn, though of the opposite sign (Attema et al., 2014). In spring, the relatively low SST suppresses shower activity over sea and near the coast. The onset of precipitation is only triggered after air has travelled over land for several kilometers and has sufficiently warmed. The subsequent growth of the PBL enables the formation of clouds and succeeding precipitation. As a consequence of this triggering mechanism over land, precipitation in spring is up to 25% lower near the coast than further inland. The larger surface roughness and hence lower wind speeds over land might play a role here (Malda et al., 2007) in addition to the temperature and associated moisture difference between the land and sea surface. Considering the importance of the land in triggering convective precipitation in spring, we consider this period interesting to study the influence of urbanization and soil moisture. In addition, large precipitation trends have been observed in spring (Daniels et al., 2014), which still need to be explained.

4.2.2 Case selection

A useful criterion for the selection of a suitable case study, is the similarity of the synoptic conditions and dominant westerly winds. Situations in which this criterion is fulfilled are identified using a weather and circulation type classification, namely the 27 type Jenkinson-Collison Types (JCT) classification scheme (Appendix A). This method was developed by Jenkinson and Collison (Jenkinson and Collison, 1977) and is intended to

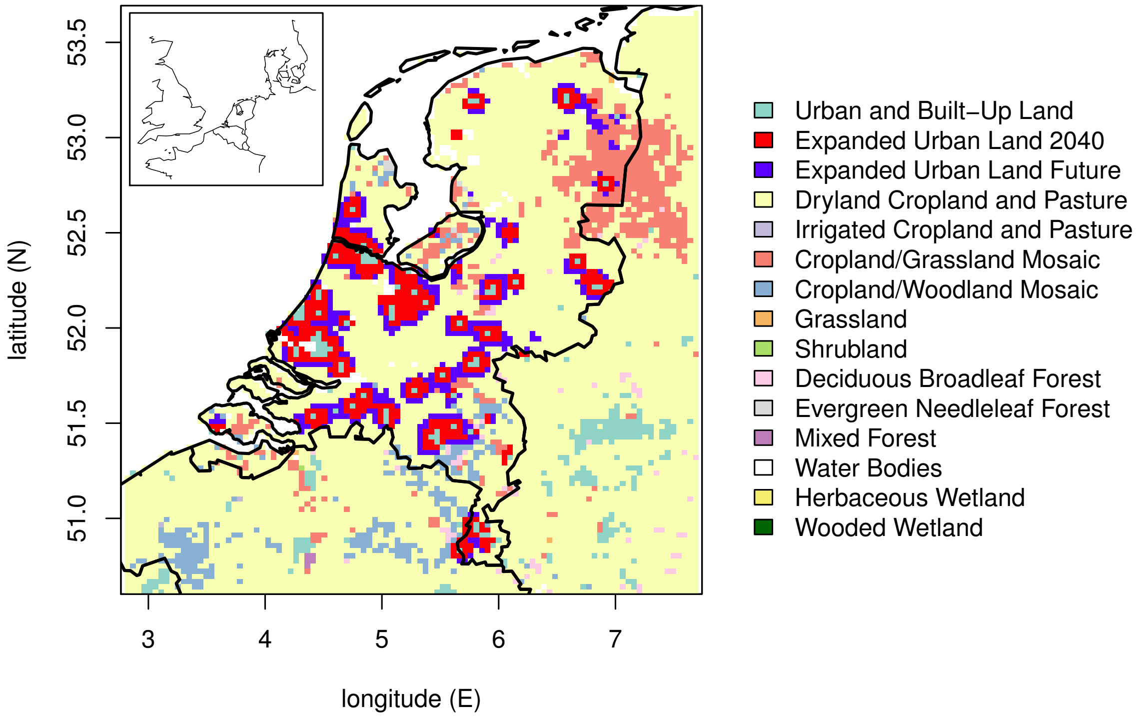

Figure 4.1 Dominant land cover in the Netherlands as given by the USGS map with the expanded urban areas in red and blue. The inset shows the full model domain.

provide an objective scheme that acceptably reproduces the subjective Lamb weather types (Jones et al., 1993; Lamb, 1950). For our purpose the JCT classification grid is altered from its original domain to a smaller domain encompassing the Netherlands. The new domain ranges from 3-12.75°E and 47.25-57.7°N and the classification scheme is rerun on 12 UTC MSLP data from ERA-Interim (Dee et al., 2011).

The 27 types of the JCT scheme are explained by combining wind directions (W, NW, N, etc.) with cyclonic, straight and anticyclonic flow, leaving three classes for pure cyclonic days, pure anticyclonic days, and a light indeterminate flow class, respectively. We look for a case with SW, W or NW wind, because precipitation is commonly brought in from the sea, and straight flow, because we are interested in land surface effects and we expect the synoptic forcing to be higher under (anti)cyclonic flow. The combination of westerly winds and straight flow occurs relatively often, about 20% of the time, so we have a large pool to sample from. The selected period, 10-13 May 1999, has straight SW flow on the first day and straight W flow on the following three days. This period is selected because of the relatively unstable air and afternoon showers that occurred, which makes it a suitable case for investigating land surface effects. Throughout the paper results are averaged over the whole of the Netherlands for the entire four day period unless otherwise specified.

4.2.3 Model setup

We use the non-hydrostatic Advanced Research Weather Research and Forecasting model (WRF, version 3.4.1) (Skamarock et al., 2008) on a single domain of about 1000 x 1000 km. The domain is centered around the Netherlands and has a horizontal grid spacing of three kilometers (Figure 4.1). The vertical grid contains 28 sigma levels of which the lowest seven levels are below 1 km to have finer resolution in the PBL. Atmospheric and surface boundary conditions are obtained from ECMWFs operational data archive every six hours. Unfortunately soil moisture data was not available from the operational archive and is therefore initialized using ERA-Interim data. Model output is stored and analyzed on an hourly basis. The sensitivity of the model to initial conditions was tested by altering the boundary conditions at initialization up to three hours before or after 12 UTC. The differences in model output after these initial perturbations were very small.

We use the Bougeault-Lacarrere PBL scheme (Bougeault and Lacarrere, 1989), the WRF Single-Moment 6-Class Microphysics Scheme (WSM6) (Hong and Lim, 2006), the RRTMG schemes for both long- and shortwave radiation (Iacono et al., 2008), the Grell 3D cumulus parameterization scheme (Grell, 1993; Grell and Devenyi, 2002) and the Unified Noah Land Surface Model (Tewari et al., 2004) with the Urban Canopy Model (UCM). The UCM is a single layer model which has a simplified urban geometry. Included in the UCM are: shadowing from buildings, reflection of short and longwave radiation, wind profile in the canopy layer and multi-layer heat transfer equations for roof, wall and road surfaces (Kusaka and Kimura, 2004; Kusaka et al., 2001). The standard values for urban canopy parameters have been retained, although it is known the UCM is sensitive to changes herein (Loridan et al., 2010).

It is also well known that the choice of parameterization schemes in WRF can have a large effect on the simulation (e.g. Jankov et al., 2005), but we have chosen not to vary this. Mooney et al. (2012) investigated twelve combinations of parameterization schemes in WRF over Europe. Their results indicated that the effect of different PBL schemes on precipitation is negligible while the effect of the long wave radiation and microphysics scheme is comparable, but much smaller than the effect of the land surface model.

4.2.4 Model simulations

All model simulations were performed with 12 hour spin-up time during which there was no precipitation. The first experiment is a control simulation (REF) with land use from the standard U.S. Geological Survey (USGS) map that is available within WRF. REF has an average soil moisture content in the top layer (top 10 cm) of 0.30 m^3m^{-3} after spin-up. The next experiment consists of a set of sensitivity simulations in which soil moisture is initialized at a constant value for all land grid points. If the value at initialization is above saturation or below wilting point for the local soil type, the land surface model adjusts the soil moisture content during the spin-up period. The initial soil moisture content is varied so we have a very dry simulation with soil moisture near wilting point (SM_0.13), a very wet simulation with soil moisture near saturation (SM_0.35) and two values in between these extremes (SM_0.18, SM_0.25). The values in the names of the different experiments denote the actual average soil moisture content (m^3m^{-3}) in the top layer that was achieved after spin-up. During the experiments, soil moisture was allowed to evolve freely.

In the next set of experiments we change the percentage of urban land cover in the Netherlands. The urban fraction in the reference simulation, based on the USGS map, is 2%, which is much lower than the actual urban fraction (8%). All urban land cover is treated similarly and falls into the category high intensity residential, this means vegetation accounts for less than 20% and constructed materials for 80 to 100% of the cover. Expanded urban land cover is calculated by a simple function that checks neighboring cells and expands the urban fraction by as much as the sum of the urban fractions in the eight neighboring cells. If urban cover is increased, the fractions of non-urban land cover in the cell are decreased proportionally. The resulting fraction of land in the Netherlands where urban area is dominant is around 13% (Figure 4.1). This amount of dominant urban area is similar to that achieved under the Global Economy scenario in 2040 (12%) (Dekkers et al. 2012). We rerun the expansion function and increase the dominant urban area to 24%. We will refer to these simulations as URB_2040 and URB_FUT respectively. In our last experiment all urban land cover in the Netherlands is removed (NO_URB). In cells where urban area is removed, the fractions of non-urban land cover are increased

Table 4.1 Overview of the conducted experiments and altered variables

Experiment	Soil moisture content (m^3m^{-3})	Urban area (%)
SM_013	0.13	as ref
SM_018	0.18	as ref
SM_025	0.25	as ref
SM_035	0.35	as ref
REF	0.30	2
NO_URB	as ref	0
URB_2040	as ref	13
URB_FUT	as ref	24

proportionally. If the cell was entirely urban (0.2%), land cover is replaced by dryland cropland and pasture, the dominant land use type in the Netherlands. All other variables in the sensitivity experiments are identical to REF and no changes in anthropogenic heat or aerosols are modelled. An overview of the eight conducted experiments and differences in their parameters is given in Table 4.1.

4.3 Model evaluation

To evaluate the performance of the model, the results from the reference simulation (REF) will first be compared to observations. The results of the sensitivity experiments will be discussed in the next chapter. After a short description of the (synoptic) weather during the selected case, we will evaluate the performance of the reference run in representing the temperature, mean sea level pressure (MSLP) and precipitation. Observations of precipitation are available within the Netherlands at a 2.4 km resolution on an hourly basis from (bias)corrected radar data (Overeem et al., 2009). The radar data is remapped to the three km resolution used in the WRF model to allow for comparison. Temperature (Haylock et al., 2008) and MSLP (van den Besselaar et al., 2011) from the E-OBS dataset version 8.0 are used for further evaluation. Comparison to these variables is done at the 0.25° resolution native to the E-OBS dataset.

4.3.1 Weather description

The month of May 1999 was on average very warm (mean maximum temperature in De Bilt was 14.2°C where 12.3°C is the long-term average) and dry (46 mm precipitation in total where 57 mm is the long-term average). Precipitation mostly fell in small showers resulting in large local differences in precipitation amounts. During the period 10-14 May the weather in the Netherlands was determined by a depression situated near 54°N 20°W at 00 UTC on 10 May. This depression travelled eastwards and arrived at the North Sea on 14 May. After the corresponding cold front passed on 10 May a west southwest current stayed in place for the next three days. It was a sunny period with normal temperatures (maxima around 16-18°C and minima around 8-10°C) and afternoon showers which developed from cumulus clouds.

4.3.2 Comparison to observations

Figure 4.2 shows the correlation and root mean square error for minimum, maximum and mean temperature, MSLP and precipitation. For temperature, the daily mean, minimum and maximum are calculated before being averaged and compared to the averaged observations. The results are generally good: the correlation is 0.99 or higher and the variance in the simulation is similar to that in temperature observations. MSLP is forced upon the model by the boundary conditions and is represented very well in the output compared to the E-OBS data. The correlation for precipitation is lower than for the other variables, but still over 0.8, because convective precipitation is one of the most difficult processes to correctly represent in a model. In any case, our results for precipitation are comparable with 5-day averaged results with WRF for Portugal (Soares et al., 2012).

4.3.3 Precipitation

Figure 4.3 shows the four day time series for precipitation from hourly observations and REF averaged over the Netherlands. On the first day precipitation amounts in REF are less than in observations because WRF underestimates the duration of the precipitation event. However, when averaged over the entire simulation period precipitation amounts are overestimated in REF. A large proportion of the overestimation of precipitation by the model occurs on the third and fourth day. On these days the onset of precipitation is too

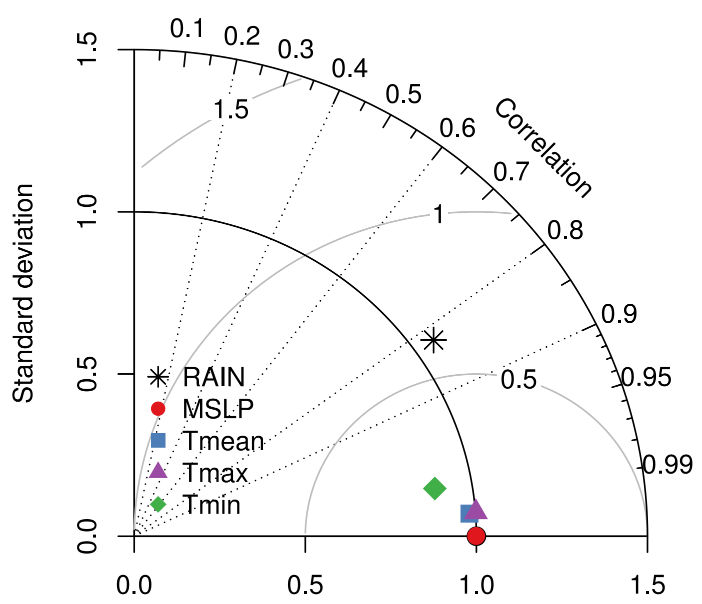

Figure 4.2 Taylor plot for precipitation (RAIN), mean sea level pressure (MSLP) and the minimum (Tmin), maximum (Tmax) and average temperature (Tmean) in the reference simulation compared to observations for the period 10-13 May 1999.

early and the simulated duration of precipitation is too long. The rate of precipitation on the other hand is relatively well captured by the model throughout the entire simulation.

Likewise, the average coastal gradient in precipitation amounts is well reproduced by the model (Figure 4.5). Little precipitation falls along the coast, moderate precipitation is found further inland and most precipitation falls toward the eastern border and in the southernmost tip of the country. Precipitation in the southernmost tip of the country is most likely orography driven, which is well captured by the model. In total however, mean daily precipitation is overestimated by about 10% and the model underestimates precipitation in the center of the country.

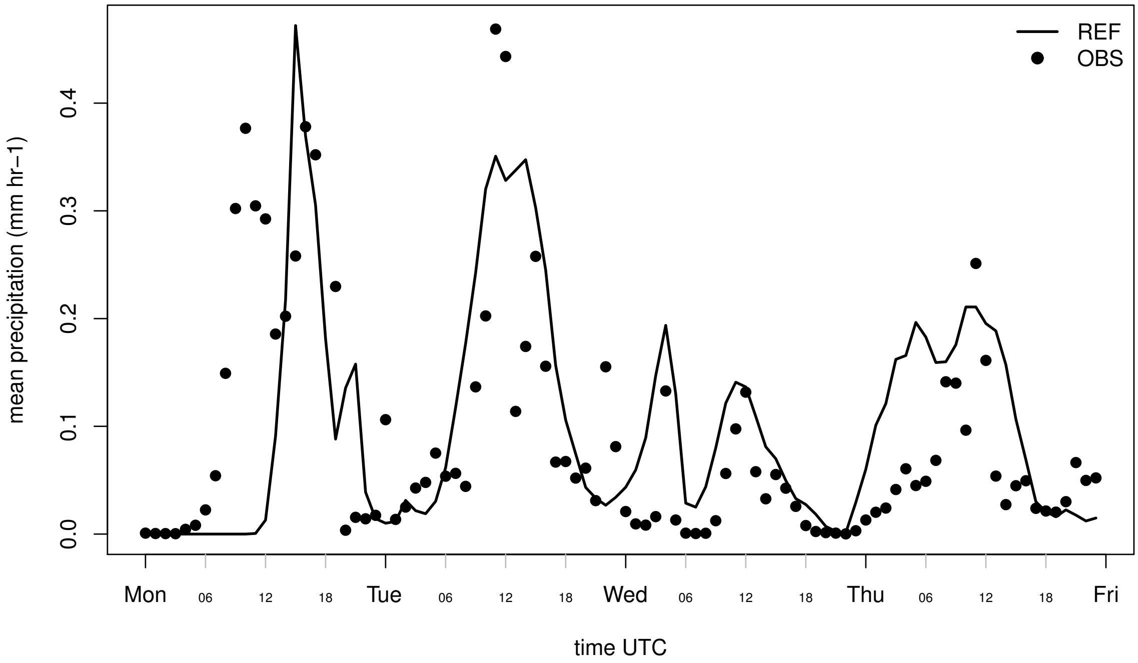

Figure 4.3 Time series of hourly accumulated precipitation in the reference simulation and radar data observations over the Netherlands for the period 10-13 May 1999.

4.4 Results

In the first section we provide the results from the sensitivity experiments with a focus on the similarities between the different sets of experiments. The second section investigates soil moisture-precipitation feedbacks, while the third section focusses on the effects of expanding urban areas.

4.4.1 Precipitation in the sensitivity experiments

In the experiments we conduct, evapotranspiration is altered in two different ways: directly, through the evaporative fraction in urban areas, and indirectly, through changes in soil moisture. In our simulations a consistent reduction of precipitation under reduced soil moisture and increased urban coverage is found (Figure 4.4). Cumulative mean precipitation

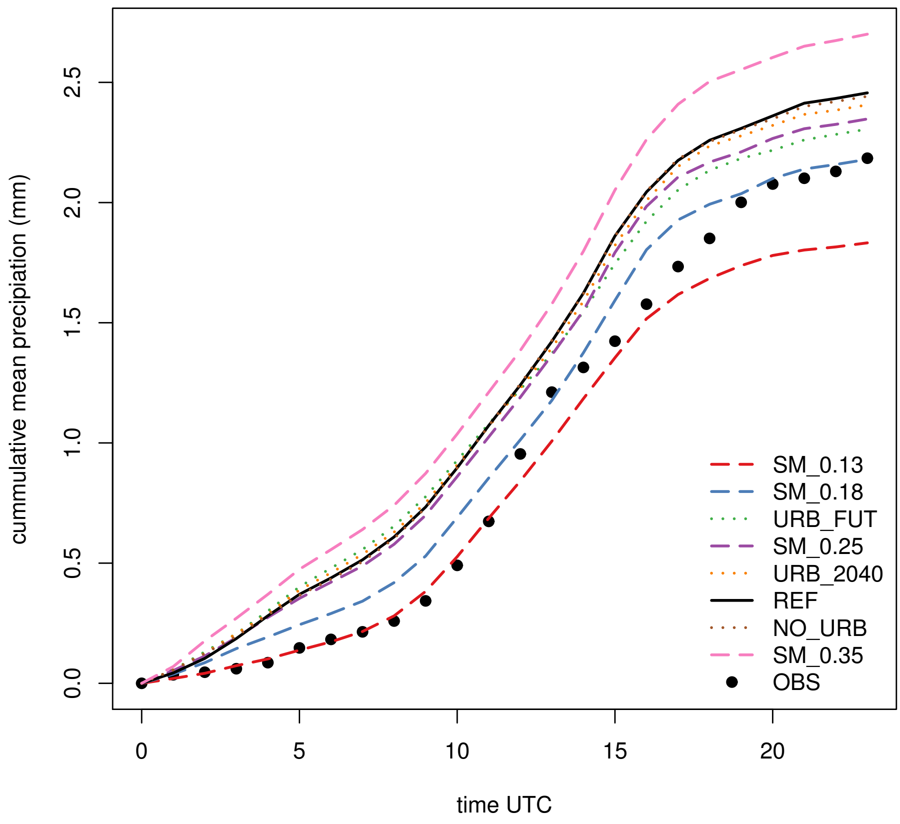

Figure 4.4 Cumulative mean precipitation in the Netherlands for the reference simulation (REF), the experiments with soil moisture initialized at different values (SM_...), the experiments with different urban extents (URB_...) for the period 10–13 May 1999.

is about 12% higher in the wettest and 24% lower in the driest experiment compared to REF.

If we consider that urban areas reduce water availability for evaporation, expanding urban areas can be regarded analogous to reducing soil moisture because the fraction of evaporating surfaces in urban areas is reduced to only 10%. In the urban expansion experiments a much smaller fraction of the Netherlands (0.1 and 0.22) is altered than in the soil moisture (SM) experiments. Nonetheless, the changes in mean precipitation are remarkably similar to a first order guess from the following estimation. If we assume the reduction of the driest SM runs to be representative for the response in the urbanization (URB) experiments, an increase of 10 and 22% in urban area would yield a decrease of 2% (24% * 0.1) and 5% (24% * 0.22) in precipitation. Aggregated at the national scale

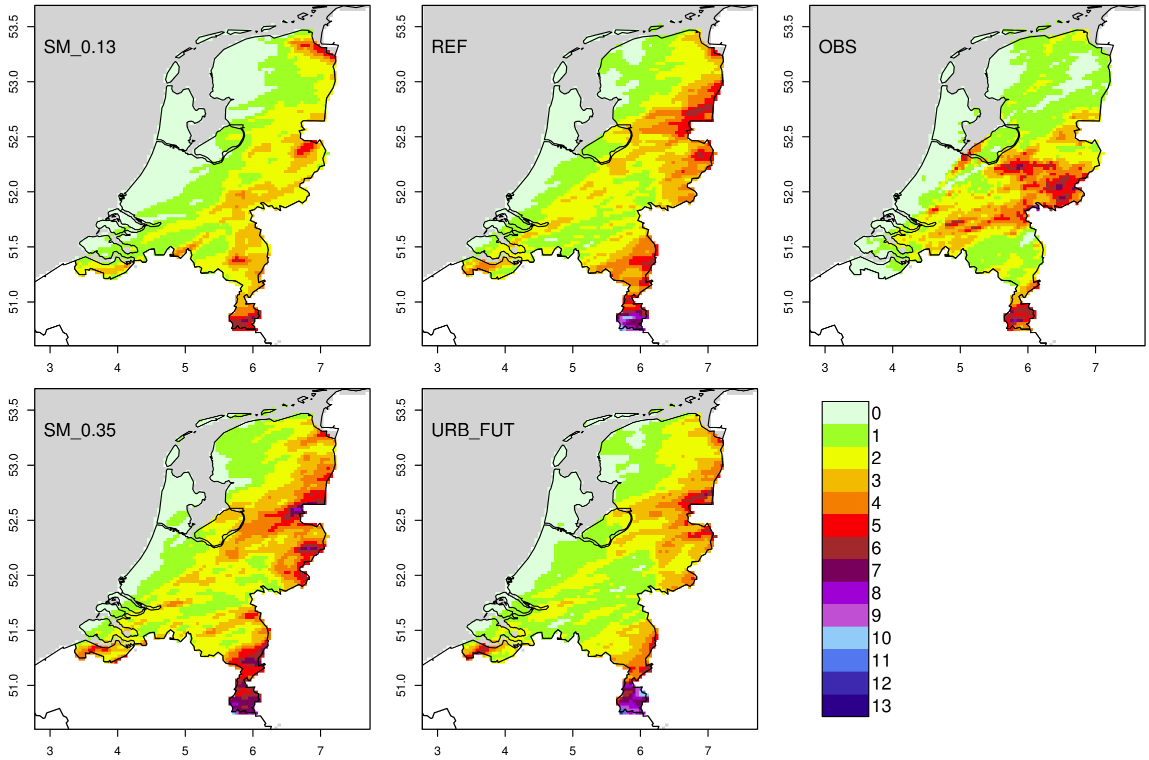

Figure 4.5 Mean daily precipitation in an experiment with low soil moisture (SM_0.13), the reference simulation (REF), radar observations (OBS) and experiments with high soil moisture (SM_0.35) and expanded urban areas (URB_FUT) over the Netherlands for the period 10-13 May 1999.

this analogy seems to hold, as the simulation results show precipitation in URB_2040 and URB_FUT is respectively about 2 and 6% reduced compared to REF. Note that precipitation in NO_URB is also slightly lower than in REF, whereas a small increase in precipitation would be expected based on its evapotranspiration.

The spatial patterns of precipitation remain quite similar to REF in all of the experiments, though the amounts are locally enhanced or reduced (Figure 4.5). For the drier runs, precipitation is shifted towards the east and north and the maxima are located in slightly different locations with regard to REF. The reduction of precipitation in the southernmost tip of the country that can be seen in all of the SM experiments could be due to the spatially uniform initialization of soil moisture and is not seen in the URB experiments. The urban expansion experiments have similar precipitation as REF along the border and the largest reductions are seen spread over the center of the country. Overall, the wet- or dryness at the start of a simulation apparently influences the atmosphere in such a way that precipitation is reduced (enhanced) over dry (wet) soils. This is indicative of a positive soil moisture-precipitation feedback.

4.4.2 Soil moisture-precipitation feedbacks

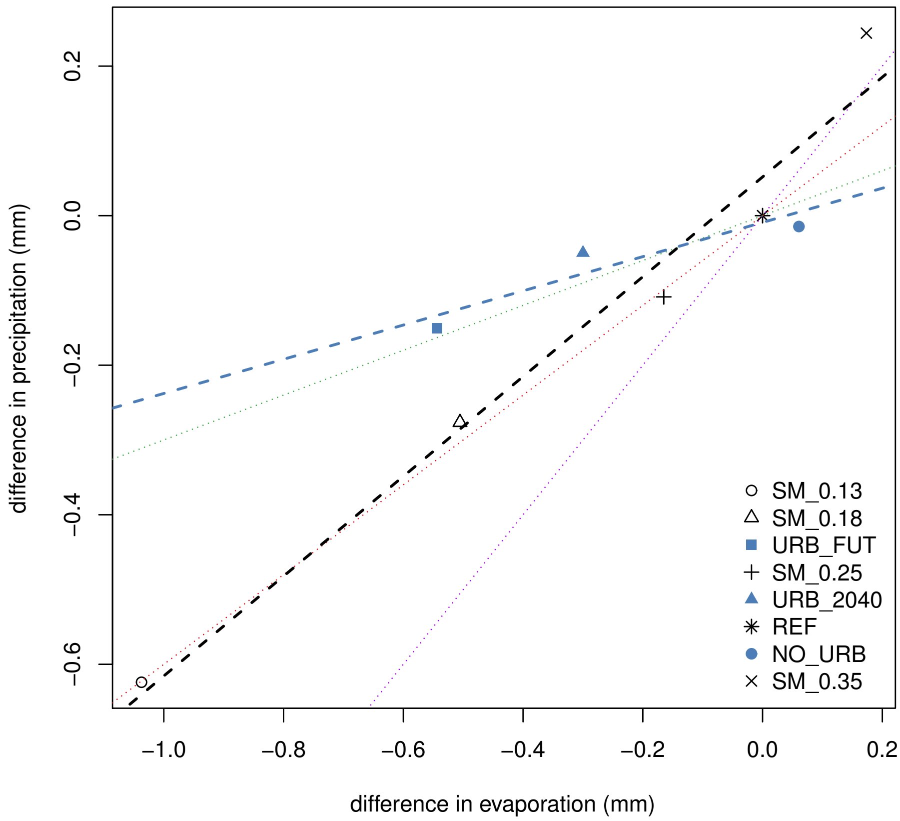

Figure 4.6 Ratio of evaporation to precipitation for the (black) soil moisture (SM_...) and (blue) urbanization (URB_...) experiments in the Netherlands for the period 10-13 May 1999. Ratios of respectively 100, 60 and 30 percent are given by the dotted lines.

The strength of the soil moisture-precipitation feedback can be assessed using the ratio of evapotranspiration to precipitation. The computed ratio for each of the experiments is given in Figure 4.6. Ratios of respectively 100, 60 and 30 percent are given by the dotted purple, red and green lines. The dashed lines are computed by linear regression through the two sets of experiments separately, both including REF. The ratio of evaporation to precipitation, i.e. the slope of the dashed lines, is about 67% for the SM experiments and

23% for the URB experiments. In other words, the positive soil moisture-precipitation feedback is not as strong in the URB experiments. Locally urban areas alter the atmosphere in a way that could constitute a negative feedback, but the effects are not strong enough in our simulations and the positive feedback remains dominant.

The mechanism underlying the weakening of the positive feedback due to urban areas is illustrated in Figure 4.7. Linear regression lines are shown for the urban expansion experiments (dotted) and soil moisture experiments (dashed), both including the reference run. In the SM experiments a reduction in soil moisture leads to an increase in PBL height. The lifting condensation level (LCL) however, rises even faster. Thus, under dry conditions, parcels from the surface do not reach the LCL as easily as under higher soil moisture conditions. This leads to a reduction in convective available potential energy (CAPE) values.

Similarly, in the URB experiments the increased urban area also leads to an increase in PBL height. In terms of the reduction of latent heat (LH), the reduction in PBL height is similar to the SM experiments. Yet, the rise in LCL is rather small in the URB experiments and similar to the rise in PBL height. Thus, parcels can still reach the LCL rather easily and convection is not reduced as much as in the SM experiments. Consequently, the urban expansion experiments have stronger triggering of precipitation.

4.4.3 Effects of urban areas

Underlying the dissimilarities in atmospheric variables between the different sets of experiments is the modification of energy partitioning at the surface in urban areas. Latent heat is reduced in urban areas due to the lower evaporative fraction and the sensible heat flux is consequently increased. The partitioning of these fluxes (Table 4.2) directly influences the near surface temperature. In addition, temperature increases due to the higher roughness and heat storage capacity in urban areas. The heat stored by buildings during daytime is returned during the night. This can be seen in Figure 4.8, that shows the spatial and temporal difference in temperature between URB_2040 and NO_URB. Temperature within urban areas and throughout the rest of the country is most enhanced just after sunset. Comparing URB_2040 to REF (not shown here) shows the mean diurnal UHI increases with more than 0.4 K within existing urban areas. The

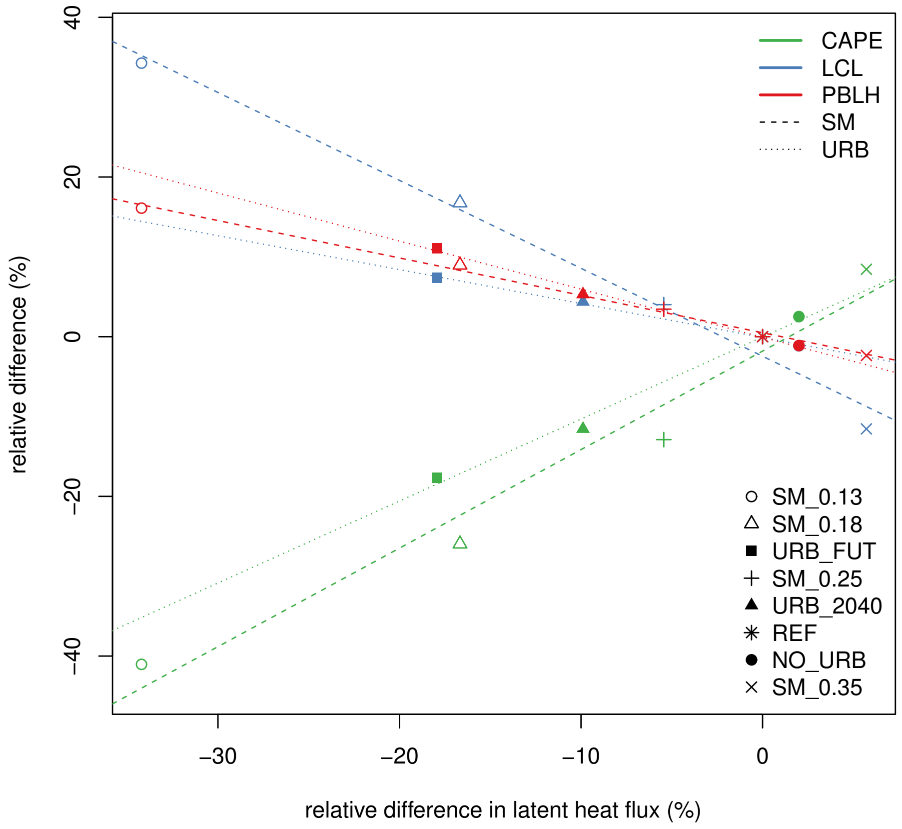

Figure 4.7 Relative mean change in convective available potential energy (CAPE), lifting condensation level (LCL) and planetary boundary layer height (PBLH) in relation to the relative mean change in latent heat flux in the Netherlands for the period 10-13 May 1999. Linear regression lines are shown for the urban expansion experiments (URB, dotted) and soil moisture experiments (SM, dashed), both including the reference run.

maximum diurnal UHI under urban coverage expected in 2040 is up to 2 K higher within existing urban areas.

The higher sensible heat flux and temperature in urban areas affect the overhead and downwind atmosphere by altering, among others, the LCL and PBL height. This can be easily seen by comparing one of the urban expansion experiments with NO_URB (Figure 4.9). In the URB experiments the PBL height is raised more than the LCL and level of free convection, effectively increasing the potential for cloud formation and the triggering of precipitation (Table 4.2). These relatively high increases in the URB experiments underlie the difference in strength of the soil moisture-precipitation feedback.

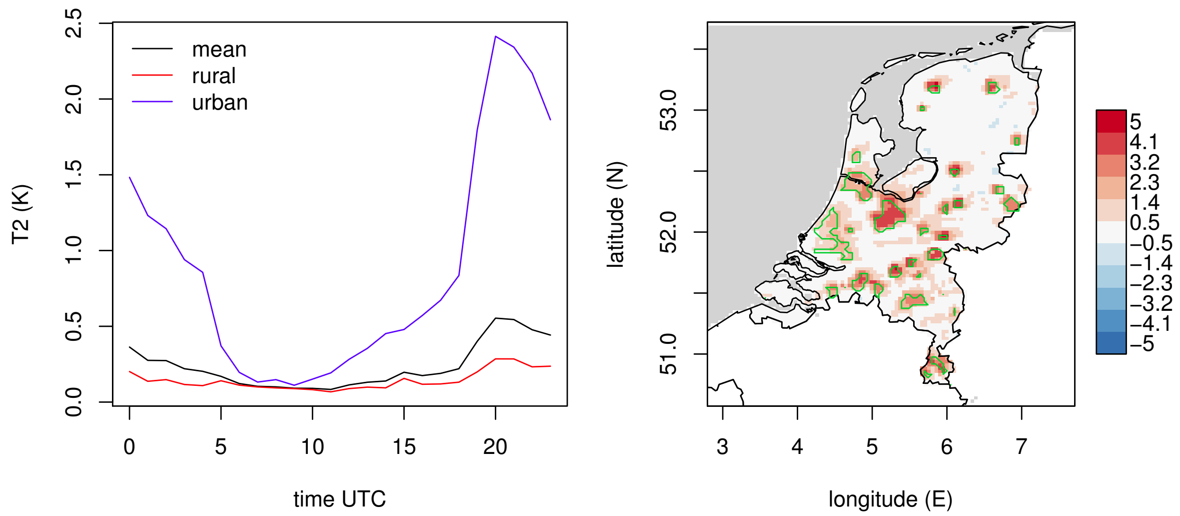

Figure 4.8 Difference in two meter temperature in the Netherlands for the period 10-13 May 1999 between the simulation with urban coverage comparable to that expected in 2040 and the simulation with urban areas removed, averaged over the entire country (mean), within urban areas (urban), and non-urban areas (rural) throughout the day (left) and at 20 UTC (right). Urban areas are outlined in green in the spatial distribution on the right.

The direct response on precipitation is not so clear however and the spatial differences in precipitation are not directly located near or downwind of cities (Figure 4.9).

4.5 Discussion

In retrospect, the period we simulated in this study belongs to what Findell and Eltahir (2003) would describe as atmospherically controlled. In an atmospherically controlled situation deep convection is triggered over both dry and wet soils and only the amount of rain can be impacted by soil moisture conditions (Findell and Eltahir, 2003). This is indeed what we find in our case, as wet soils give larger precipitation amounts. The reduction of precipitation we find after expanding urban areas in this study is similar to earlier findings for Europe by Trusilova et al. (2009, 2008), but in contrast with many other studies, mostly situated in Asia and the USA (Han et al., 2014). This may be related

Table 4.2 Mean daytime (6-18 UTC) values of the latent heat flux (LH), sensible heat flux (HFX), two meter temperature (T2), percentage of time and area that the planetary boundary layer top is over the level of free convection (PBL > LFC), same for lifting condensation level (PBL > LCL), and precipitation (RAIN) over the Netherlands for the conducted reference (REF), soil moisture (SM) and urbanization (URB) experiments.

Variable	SM_013	SM_018	URB_FUT	SM_025	URB_2040	REF	NO_URB	SM_035
LH [W m-2]	100.2	128.3	125.4	146.0	138.4	154.6	157.6	163.2
HFX [W m-2]	156.7	127.1	117.1	108.1	109.6	100.6	98.6	88.1
T2 [C]	16.4	15.9	15.7	15.6	15.6	15.5	15.4	15.2
PBL > LFC [%]	40.1	46.1	49.2	49.7	49.7	51.8	51.8	55.5
PBL > LCL [%]	63.3	70.7	76.0	75.9	76.4	77.4	77.3	80.7
RAIN [mm]	1.8	2.2	2.3	2.3	2.4	2.5	2.4	2.7

to the typical dry surface conditions around the bigger cities in the USA and Asia, while in our case the urban surroundings are much wetter.

Our estimated ratio of evapotranspiration to precipitation is of similar size as the rough estimate for Europe made by Schär et al. (1999). The ratio of evaporation to precipitation, unlike the recycling ratio (Budyko, 1974; Eltahir and Bras, 1994, 1996), combines precipitation that truly originates from the region of interest with precipitation that originates from sea but is triggered by moist conditions over land (e.g. Bisselink and Dolman, 2009). That this triggering of advected precipitation also plays a role in our simulations can be inferred from the difference in feedback strength between the different sets of experiments. The same change in evaporation gives a smaller precipitation reduction in the URB experiments due to enhanced triggering.

With respect to temperature, the simulated average and maximum diurnal UHI are in reasonable agreement with observations of UHI in the Netherlands. We find an average and maximum diurnal UHI of 0.4 and 1.3 K respectively. In summer higher UHIs of respectively 0.9 and 2.3 K were measured (Steeneveld et al., 2011; Wolters and Brandsma, 2012). Wolters and Brandsma (2012) however show a clear dependency of UHI intensity on wind speed and measurements of the average UHI in spring are approximately 30% lower than in summer. Average wind speed during our case study was more than 3 ms^{-1}. Wind speeds like these could reduce the UHI by another 50% making our estimate comparable with documented measurements. This suggests correct heat fluxes are modelled (see also Figure 4.2), which gives confidence for the representation other atmospheric variables.

With respect to precipitation however, there are some obvious problems in the location of simulated precipitation compared to radar observations. Although models are often

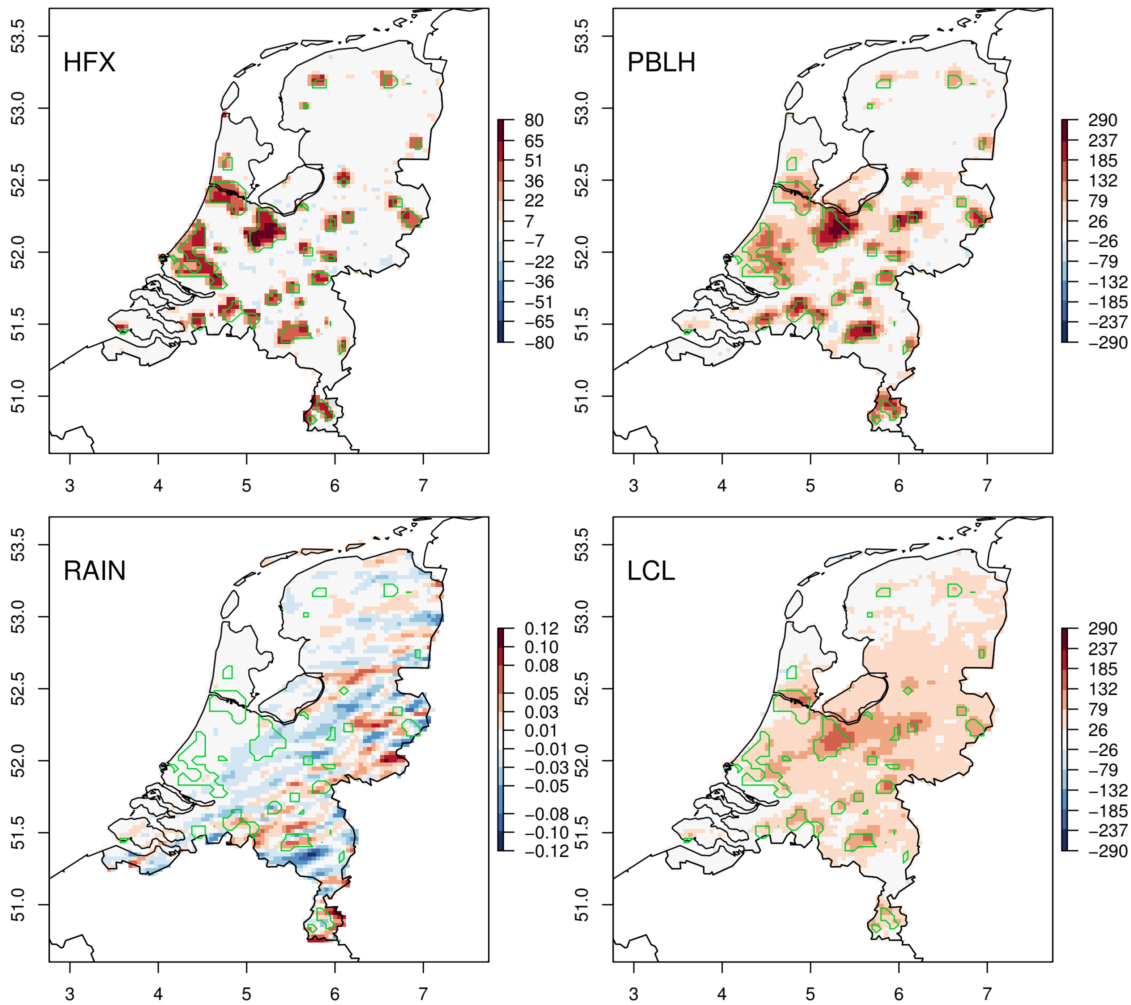

Figure 4.9 Difference in sensible heat flux (HFX), planetary boundary layer height (PBLH), precipitation (RAIN) and lifting condensation level (LCL) between the simulation with urban coverage comparable to that expected in 2040 and the simulation with urban areas removed. Urban areas are outlined in green.

used to study changes in precipitation after urbanization, the correct representation of precipitation remains challenging. Li et al. (2013) for example show that the biases in WRF wind fields play a major role in the biases in precipitation. Nonetheless, models are useful tools in understanding the processes that govern (changes in) precipitation and we try to use it as such.

One shortcoming of the current model setup is the usage of the standard USGS land-use map as it underestimates urban land cover in the Netherlands. This can easily be improved, but might not have a large influence on precipitation (De Meij and Vinuesa, 2014). In addition, all urban areas are currently treated similarly in the simulations, while WRF allows for a distribution into three classes, adding a low intensity residential and commercial/industrial/transportation class.

Other factors that were not taken into account in this study and have been shown to affect local precipitation are urban pollution and aerosols (Guo et al., 2014; Han et al., 2012). Aerosols typically reduce the size of cloud droplets, initially reducing precipitation, and may increase the probability of reaching super cooled levels and as such intensify downwind convective cells. However, under very high aerosol concentrations moisture can be transported out of the storm in the ice-phase which decreases precipitation efficiency (Carrio and Cotton, 2011; Carrio et al., 2010). The forcing of aerosols on precipitation seems to be much smaller than the forcing of land use and land cover changes in an urban environment however (Hosannah and Gonzalez, 2014) and we did not attempt to include these effects in the current study.

4.6 Conclusions

This study investigates the effects of surface conditions on precipitation in the Netherlands in isolation of climatological changes like large scale circulation and sea surface temperature. To investigate this, high resolution WRF simulations are conducted with different soil moisture initializations and urban cover scenarios for 10-13 May 1999. In general, in both the soil moisture and urbanization experiments, we find a positive soil moisture-precipitation feedback. In other words, precipitation is favored over wet soils and reduced over dry soils or after urban expansion. Overall, the sensitivity of precipitation to increased urban coverage is lower than to reduced soil moisture.

Underlying this difference in sensitivity, or feedback strength, are differences in the response of the PBL height and the LCL. In the soil moisture experiments, the LCL increases more strongly than the PBL and a larger reduction in CAPE is found. In the urbanization experiments the PBL increases somewhat more than the LCL, and CAPE is not reduced as much. As a result, for a similar reduction in evaporation, a smaller reduction in precipitation is achieved in the urbanization experiments. Consequently, the ratio of evaporation to precipitation, a measure of the soil moisture-precipitation feedback, is about 67%, while it is only 23% in the urbanization experiments.

Chapter 5

Relative impacts of land use and climate changes on summer precipitation*

The effects of historic and future land use on precipitation in the Netherlands are investigated on 19 summer days with similar meteorological conditions from the period 2000-2010. The days are selected with a circulation type classification and a clustering procedure to obtain a homogenous set of days. Changes in precipitation are investigated in relation to the present day climate and land use, and in the perspective of future climate and land use. To that end, the weather research and forecasting (WRF) model is used with land use maps for 1900, 2000, and 2040. In addition, a temperature perturbation of +1°C, assuming constant relative humidity, is imposed as a surrogate climate change scenario. Decreases in precipitation are simulated following conversion of historic to present, and present to future, land use. The temperature perturbation under present land use conditions increases precipitation amounts by on average 7-8% and amplifies precipitation intensity. However, when also considering future land use, the increase is reduced to 2-6% on average, and no intensification of extreme precipitation is simulated. In all, the simulated effects of land use changes on precipitation in summer are smaller than the effects of climate change, but not negligible.

*This chapter is in preparation as: Daniels, E. E., Lenderink, G., Hutjes, R. W. A., and Holtslag, A. A. M. (2016). Relative impacts of land use and climate changes on summer precipitation in the Netherlands.

5.1 Introduction

Humans can exert influence on precipitation through modifications in land use (Kalnay and Cai, 2003; Mahmood et al., 2014) next to other anthropogenic forcings such as climate change (Zhang et al., 2007). Currently, land conversion takes place at a rapid pace and this will likely continue in the future (Angel et al., 2011; Mahmood et al., 2010). Therefore, this type of human influence on the climate system will continue, and will probably become more significant in the coming decades (Mahmood et al., 2010; Pielke et al., 2007).

In the Netherlands, the most important land cover changes in the last century were the conversion of large heather areas into agricultural or grassland and expansion of urban areas (Feranec et al., 2010; Verburg et al., 2004). In addition, almost 1650 km2 of land was reclaimed from the sea in the former Zuiderzee, now called Lake Yssel (Hoeksema, 2007). Urban areas have increased from about 2% in 1900, to 13% in 2000, and are projected to further increase to 24% in 2040 (Dekkers et al., 2012). Precipitation in the Netherlands has increased by about 25% over the last century, especially along the West coast (Buishand et al., 2013). The increase of sea surface temperatures and changes in circulation seem to be the major causes for this increase (Attema et al., 2014; van Haren et al., 2013). In addition, there is some evidence that urbanization plays a role (Daniels et al., 2016).

In contrast to the above, our earlier study using a model to investigate land surface changes in the Netherlands in spring found that precipitation is in fact reduced after expansion of urban areas (Daniels et al., 2014). That study also tested the sensitivity of precipitation to soil moisture and found a positive feedback, that is, wet (dry) soils increase (decrease) the amount of precipitation. The reduction of precipitation after urban expansion was dominated by the model's response to reduced moisture, overruling the enhanced triggering of precipitation by boundary layer processes. However, only a 4-day case study was investigated and questions can therefore be placed with respect to the climatological representability of the results. In addition, the simulated land use changes were conceptual, rather than realistic and only focused on changes in urban extent, ignoring the expansion of agricultural areas for example.

The present study aims to improve on both aspects, by (1) sampling a larger set of meteorological cases, and (2) evaluating the effects of more realistic land cover changes. Our main interest is the precipitation response to the altered land surface and the physical processes underlying this response. We investigate this response in the summer season. The summer months typically have a larger shower activity, connected to unstable atmospheric conditions. This relatively intense type of precipitation, arising from (deep) cumulus convection, is expected to be most influenced by land surface changes (Cotton and Pielke, 2007; Pielke et al., 2007) and expected to increase under climate change (Fischer et al., 2014). Also, the largest impact of urban areas on precipitation along the Dutch West coast was found in summer (Daniels et al., 2016).

Additionally, the current study aims to put the effects of historic and future land use changes on precipitation in the perspective of climate change. This will be done by imposing an increase in overall temperatures as a surrogate climate change scenario (Schar et al., 1996). On a global scale, climate change is expected to increase both mean and extreme precipitation in response to an intensification of the hydrological cycle (Huntington, 2006; Wu et al., 2013). Here, the precipitation response to land use changes in the Netherlands, and climate change, is investigated for multiple summer days. The selection procedure for the investigated events and the model setup will be described in the next section. Followed by the results, discussion and conclusions thereafter.

5.2 Data and methods

5.2.1 Case selection

Selection of days to use as case studies is conducted with the help of a circulation type classification, similar to Daniels et al. (2015). We make use of the nine type Jenkinson-Collison Types (JCT) classification scheme. This method was developed by Jenkinson and Collison (1977) and is intended to provide an objective scheme that acceptably reproduces the subjective Lamb weather types (Jones et al., 1993; Lamb, 1950). The classification has eight weather types (WTs) representative of the prevailing wind direction (W, NW, N, NE, E, SE, S, and SW, where W = 1 etc.) and one that is treated as unclassified (WT9). Computation of the WTs is done using 12 UTC MSLP data from ERA-Interim (Dee et al., 2011) at 16 points in the area 47.25 to 57.75°N and 3 to 12.75°E (Figure 5.1) with the 'cost733class' software (Philipp et al., 2010, 2014).

Previous work has shown that the downwind effects of urban areas on precipitation in the Netherlands are largest under WT9 (Daniels et al., 2016). Under the light, unclassifiable,

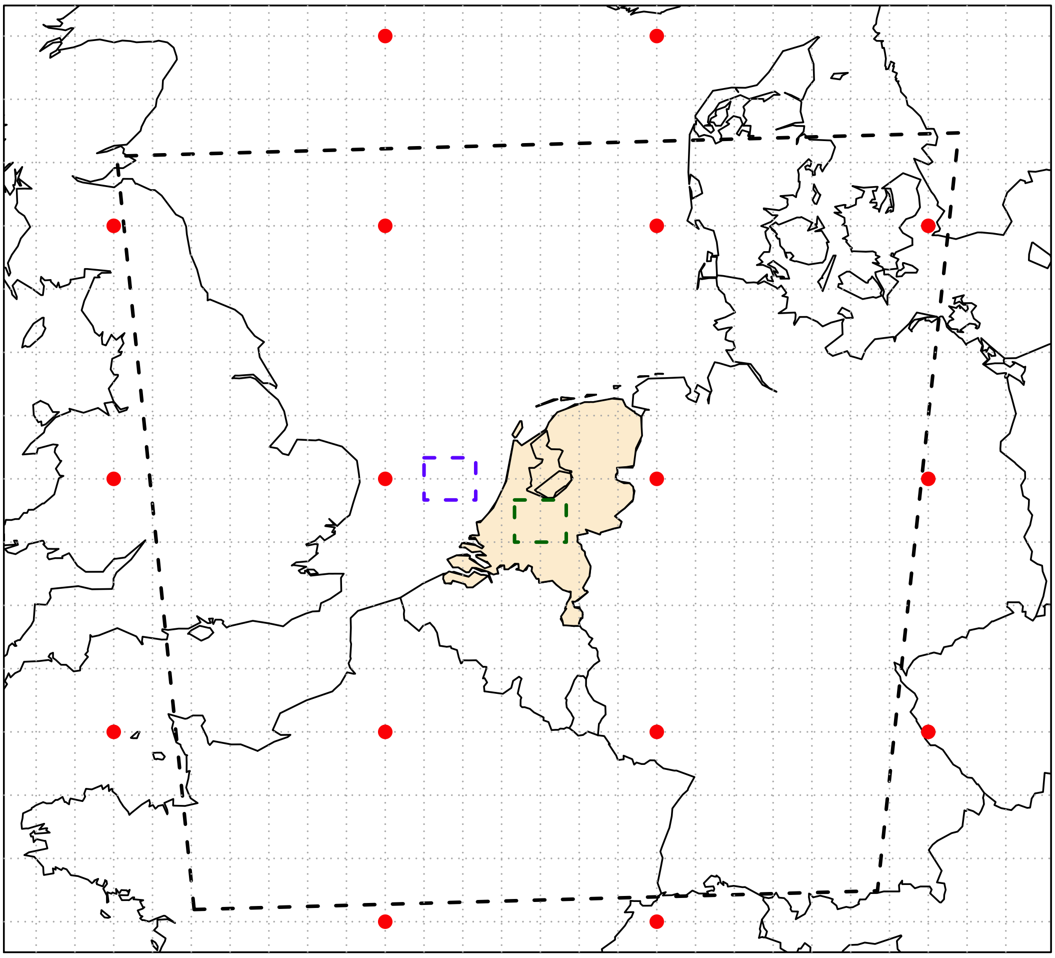

Figure 5.1 Map of part of Europe showing the 16 (red) points used in the circulation type classification, the WRF model domain (black) and the land (green) and sea (blue) area used for averaging in the selection procedure.

flow that occurs in this weather type, the atmosphere seems to be most susceptible to the land surface. All summer (JJA) days in the period 2000-2010 are classified with the JCT scheme, but only days with WT9 and more than 1 mm of precipitation at one station or more are used for further selection. The remaining 215 days are grouped using a statistically objective k-means clustering procedure (Hartigan and Wong, 1979) in R (Core team, 2013). The k-means clustering partitions n observations into k clusters, in which each observation belongs to the cluster with the nearest mean in a principle component space. Clustering is done to obtain a homogenous set of days with similar meteorological conditions. The similarity of the cases should result in comparable results and enable generalization of conclusions.

Seven parameters are used in the clustering procedure: (1) mean precipitation; (2) total column water; (3) vertical velocity at 700 hPa; (4) horizontal wind speed at 700 hPa; (5) K-index; (6) land-sea temperature difference; and (7) a measure of the distribution and "patchiness" of precipitation, computed as the difference between maximum precipitation and the 85th percentile. Parameters 2, 3, 4 and 5 are derived from 12 UTC ERA-Interim data averaged over the center of the Netherlands (4.75 to 5.75°E and 51.75 to 52.25°N, Figure 5.1). Parameter 6 is derived from ERA-Interim data as the difference between the two meter temperature over this land area and sea surface temperature (SST) averaged over a nearby ocean area of similar size (3-4°E and 52.25-52.75°N, Figure 5.1). Parameter 1 and 7 are computed over the whole of the Netherlands using daily precipitation data collected at 8 UTC from about 320 stations. The K-index (George, 1960) is a linear combination of temperature (T) and dewpoint (Td) at various levels (T850 - T500 + Td850 - (T700 - Td700)) and is a measure of convection used to forecast air mass thunderstorms. The parameter values are normalized and scaled, by subtracting the mean and dividing by the standard deviation, before being used in the clustering algorithm.

The k-means clustering algorithm was set to use 12 clusters, repeated 1000 times and the best, stable, solution is used. A cluster with higher than mean precipitation was selected (see Figure 5.2), since sufficient precipitation is needed to investigate the response to alternative land use maps. Total column water is about average in the selected cluster, while it has the most negative vertical velocity (omega), of about 0.3 Pa/s. Since omega is positive with increasing pressure, this means the largest upward speeds are selected. A large upward vertical velocity is associated with strong hourly precipitation and convective showers (Loriaux et al., 2013). Low wind speed was found to be favorable for detection of urban effects in the Netherland (Daniels et al., 2016) and is therefore desirable. The average K-index in the selected cluster is over 20, which is the average threshold for likelihood of thunderstorms. The land-sea temperature difference is amongst the lowest. High SST is known to cause enhanced precipitation (in the coastal area) mainly in summer (Lenderink et al., 2009). This could interfere with our land use experiments and is therefore not sought. Finally, the selected cluster has quite patchy precipitation, indicative of convective conditions as desired. The selected cluster consists of 19 days (see Figure 5.6 for the dates), that will be averaged on an hourly basis for many of the analyses presented in the results section.

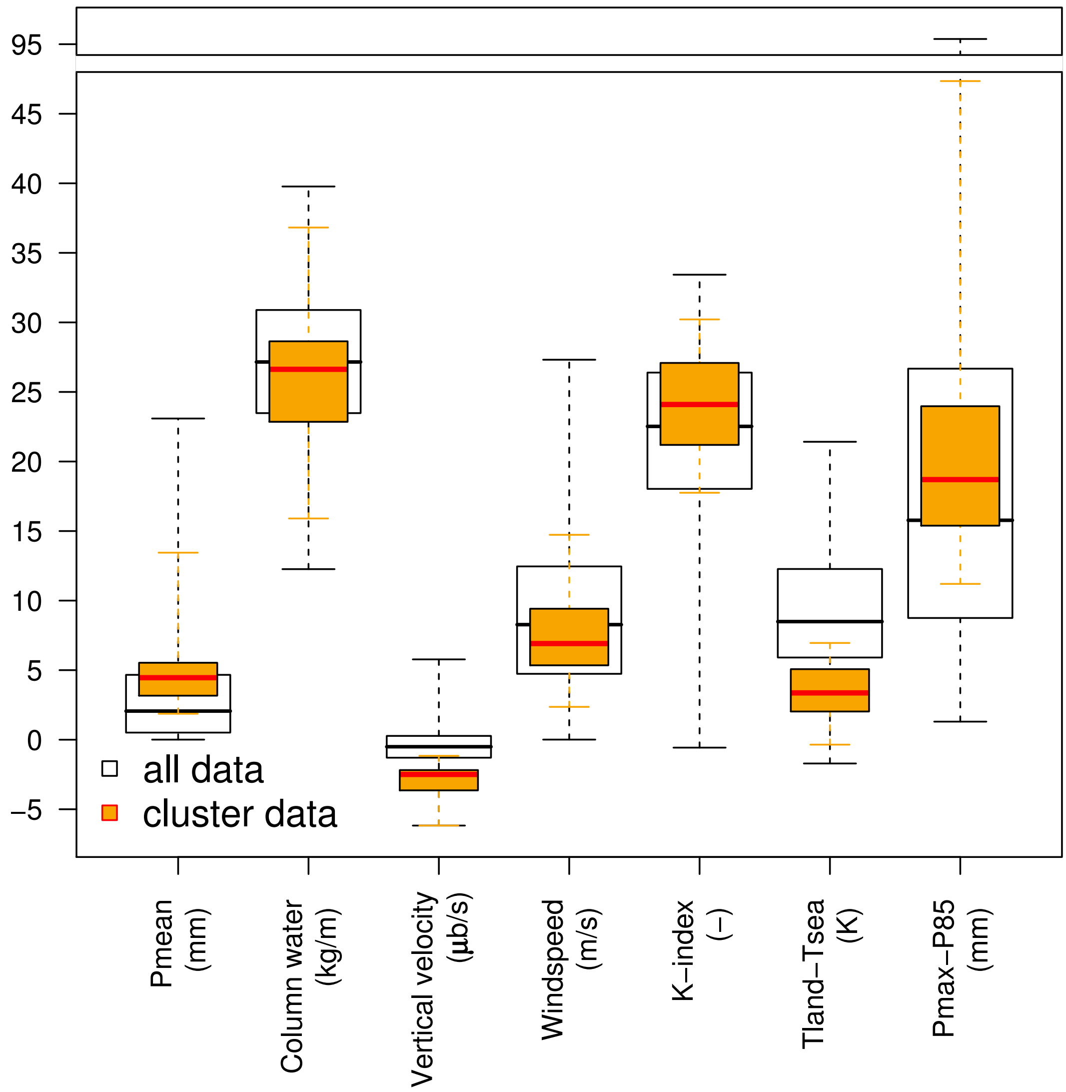

Figure 5.2 Boxplots of the seven parameters used in the procedure to select days to simulate with the WRF model. Boxes of the days included in the selected cluster are given in orange and boxes of all summer days classified as WT 9 in the period 2000-2010 are given in white.

5.2.2 Model setup

We use the non-hydrostatic Advanced Research WRF model (ARW, version 3.4.1) (Skamarock et al., 2008) on a single domain of 1000 x 1000 km (see Figure 5.1). The model has a horizontal grid spacing of 2.5 km and the vertical grid contains 40 sigma levels. Atmospheric and surface boundary conditions are obtained from ERA-Interim every six hours. Model output is stored and analyzed on an hourly basis. All simulations start at 12 UTC the previous day and, unless otherwise specified, results from 0-0 are used in the analyses.

Following earlier studies with WRF in the Netherlands (e.g. Daniels et al., 2015; Steeneveld et al., 2011; Theeuwes et al., 2013), we use the YSU PBL scheme (Hong et al., 2006), the WRF Single-Moment 6-Class Microphysics Scheme (WSM6) Hong2006, the RRTMG schemes for both long- and shortwave radiation (Iacono et al., 2008), the Grell 3D cumulus parameterization scheme (Grell, 1993; Grell and Devenyi, 2002) and the Unified Noah Land Surface Model (Tewari et al., 2004) with the Urban Canopy Model (UCM). The UCM is a single layer model which has a simplified urban geometry. Included in the UCM are: shadowing from buildings, reflection of short and longwave radiation, wind profile in the canopy layer and multi-layer heat transfer equations for roof, wall and road surfaces (Kusaka and Kimura, 2004; Kusaka et al., 2001).

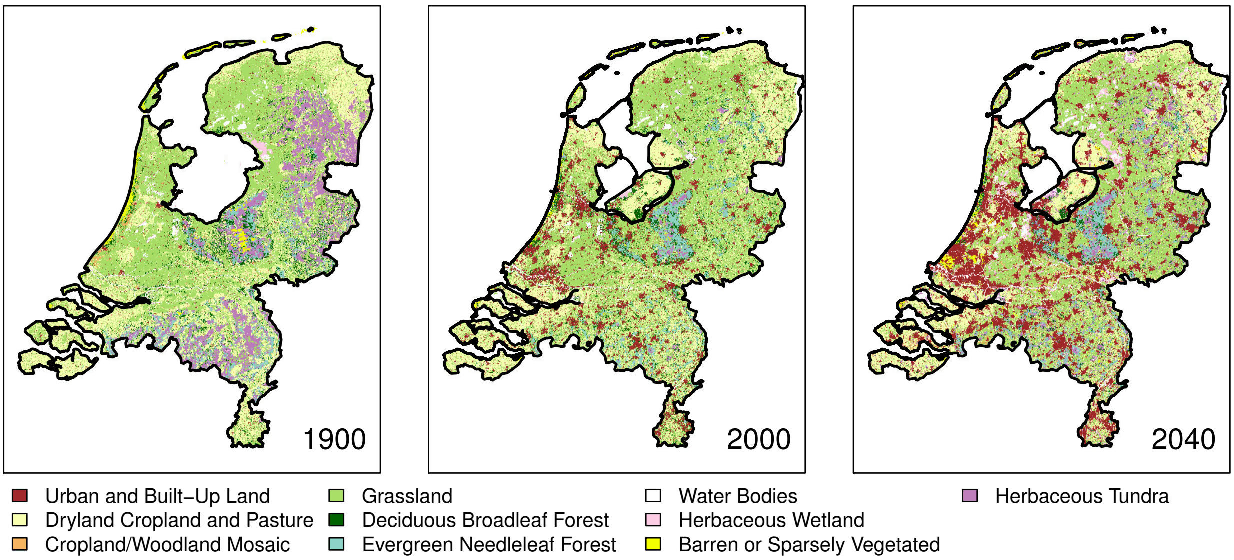

Figure 5.3 Dutch land use in 1900, 2000 and 2040, based on the HGN, LGN4 and GE2040 maps.

Where possible within the model domain, the European land-use map Corine (EEA, 2002) was used, supplemented with a high resolution map for the Netherlands. Corine is not available over the UK, so there the standard USGS map at 30′ resolution available within WRF is used. Reclassification of the Corine land-use map is done following Pineda et al. (2004), but intertidal flats are classified as water instead of herbaceous wetlands. Three high resolution maps were used for the Netherlands: HGN1900 (Kramer et al., 2010), LGN4 (Hazeu et al., 2010, 2011; Wit, 2003), and GE2040 (Dekkers et al., 2012), representing land use in 1900, 2000 and 2040 respectively (see Figure 5.3). The future map is based on the Dutch Global Economy scenario (CPB et al., 2006), a national scenario consistent with the SRES A2 scenario. The SRES scenarios have been replaced by Representative Concentration Pathways (RCP) and Shared Socioeconomic Pathways (SSP). The SRES A2 scenario is most alike SSP3 and between RCP 6.0 and 8.5 in carbon emissions. Reclassification of the Dutch land use maps is done as specified in Table 5.1. GE2040 unfortunately did not distinguish between different dry nature classes, so the differentiation was copied from the LGN map. Therefore, all dry nature in GE2040 was first classified as herbaceous tundra. Next the newly classified herbaceous tundra was reclassified to Barren or sparsely vegetated areas, Evergreen needle leaf, and Deciduous broadleaf forest when it overlapped with the areas classified as such in the LGN map.

5.2.3 Model simulations

Three model simulations: HIS, REF, and FUT, are done with the land use maps of respectively 1900, 2000 and 2040 in the Netherlands. These simulations have exactly the same boundary conditions. In 1900 the creation of land in Lake Yssel had not yet taken place. To test the effect of this conversion separately from the changes in land use an additional simulation with the historic land use map was done, this time with the current land extent (similar to that in REF). All previously non-existent land is assumed to be covered with grassland (the most common land cover class) in this simulation. This simulation is referred to as HIS+Ys.

Furthermore, to be able to put the land cover changes in the perspective of climate change, simulations with the present and future land use maps and a temperature perturbation of +1°C are conducted. These will be referred to as REF+1 and FUT+1. The global surface temperature is predicted to increase with at least 1°C under all concentration pathways by 2050 (IPCC, 2013). The surrogate climate change scenario is

Table 5.1 United States Geological Survey land use category descriptions and parameter settings used in WRF, with the national land use map classes (HGN, LGN and GE2040) that are reclassified as such.

USGS land use category	Land use description	z0 (m)	Albedo (-)	Green vegetation fraction (%)	Leaf Area Index	Emissivity (%)	HGN/LGN class description	GE2040 class description
1	Urban and built-up land	0.5	0.15	0.1	1	0.88	Buildings and roads	Urban area, commercial /industrial, seaport, building lot, infrastructure
2	Dryland cropland and pasture	0.15	0.17	0.8	5.68	0.985	Crops and bare soil	Arable land
6	Cropland/ woodland mosaic	0.2	0.16	0.8	4	0.985	Other	recreation - single day, recreation - stay, perennial crops
7	Grassland	0.12	0.19	0.8	2.9	0.96	Grassland	Grassland
11	Deciduous broadleaf forest	0.5	0.16	0.8	3.31	0.93	Deciduous forest	Nature - dry
14	Evergreen needle leaf	0.5	0.12	0.7	6.4	0.95	Coniferous forest	Nature - dry
16	Water bodies	0.0001	0.08	0	0.01	0.98	Water	Water
17	Herbaceous wetland	0.2	0.14	0.6	5.65	0.95	Reed swamps	Nature - wet
19	Barren or sparsely vegetated	0.01	0.38	0.01	0.75	0.9	Drifting sands and sandbanks	Greenhouse horticulture, nature -dry
20	Herbaceous tundra	0.1	0.15	0.6	3.35	0.92	Heath land and raised bogs	Nature - dry

applied to the initial land and atmospheric conditions of the simulations, as well as to the driving sea surface temperature following the methodology by Attema et al. (2014), who suggest a vertically uniform temperature perturbation is appropriate at mid-latitudes. The relative humidity is unchanged in these simulations, which implies an absolute surface humidity increase of 6–7%.

Urban areas outside of the Netherlands are removed in the historic, and expanded in the future land cover scenarios, in the same way as in Daniels et al. (2014). Angel et al. (2011)'s projections of urban land cover are used to determine the level of expansion. Across the globe, urban land cover has increased due to people migrating to urban areas and because the population density within cities decreased (Marshall, 2007). Within Europe a population density decline rate of 2% per annum has been reached between 1990 and 2000 (Angel et al., 2011). We assume a conservative increase with a decline rate of 1% for the future. Urban areas are therefore less than doubled in our simulations, consistent with Angel's projection for Europe and Japan in 2050 with an annual density decline of 1%.

5.2.4 Precipitation data

In the Netherlands, measurements of precipitation are available from the national meteorological institute (KNMI). Gauge measurements are available on a daily basis (8-8 UTC) at about 320 stations. Gridded observations of precipitation are available at a 2.4 km resolution on an hourly basis from (bias)corrected radar data (Overeem et al., 2009). Modelled precipitation amounts are best compared with radar data, because of the similarity in resolution and spatial extent. Unfortunately for four of the 19 selected cases there is no radar data available, so some averages shown in the results sections consist of fewer cases.

5.3 Results

The focus of this paper is on the sensitivity of precipitation to changes in land surface conditions in historical and future perspectives. The precipitation response to the perturbations in the experiments will be described in the next section. To clarify these responses, the section after that focusses on the (differences in) atmospheric conditions and processes leading to the formation of precipitation.

In general, the WRF model overestimates precipitation amounts compared to both station and radar data (Figure 5.4). The days marked with red markers only have station data, and no radar data available. There is one day where precipitation amounts are grossly overestimated, namely for June 30 2003. This day is marked with an open dot in the scatterplot. This is the only day in the selection that has easterly winds and the poor model performance could therefore be related to the chosen position of the domain. This day was excluded from further analysis. The average wind direction on the other days is southwest, alike the year round dominant wind direction in the Netherlands.

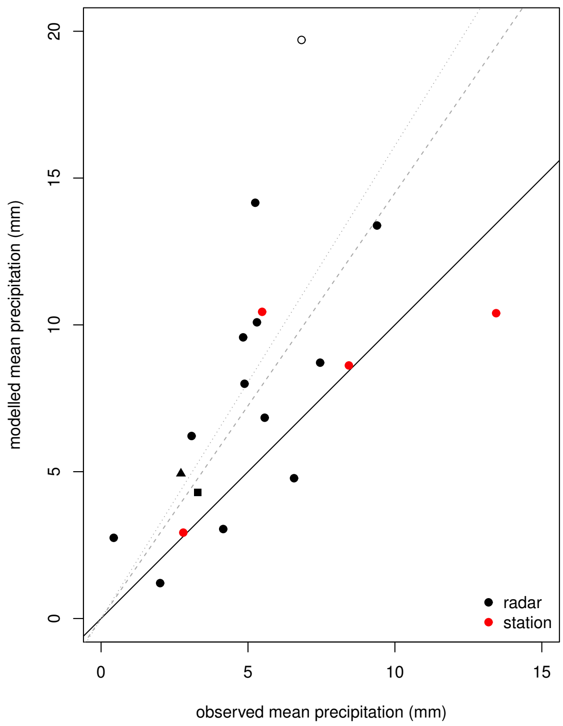

Figure 5.4 Scatterplot of observed and modelled daily mean precipitation (mm) by radar (black, 0-0 UTC) and at stations (red, 8-8 UTC) over the Netherlands. The dotted and dashed lines give a linear regression between precipitation modelled and observed by radar, respectively in- and excluding the day indicated with an open dot (2003-06-30). The days with a square (2007-07-22) and triangle (2000-07-29) are illustrated spatially in Figure 5.5. The solid 1:1 line represents a perfect correlation.

The performance of the model to represent spatial precipitation patterns is reasonable overall, but quite variable (Figure 5.5). The precipitation pattern of 2000-07-29 for example is well represented by the model. This day is denoted by a triangle in Figure 5.4. As an example in which the model does not represent the spatial precipitation pattern well the precipitation pattern of 2007-07-22 is given. This day is denoted by a square in Figure 5.4. Compared to the previous example, this day is more accurately modelled in terms of amounts, but the modelled spatial distribution is quite distant from that observed. The average spatial distribution of all 18 cases overestimates the amount of precipitation compared to observed station data by almost 50%. Nevertheless, the model seems to capture the relatively high precipitation amounts in the center of the country and lower rainfall amounts in the northern parts.

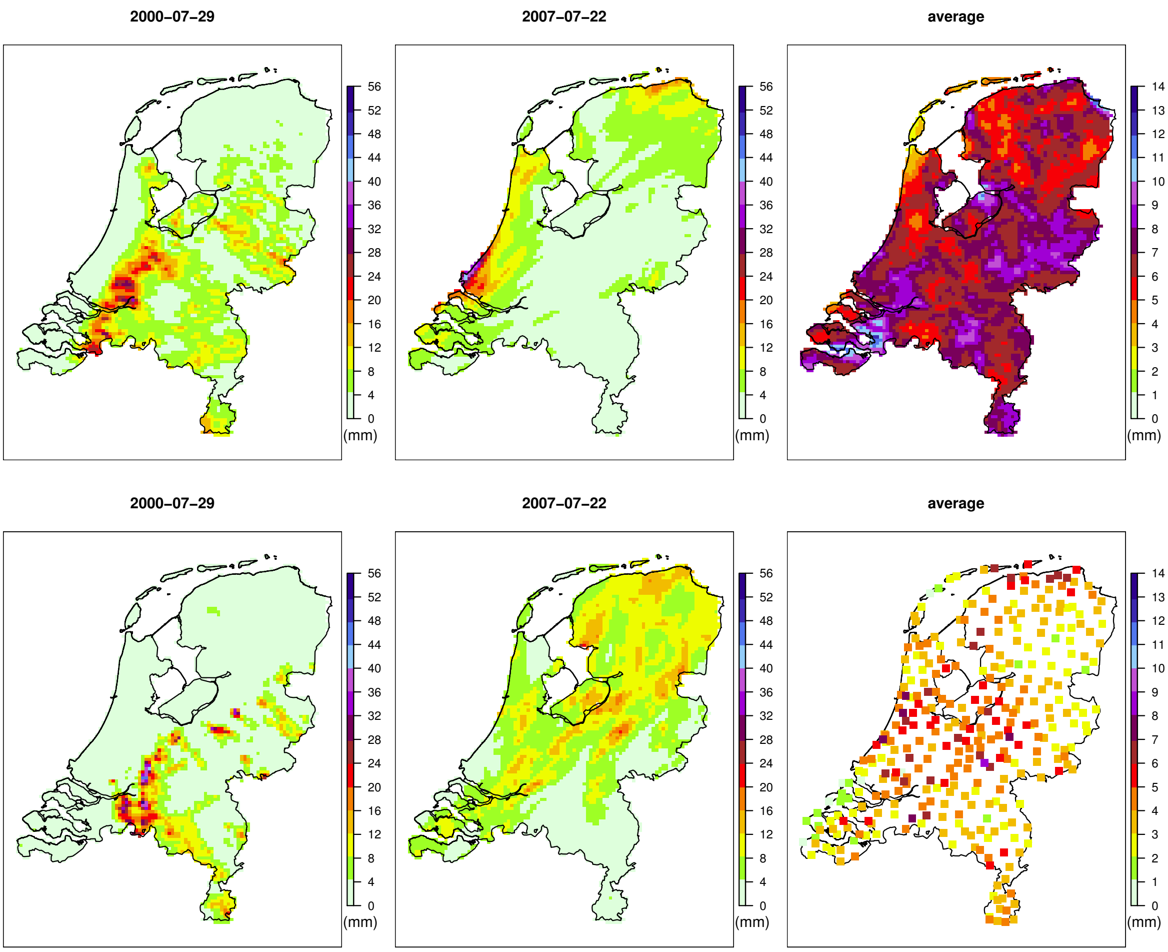

Figure 5.5 Daily mean precipitation (mm) simulated by the model (top) and observed (bottom) on (from left to right) 2000-07-29, 2007-07-22 (0-0 UTC) and averaged (8-8 UTC) over the 18 selected cases.

The daily evolution of precipitation in observations and in the model is given in Figure 5.8, that will be discussed more thoroughly in the next section. Compared to radar data, the model is three hours too early in simulating the intensification of precipitation, and the modelled precipitation peak is two hours too early. In addition, the average precipitation intensity is often higher than in observations. The separation of the model and observations in the evening is caused by only two days and is therefore not a generic feature. The comparison between the radar data and the modelled amounts in Figure 5.8 is not entirely consistent, however, since the averages are made over a different number of cases (14 vs 18 respectively). Repeating the analysis with the 14 cases leads to the same results.

5.3.1 Precipitation response

Despite the fact that we select days with similar atmospheric conditions, the response of precipitation to the land use and climate perturbations is not uniform and varies strongly between the different cases. In Figure 5.6 the relative difference of precipitation between the land cover/temperature scenarios and REF is given for each of the 19 cases. The average precipitation difference given here, is calculated over the 18 cases (excluding the 2003-06-30 case) by averaging the relative change per case. The mean precipitation difference is, on the other hand, directly calculated from the averaged precipitation amounts over the 18 cases as given in Figure 5.7. Although the strength and sometimes the sign of the response differs between the days in every simulation, a generic picture of a decrease of precipitation appears as a response to changes in land use. From historic to present, and from present to future, land use the decreaese is about 3-5% and 2-5% respectively.

One of the averaging methods shows a difference between HIS and HIS+Ys, suggesting that the creation of land in Lake Yssel caused a moderate reduction of precipitation in the last century. The other method gives the same response for both HIS scenarios, suggesting the creation of land in Lake Yssel did not influence the total precipitation response. Either way, the model simulates a reduction of precipitation between HIS(+Ys) and REF. Similarly, the difference between FUT and REF is negative, so a reduction of precipitation is simulated by the model after incorporation of future land use.

On average, the fields of the precipitaiton differences between the simulations are quite patchy (Figure 5.7). All simulations show small areas of enhancement as well as areas of reduction in precipitation. The reduction of precipitaiton in FUT is seen over large parts of the Netherlands. Urbanization mainly takes place along the west coast,

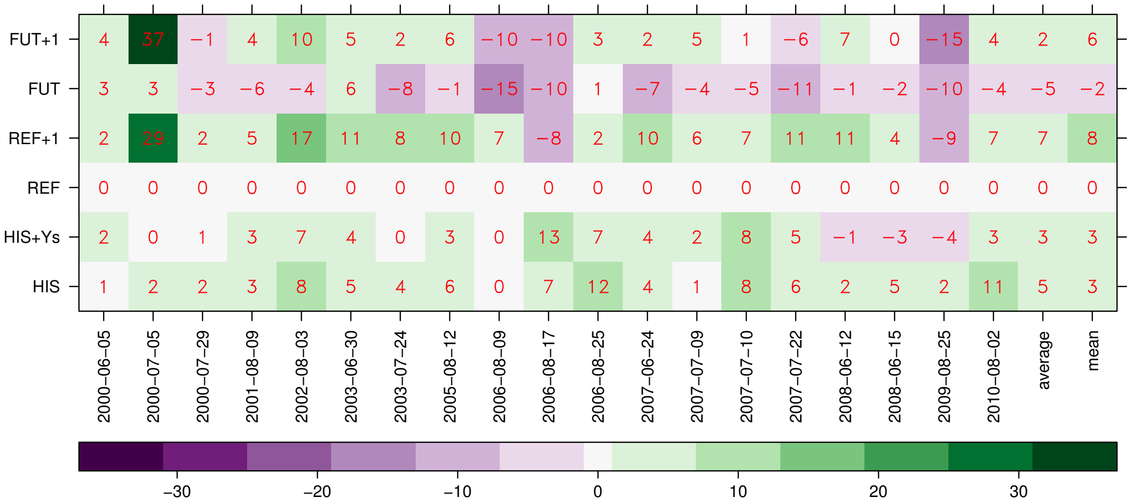

Figure 5.6 Relative precipitation difference (%) in each of the cases for all experiments compared to REF. Here the average is directly calculated over the 18 selected cases and the mean is calculated using the mean spatial differences as given in Figure 5.7

where the reduction of precipitation seems to be moderate. The relatively small reduction might be caused by the downwind enhancement of precipitation by urban areas, though the patchiness in the rest of the country doesn't seem supportive of this hypothesis. In the HIS simulation, the largest enhancement is located on the eastern side of Lake Yssel. This increase is not visible in the HIS+Ys simulation, so it might be caused by the relatively high SST and evaporation over Lake Yssel itself and subsequent higher moisture content of the air when it reaches the coast. The enhancement of precipitation in REF+1 and FUT+1 is most pronounced along the south-eastern border of the country. The relatively large spatial changes shown here average out to the relative changes given before in the order of 2 to 8%, which is only 0.1 to 0.6 mm. So the average changes between the runs are much smaller than the patchy spatial differences.

It is interesting to see if the precipitation response to the perturbations is happening equally throughout the day, or whether it occurs during a specific moment. In the mean daily evolution of precipitation, the differences between HIS(+Ys) and REF are hardly distinguishable (Figure 5.8). The differences between FUT and REF manifest themselves in the middle of the day when the intensity of precipitation is lower in FUT. This reduction

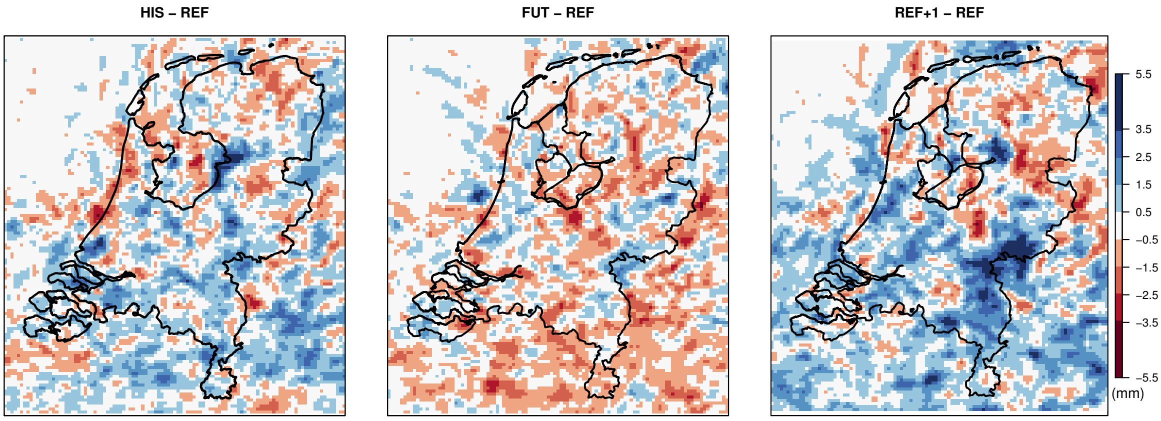

Figure 5.7 Spatial precipitation differences (mm) between the HIS, REF+1, and FUT experiments and the reference experiment.

of precipitation is also seen in FUT+1 and must be caused by land use changes, like the expansion of urban areas. The most pronounced temporal differences are visible in the temperature perturbation experiments: REF+1 and FUT+1. The differences are most evident in the early morning between 2 and 8 UTC. This difference is, however, mainly caused by the precipitation enhancement on 2000-07-05, the day with the largest response to the temperature perturbations. So the only systematic differences between REF and other simulations are seen with FUT and FUT+1 in the middle of the day.

The surrogate climate change experiments: REF+1 and FUT+1 are conducted to allow a comparison between changes in precipitation due to land use changes and due to climate change. In our simulations, precipitation in the Netherlands increases in the temperature experiments. The 7-8% rainfall increase in REF+1 (Figure 5.6) is close to the increase of about 7% K^{-1} in near surface humidity that follows from the Clausius-Clapeyron equation (O'Gorman and Muller, 2010). FUT+1 shows a more moderate increase in precipitation of 2-6%. The increase seems to be offset by the reduction in precipitation from the expected land use change that is obtained in FUT. Interestingly, it appears that the precipitation response to land use change and to the climate perturbation can be added linearly. So the mean and average values in Figure in REF+1, of respectively 8 and 7%, are reduced with the mean and average values in FUT, of -2 and -5% respectively, to attain the mean and average values in FUT+1, of 6 and 2% respectively.

The extremes of precipitation are hardly affected in the land use scenarios. There is some effect in the surrogate climate change scenarios however. The distributions of

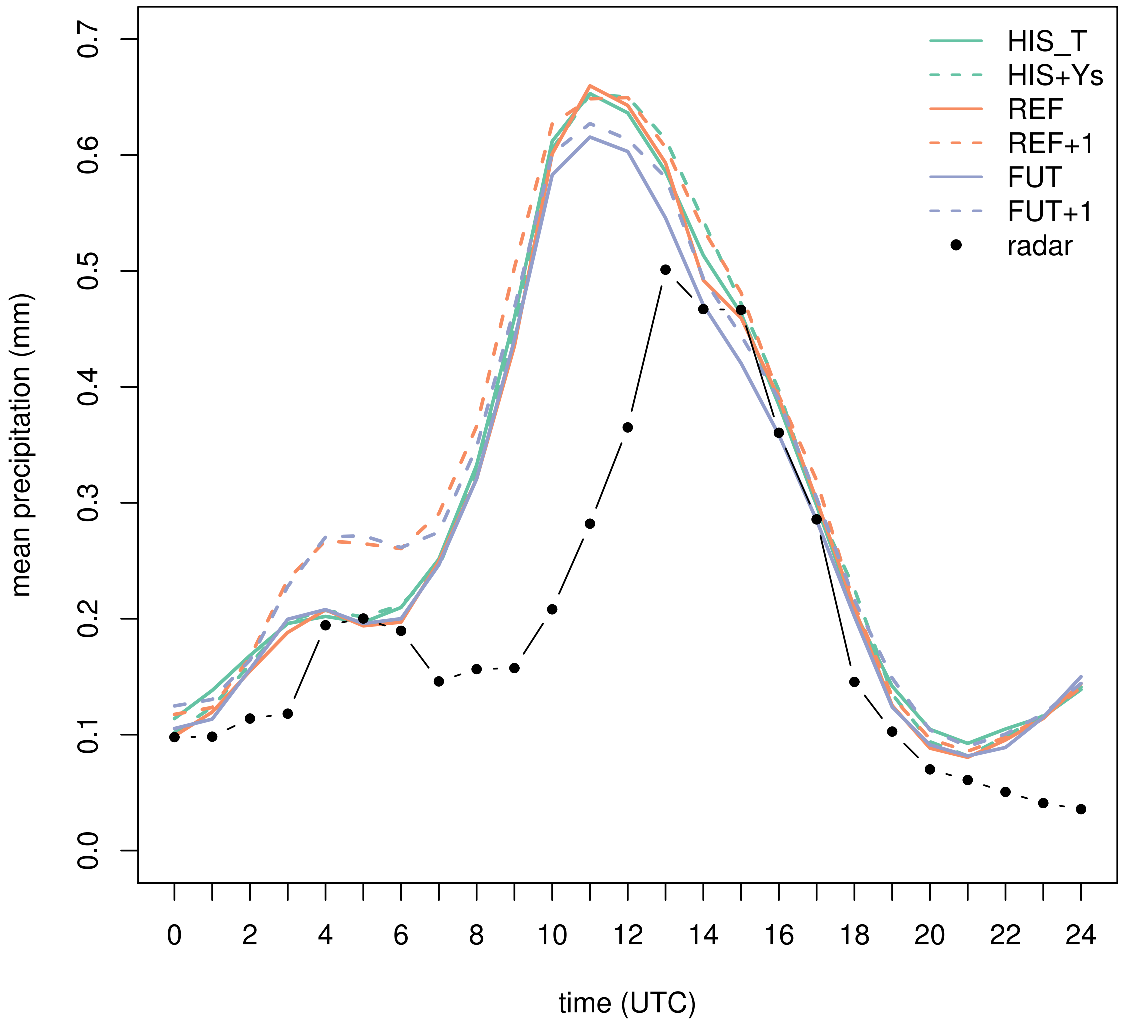

Figure 5.8 Diurnal cycle of mean precipitation (mm) over the Netherlands in the different experiments (averaged over 18 cases) and given by radar data (averaged over 14 cases).

precipitation are very similar in all of the experiments, except for REF+1 (Figure 5.9). The REF+1 simulation reveals a considerable increase in precipitation extremes. In the tail of the distribution the difference with REF is more than 20%. For more moderate extremes (> 15mm) the difference between REF+1 and REF is about 10%. Although mean precipitation increases in FUT+1, the distribution remains similar to REF. Apparently extreme precipitation is in this case influenced more by land use changes than by mean precipitation. The atmospheric conditions and relatively little (deep) convection in FUT+1 seem to play a role in this difference.

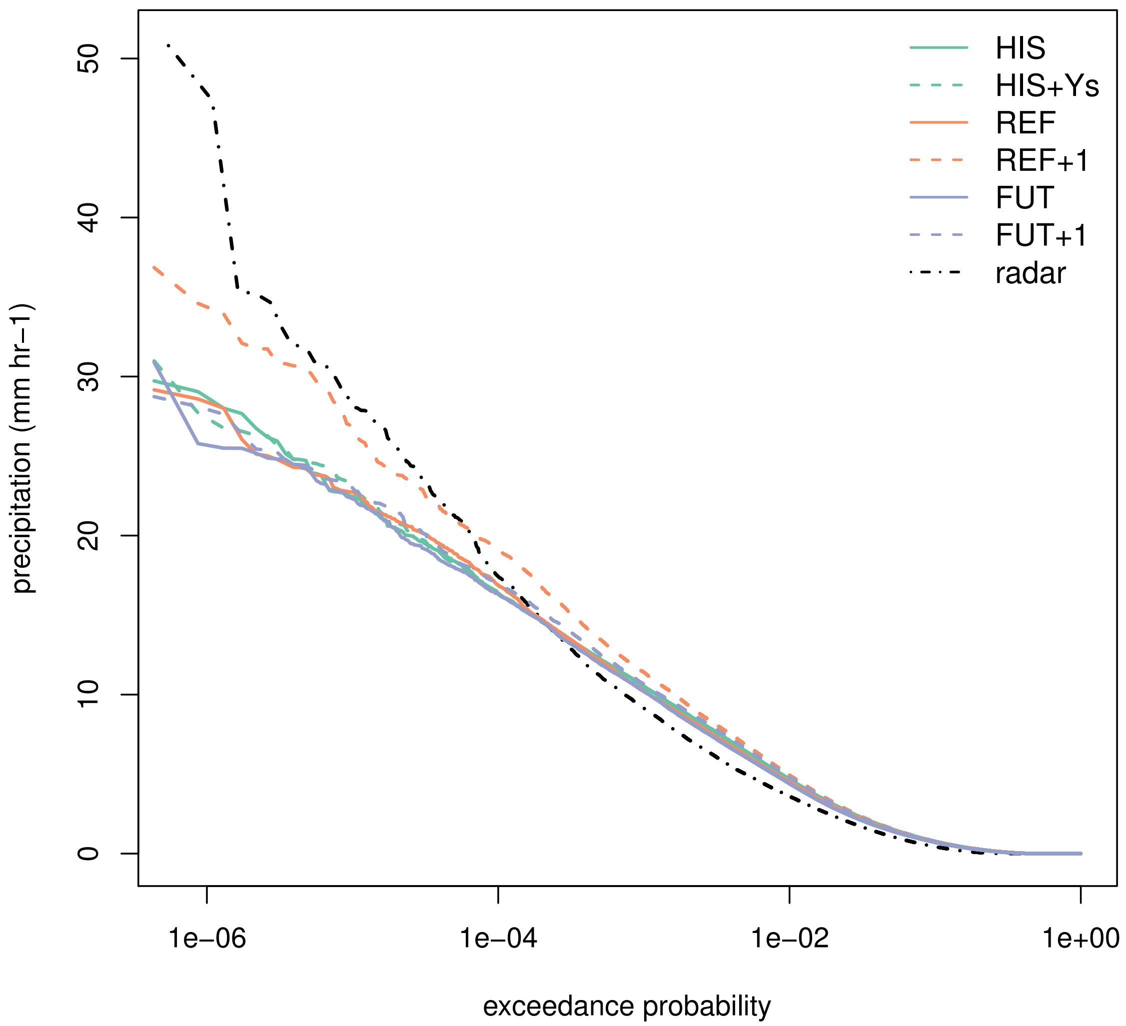

Figure 5.9 Distribution of hourly precipitation (mm) for each of the experiments and radar data, averaged over the 14 days that have radar data available.

5.3.2 Surface and atmospheric conditions

To understand the differences between the various simulations, this section focusses on surface and atmospheric conditions. We first consider changes in the latent and sensible

Table 5.2 Mean daily (0-0 UTC) values of latent heat flux (LH), sensible heat (HFX), convective available potential energy (CAPE), precipitation (RAIN), and daytime (6-18 UTC) values of the percentage of time and area that the planetary boundary layer top is over the level of free convection (PBL > LFC), likewise for lifting condensation level (PBL > LCL), over the Netherlands for the conducted experiments

Variable	Unit	HIS	HIS+Ys	REF	REF+1	FUT	FUT+1
LH	W/m^2	88.6	82.5	81.1	83.7	73.0	75.4
HFX	W/m^2	40.2	38.4	39.4	38.0	43.8	42.6
CAPE	J/kg	330.1	311.4	301.2	360.6	290.1	346.7
PBL>LCL	%	54.2	54.0	52.7	52.9	51.0	51.2
PBL>LFC	%	45.3	45.0	43.7	44.0	41.7	42.1
RAIN	mm	7.5	7.3	7.2	7.7	6.9	7.5

heat flux and changes in two meter relative humidity (Table 5.2). In HIS both a higher latent and sensible heat flux are seen in comparison to REF and to HIS+Ys (Figure 5.10). This is largely caused by the inclusion of part of Lake Yssel in the averaging, as the high lake temperature, and low albedo, causes both fluxes to be enhanced. In HIS+Ys the latent heat flux and relative humidity are somewhat higher than in REF, but the sensible heat flux is lower. Consequently the available moisture in both historical simulations will be higher and this boosts precipitation amounts. In the FUT simulations the reverse effects happens as moisture is reduced after expansion of urban areas and other land use conversions.

In REF+1 the heat fluxes are not that different from REF. Nevertheless, there is a large precipitation response. The imposed temperature perturbation with constant relative humidity increases the amount of moisture at the time of initialization and the amount that enters the model domain at the boundaries, causing precipitation to change, but fluxes to remain the same. In FUT and FUT+1 a reduction of the latent heat flux is simulated in comparison to REF. Also, in both experiments relative humidity at the surface is lower than in REF. The expansion of urban areas leads to an increase of the sensible heat flux and a decrease of the latent heat flux, since potential evaporation is reduced within urban areas. This decreases overall moisture availability. The surface responses in FUT and FUT+1 look relatively similar, though the precipitation response relative to REF is of opposed sign in the experiments (Figure 5.6).

Figure 5.11 shows the median of the diurnal cycle of the planetary boundary layer (PBL), lifting condensation level (LCL), level of free convection (LFC), and convective available potential energy (CAPE) calculated at the lowest model level, of the 18 cases in

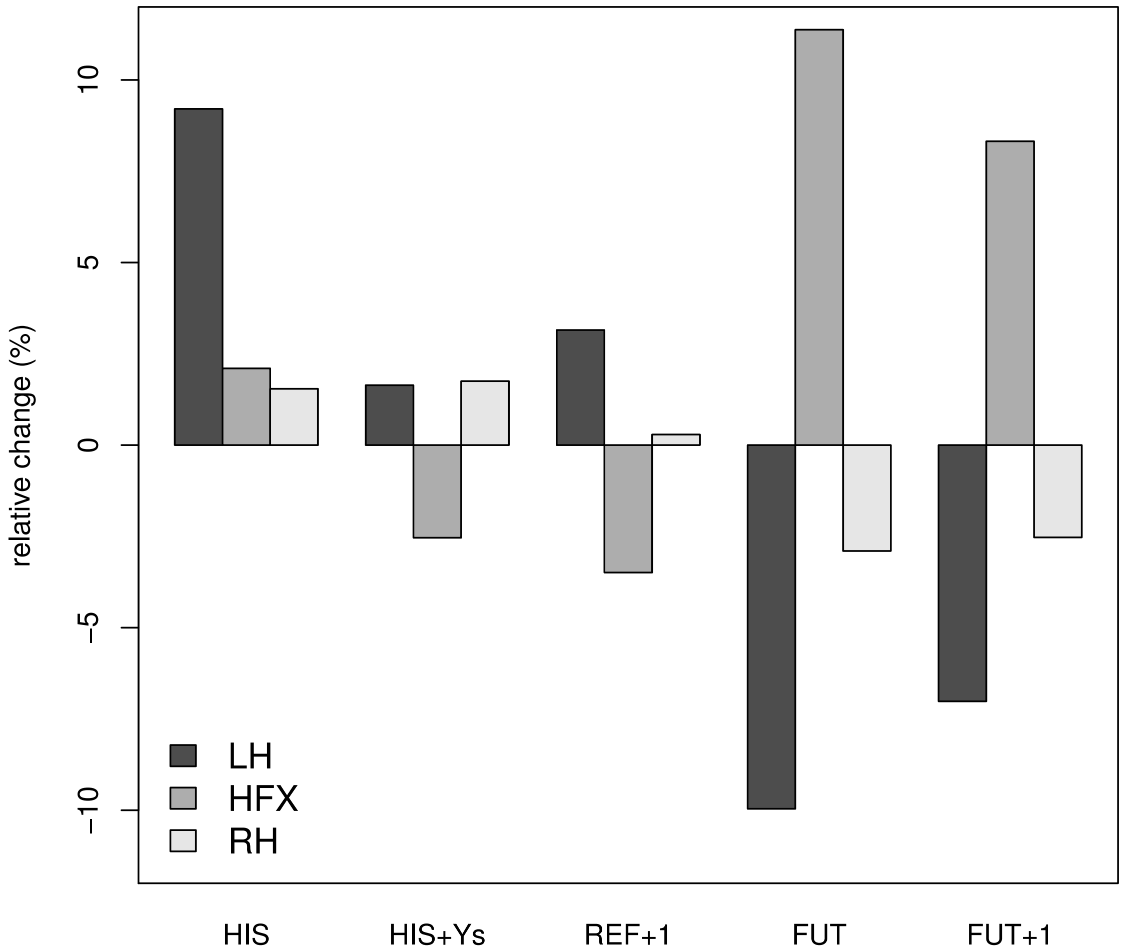

Figure 5.10 Mean relative change (%) over the Netherlands in latent heat flux (LH), sensible heat flux (HFX) and relative humidity (RH) in each of the experiments in comparison to the reference experiment.

the REF experiment. We show the median because the mean is more sensitive to outliers. For REF+1, FUT and FUT+1 the average difference with regards to REF is given for each of these variables. The differences are normalized with respect to the mean values in REF, so a relative increase is given at every time. On average, the PBL increases to about 800 m during daytime and reaches the LCL at around 9 UTC. In the figure, the LFC remains well above the PBL and LCL. In many individual cases, however, the LFC drops to about 800 m as well, permitting (deep) convection. The LFC reaches its lowest level at 11 UTC. This coincides with the time of the highest precipitation intensities in the model (Figure 5.8). CAPE increases up to 9 UTC while the LFC decreases, then stabilizes because of the rain and associated temperature and humidity changes. The early onset and intensification of precipitation in the model (Figure 5.8) contributes to the small buildup of CAPE and could explain the underestimation of extreme precipitation compared to observations (Figure 5.9).

In REF+1 the temperature is higher, while the PBL is quite similar to REF. During daytime there is little difference between REF and REF+1 regarding the LCL and LFC. In addition, we compute the fraction of space and time that the PBL is higher than the LCL and LFC respectively (Table 5.2). We consider this a measure of the amount of triggering that occurs. In REF+1 approximately the same amount of triggering (PBL higher than LCL/LFC) occurs as in REF. At night the LCL and LFC are lower in REF+1 than in REF. CAPE is higher throughout the day in REF+1 than in REF, likely due to the enhanced moisture content above the PBL as a result of the imposed climate change scenario. This leads to the simulation of higher precipitation amounts and intensities in REF+1 (Figure 5.9). In FUT the large sensible heat flux causes the PBL to grow more during the day and stay higher during the evening than in REF. The relatively large sensible heat flux also affects and raises the LCL and LFC. In comparison to REF, CAPE decreases in FUT from 8 UTC onwards when temperatures go up and relatively little moisture is available. Consequently, less precipitation is simulated.

In FUT+1 a combination of atmospheric processes from FUT and REF+1 can be seen. The LFC remains lower (like in REF+1), while the PBL and LCL are slightly higher (like in FUT). Accordingly, CAPE is higher than in REF in the beginning and end of the day (like in REF+1) and drops early in the day (like in FUT). In FUT+1 in total, precipitation is enhanced by the moisture availability from the boundary conditions imposed through the climate change scenario, but high intensity precipitation is not simulated because there is little triggering and (deep) convection. Strong precipitation events are caused by convective instability, which is measured by CAPE, and generally occur during daytime. In FUT+1, CAPE is mainly enhanced during nighttime, not during daytime. The relatively low values of CAPE during daytime likely explain the absence of a response in the tail of the precipitation distribution in FUT (Figure 5.9).

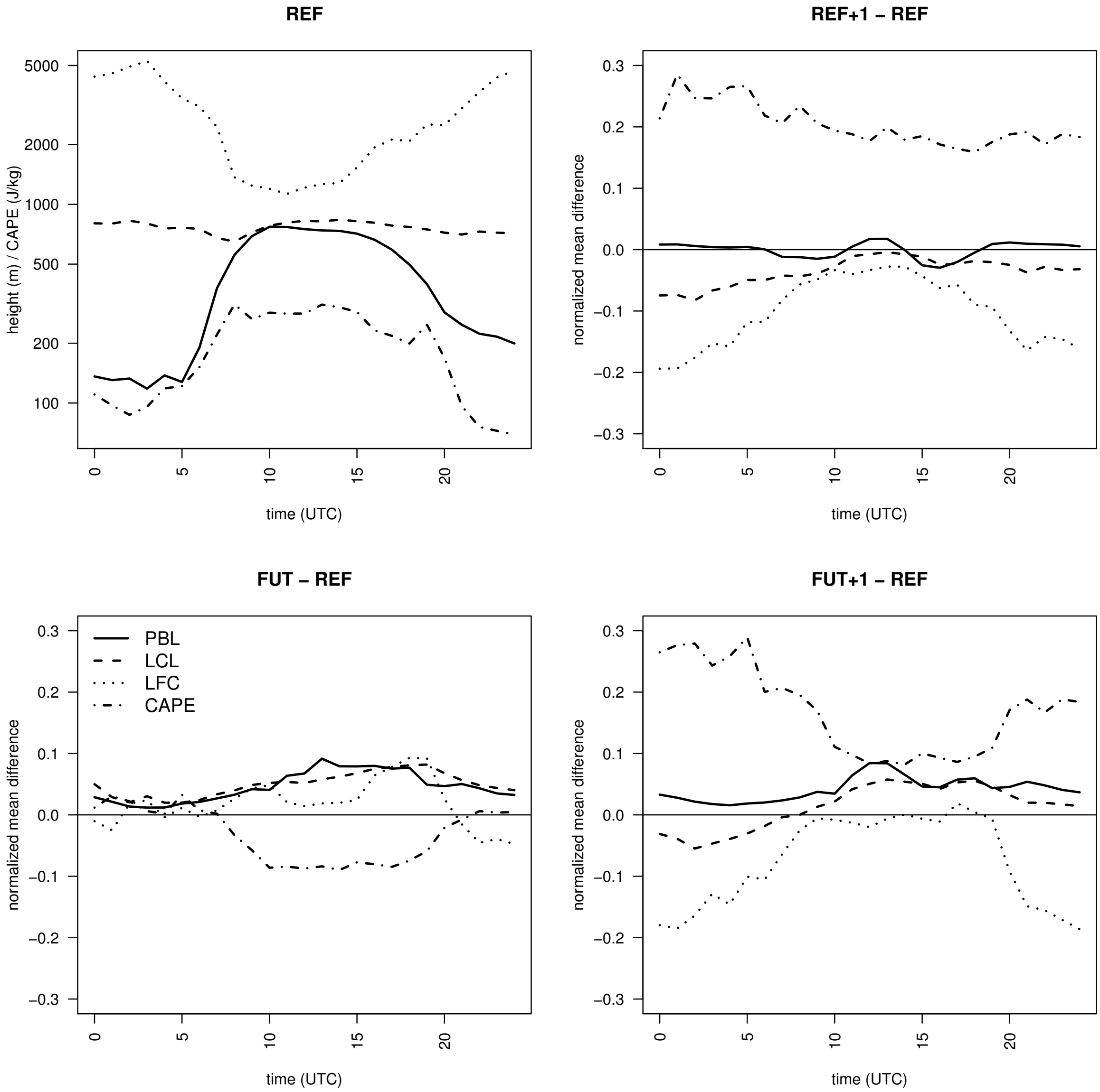

Figure 5.11 Diurnal cycle of the planetary boundary layer (PBL,solid), lifting condensation level (LCL,dashed), level of free convection (LFC,dotted) [m] and convective available potential energy (CAPE,dash-dotted) [J/kg] in the reference experiment and normalized mean difference of these variables in the experiments with a temperature perturbation and reference land cover (REF+1), future land cover (FUT), and a temperature perturbation and future land cover (FUT+1).

5.4 Discussion

Although WRF is a widely used atmospheric model, questions regarding the choice of parameterization schemes and the models validity for the specific conditions always remain. The sensitivity to different parameterization schemes was not specifically investigated in this study, while this is known to be important (Gallus and Bresch, 2006; Jankov et al., 2005; Rajeevan et al., 2010; Ruiz et al., 2010; Zeng et al., 2012). The chosen YSU PBL scheme is a first-order nonlocal scheme that is widely used under convective conditions (Hu et al., 2010). The HIS, REF, and FUT experiments were duplicated without the convection scheme, but this was found to have little effect on precipitation amounts and is therefore not shown. The utilized and presented model design is consequently only one version of reality, of which many more could be simulated. In this paper our main interest is the response of the model to changes in land use, however, which can still be investigated. In addition, the model was used in a slightly different setup for a four day case in spring and comparable results regarding the response of precipitation to increased urban areas were found (Daniels et al., 2015). A similar reduction in precipitation was also found with the MM5 model for Europe as a whole (Trusilova et al., 2009, 2008), which gives confidence in the results.

The utilized procedure to select cases for simulation was intended to obtain a homogeneous set of days with similar meteorological conditions and lead to comparable results. A large spread among responses to land use and temperature experiments was found between the cases however, so the intended comparability was not fully accomplished. This could be a model artefact, or a realistic response showing how differently the atmosphere reacts to similar conditions, thus showing natural variability. Nevertheless, the majority of cases has a similar sign in its response. Our estimates could be biased by the selection procedure that selected cases with rather strong convective activity. Consequently, convection will always be triggered in the selected cases and a potential feedback increasing precipitation through enhanced triggering was excluded. Examples of this feedback can be found in Findell and Eltahir (2003), Santanello et al. (2011), Taylor et al. (2012), and others. The Netherlands is however not located in a region where strong feedbacks of this type are expected (Seneviratne et al., 2006; The GLACE Team et al., 2004) and the influence of changes in climate, SST or circulation are likely more important (Attema et al., 2014; van Haren et al., 2013). Would the selection procedure have been more successful in identifying similar events, we could have made a composite event by averaging the initial and boundary conditions, similar to Mahoney et al. (2012). Their procedure sounds promising, because it could reduce simulation time and provide a more representative response, but the selection of cases to average is apparently not straightforward (see also Figure 6.3).

In this study reductions in precipitation from historic to present, as well as from present to future land use are obtained for selected summer cases in the Netherlands. Observations show, however, that precipitation has on average increased by about 25% in the last century (Buishand et al., 2013). So apparently factors other than land use changes have been dominant. The observed change in precipitation was larger in the winter half year than the summer half year nonetheless, and the trend in the summer months (June – August) in the period 1951-2009 was only about 5% (Daniels et al., 2014). Hence, land surface changes in the last century might have mitigated some of the precipitation increase in summer and hereby have contributed to the relatively low increase observed in summer. The same seems to happen in the future in the simulations: combining future land use with the expected temperature rise, reduces the precipitation increase in the model. This might only hold for summer however, because historical and theoretical evidence suggests that the precipitation response to land use changes is lower in cases with non-convective precipitation (Cotton and Pielke, 2007; Pielke et al., 2007). Studies for different types of precipitation, taking place in other seasons, are therefore desirable as well.

The climate change scenario used here maintains constant relative humidity in the model. The resulting response in precipitation under current land cover conditions (REF+1) is close to the expected increase in near surface humidity of about 7% estimated with the Clausius-Clapeyron equation. It is interesting to note that in all simulations, except for REF+1, no differences in extreme precipitation were simulated. In general it are not the changes in mean, but the changes in extreme precipitation that may cause problems for society, with for example landslides or urban flooding (e.g. Feddema et al., 2005; Hibbard et al., 2010; Mahmood et al., 2014). In REF+1 precipitation over 15 mm/hr increases with 10% or more. This increase is higher than the average increase in extreme precipitation simulated by global climate models (GCMs), which is about 6% per degree global warming (Kharin et al., 2007, 2013). Mean precipitation also increases more in our simulations (7-8%) than in GCMs (3%) (Allen and Ingram, 2002). This can partly be explained because we investigate hourly data, while GCMs data is generally daily. In addition, GCMs generally show a decrease in the occurrence frequency, and increase in intensity of precipitation. Because we only selected cases in which precipitation occurs, there can be no difference in the occurrence frequency in our simulations. Our estimates are therefore higher than those made by GCMs, but similar to comparable studies (Attema et al., 2014).

5.5 Conclusions

This paper aims to quantify the precipitation response to historic (1900) and future (2040) land use change in the Netherlands, and put this response in the perspective of climate change. To achieve this, historic, present and future land use maps are incorporated into the WRF model. In addition, simulations with a temperature perturbation of +1°C are done as a surrogate climate change scenario. The investigation is done for 18 summer days with similar characteristics that were selected with a circulation type classification and k-means clustering procedure. On average, precipitation decreases from historic to present land cover with 3-5%, and decreases with 2-5% from present to future land cover. Creation of land in Lake Yssel might have caused a decrease of precipitation, but the evidence is not exhaustive. Under the present climate, the simulated land use changes hardly have any influence on extreme precipitation.

Observations of precipitation in the last century show a year-round increase of 25%, but only 5% in summer. This paper shows that the relatively low increase of precipitation in summer due to climate change might have been offset by the effects of land use conversion. The same land use-climate compensation occurs in our simulations for the future. Precipitation increases by 7-8% on average in response to the temperature perturbation in the climate simulations and has a disproportional impact on extremes. Expected land use changes, including the expansion of urban areas, reduce this increase however. As such an average precipitation increase of 2-6% is achieved in the simulation that combines future land use with climate change. No increase in extreme precipitation is found in the combined future land use-climate change simulation. Overall, although the precipitation response to land use changes is smaller than the response to climate change, it is not negligible in the summer period in the Netherlands. Our simulations suggest this might be especially true for precipitation extremes.

Chapter 6

General discussion and outlook

The effects of the land surface on precipitation are of importance for (1) our understanding of the climate system, (2) improving weather and climate modelling systems, and (3) adaptation to climate change. Projections of precipitation over Europe generally show an increase of mean and heavy precipitation over the North and a decrease over the South (Beniston et al., 2007; Rajczak et al., 2013). Projections solely of heavy precipitation show an intensification (Fischer et al., 2014) and increase in occurrence (Sunyer et al., 2012) over nearly all parts of Europe. In addition, the number of hurricanes that will hit western Europe are predicted to increase under climate change (Haarsma et al., 2013). Others warn these estimates are highly uncertain (e.g. Willems et al., 2012a,b). Nevertheless, our society will likely have to deal with higher intensity precipitation in the future.

It is not surprising that there is increasing interest in extreme weather and climate phenomena. Extreme weather has the potential to cause severe societal, economic and environmental impacts (e.g. Pitman et al., 2012). In addition, the vulnerability of society to weather extremes is projected to increase in coming decades (EEA, 2012). For the period until 2040, however, vulnerability increases at least as much from increasing exposure and value of capital at risk as from climate change (Bouwer, 2013). Over any period, whether looking at the past or at the future, natural variability makes it hard to detect a climate change signal. In future projections this internal variability is not fully simulated and should be added on top of the projected patterns (Deser et al., 2012). In observations natural variability causes the fluctuations around the mean. Land surface effects might be a similar additional forcing, causing (spatial) variability in observations and contributing to the uncertainties in climate model predictions. This is because land surface effects are generally not well incorporated into the models that are used to make such predictions on a global to regional scale. On a local scale, however, land surface effects can be as important as changes in meteorological processes (Whitfield, 2012). This thesis focusses on the impacts of the land surface on precipitation in the Netherlands. The Netherlands is a small country, so we inherently look at issues on a local scale.

Changes in precipitation in the Netherlands over the last century have been investigated by several researchers (e.g. Buishand et al., 2013; Keijzer and van Boxtel, 2003; van Boxtel and Cammeraat, 1999). Mostly these changes have not been related to characteristics of, or changes in the land surface, however, and this thesis will add to this knowledge gap. In addition to investigating the impact of the land surface on changes in precipitation, it is interesting to know the influence of land use on current precipitation patterns. ter Maat et al. (2013) for example investigated precipitation in a small part of the Netherlands, the Veluwe area, and found that land use influenced the locally observed climatological rainfall maximum. This topic remains relatively unidentified for the rest of the country, like some other questions put forward in earlier research (e.g. van Boxtel and Cammeraat, 1999). Remaining questions from earlier research that have been dealt with in this thesis are on the effect of the creation of land in lake Yssel (1930-1968) and the impact of increased urbanization and the urban heat island on precipitation. In this thesis, these questions were combined with sensitivity experiments conducted with the weather research and forecasting (WRF) model. Such modelling experiments assist in understanding changes in precipitation and attributing these to land surface characteristics and changes. This synthesis will start with a historical overview of research on the urban heat island and urban precipitation enhancement, worldwide and for the Netherlands.

6.1 Historical overview of urban effects

The urban heat island (UHI) has been identified decades ago and investigated thoroughly (e.g. Arnfield, 2003; Oke, 1982; Steeneveld et al., 2011; Theeuwes, 2015; Zhou et al., 2013). In the Netherlands, UHIs over 5°C have been measured despite the relatively small size of Dutch cities (Steeneveld et al., 2011; van der Hoeven and Wandl, 2015; Wolters and Brandsma, 2012). Internationally, there is a large body of literature dealing (mostly) with precipitation enhancement due to urban areas as well (see e.g. Han et al., 2014; Lowry, 1998; Shepherd, 2005, and references therein). During the 60's and 70's the topic of urban effects on precipitation received ample attention in the USA after the discovery of the so-called La Porte weather anomaly (Changnon, 1968; Stout, 1962). As a result the extensive field observation program METROMEX was initiated (Ackerman et al., 1987; Changnon et al., 1977). These and later studies, usually focused on precipitation amounts in the vicinity of urban areas. In general, observational evidence shows that urban areas tend to enhance precipitation amounts and/or intensity, both within the city itself and especially downwind (i.e. to the east under westerly winds) of the city, up to a distance of 75 km. The enhancement is typically 5 to 25% over background values and largest in summer. In recent years, the interest has shifted from precipitation enhancements downwind of cities to climate within urban areas themselves and several projects have been initiated to investigate precipitation (e.g. http://www.raingain.eu) (Fencl et al., 2013).

In the Netherlands there was also some attention for urban effects on precipitation around the end of the 70's. A first (debated) investigation was presented at a symposium of the International Association of Scientific Hydrology in Amsterdam (Yperlaan, 1977) and subsequent work appeared in Buishand (1979), Kraijenhoff van de Leur and Prak (1979) and Witter (1984). The Dutch research from the 70s mostly investigated statistical significance of the urban effects and did not study physical causes. Yperlaan (1977) found increases in precipitation near major cities in the Dutch West coast in winter and spring, and indications of enhanced precipitation in summer. Kraijenhoff van de Leur and Prak (1979) only investigated summer precipitation occurrences of 30 mm or more and found a preference zone for these high rainfall amounts from the SW to the NE of the country (downwind of the major cities) and in the southernmost tip. Buishand (1979) compared monthly rainfall totals in urbanized and rural areas along the West coast. The largest increases in precipitation (about 10%) were found in winter and summer in the urban regions around Amsterdam and Rotterdam.

Witter (1984) used the most advanced methodology and classified days according to one of the ten circulation types (i.e. "Grosswetterlagen") of Hess and Brezowsky (1977). The grouping of rainfall stations into urban affected and urban unaffected then depended on the ground level wind direction most frequently occurring in each of the circulation types. He found significant increases in precipitation at urban affected stations for circulation types with a west-, north- and southerly component (type 1, 6 and 10) throughout the year, and for easterly circulation (type 8) in summer only. The results for the remaining circulation types were inconclusive or showed contrary results. Though not significant, he found an increase in both summer and winter rainfall at urban affected stations for the entire Randstad area. Yperlaan (1977) only used data from 1958–1970, while the other three studies made use of data in approximately the period 1930–1975. In the latter studies, the investigated period was split in half to compare the earlier period with little industrial activity to the more recent one. However, the lowering of the rain gauges in the period 1946–1954 likely had an effect on the increases that were found between the two periods as well (Buishand, 1979).

Recently, a large body of studies using numerical (mesoscale) models has become available that support the observational evidence of urban precipitation enhancements (e.g. Chin et al., 2010; Han et al., 2012; Inamura et al., 2011; Kusaka et al., 2014; Miao et al., 2010, 2011; Pathirana et al., 2014; Rozoff et al., 2003; Schmid and Niyogi, 2013; Sertel et al., 2011; Shem and Shepherd, 2009; Shepherd et al., 2010; Wan et al., 2013; Wang et al., 2013; Yang and Wang, 2012; Yang et al., 2014; Zeng et al., 2012; Zhang et al., 2010). However, there are also a few studies that find precipitation is reduced due to urban expansion or the associated reduction of evaporation (Lin et al., 2013; Wang et al., 2012). In addition, some studies find an opposed signal between winter and summer (e.g. Cheng and Chan, 2012). The only known European studies are included in this last category. Trusilova et al. (2009) and Trusilova et al. (2008) find that inclusion of urban areas results in an increase of urban precipitation in winter (0.09 mm day^{-1}) and a reduction in summer (-0.05 mm day^{-1}).

Most modelling studies that investigate the effect of urban areas drastically expand urban areas and/or compare a simulation with present day with a simulation in which all urban areas have been removed. This can be considered more as a sensitivity analysis, then as an explanation of historic or projected future changes in precipitation. Modelling studies with realistic land use changes are much more scarce. They are usually quite local in focus and have for example investigated the onset of the Indian summer monsoon (Yamashima et al., 2015), precipitation amounts in Monsoon Asia (Yamashima et al., 2011), winter precipitation in Japan (Sugimoto et al., 2015), the July climate of the United States (Roy et al., 2003), or the regional climate in Australia (McAlpine et al., 2007). Still other studies with realistic land use changes did not investigate precipitation, but only looked at temperature or wind for example (e.g. Kamal et al., 2015). It would be interesting to expand these studies to a larger area and investigate non-local effects. On a global scale major impacts of land cover changes are hardly detectable, but it has been shown that land cover changes cause statistically significant changes in regional temperature and precipitation, (e.g. Feddema et al., 2005; Lawrence and Chase, 2010). In addition, some studies find that the areas where statistically significant changes occur are displaced from the location of land cover change (Zhao et al., 2001). This makes it hard to investigate the precipitation impacts of land cover changes on a regional scale and could explain why relatively few studies have been done.

6.2 Precipitation enhancement by urban areas

The evidence we present in Chapter 3 about enhanced precipitation downwind of urban areas along the Dutch West coast agrees well with international and national observations. Depending on the month and the geostrophic wind direction, we find that precipitation is enhanced up to 20% within a distance of 20 km and that some signal is still detectable up to 50 km downwind. The methodology we utilized is similar to the one by Witter (1984), though we use geostrophic instead of ground wind direction. In addition, we only investigated the period after 1951 to exclude the influence of the gauge lowering. Our results agree with the earlier Dutch findings and strengthen the hypothesis that urban areas enhance precipitation amounts.

The influence of urban areas on precipitation within cities themselves seems to be limited in the Netherlands (Daniels and Overeem, 2015; Overeem, 2014). Based on radar data in the 2001-2010 period, the enhancement within cities is estimated to be about 3.5%. This investigated period is relatively short, and the results could therefore not be given with a reasonable level of significance. In fact, both studies suggest that the intensity of precipitation in urban areas is equal to that in the rest of the country. So it rains more often, but not stronger in urban areas. Downwind of urban areas though, we showed in Chapter 3 using daily precipitation observations that intensity did increase. In general, although the effects of urban areas on precipitation in the Netherlands are hardly ever statistically significant, a very consistent picture regarding the sign (i.e. always positive) was given in Chapter 3 and previous research. While the enhancements are not very large (typically 3–10%) they are persistent and could be important for farmers, water managers or spatial planners for example.

The enhancement of precipitation downwind of urban areas was investigated with observational data in Chapter 3 of this thesis. It is also interesting to see whether the WRF model correctly simulates this as well as the enhancement within cities themselves, which was found with radar data. Therefore, we determine “urban” and “rural” pixels from the present-day land use map of the Netherlands in the West Coast. Pixels with an average urban fraction over 0.25 are classified as urban, the remainder (about two thirds of the area) is rural (Figure 6.1). In addition, the downwind area of cities (up to 18 km) is determined under south-westerly wind. For both these areas the precipitation difference, relative to the rural area is determined. We do this for the 14 cases studies presented in Chapter 5 that also have radar data available. We only use the WRF simulations with present-day land use.

The precipitation difference between urban and rural pixels in the radar data of the previously mentioned 14 days is about 4%. So the precipitation difference between urban and rural areas in the Randstad in these days is similar to that observed year-round (3.5%). The average difference in the WRF simulations on these days is about 10%. It seems that WRF indeed simulates the enhancement of precipitation within urban areas along the West coast, albeit a bit too much. The model accurately simulates high precipitation amounts in the South of the West Coast and lower amounts in the North (Figure 6.1). Downwind of urban areas, the difference between "urban" and "rural" pixels is 15% based on radar data. In the WRF simulations this difference is only 8%. Although this analysis strongly depends on the simulated precipitation pattern, it gives some insight whether enhancement of precipitation from urban areas is correctly simulated in WRF. Surprisingly, after consistently finding reductions in precipitation with WRF after expansion of urban areas, the model does realistically simulate more precipitation within and downwind of cities. This is in line with international literature that also finds enhancements of precipitation downwind of urban areas. Other studies hardly report on differences in precipitation more remote from the investigated urban areas, which might explain why decreases are rarely reported.

Finally, we investigated the effects of urban areas from a different perspective that focusses more on the presence and influence of aerosols. We investigate the presence of a weekly cycle in precipitation. A similar procedure has also be used for other meteorological variables (e.g. Arnfield, 2003; Kanda, 2007; Rosenfeld and Bell, 2011). Human induced, aerosol producing activities (e.g. transportation, industrial production) are often reduced during weekends and because there are no natural processes with a weekly cycle, any observed weekly variations are considered an anthropogenic signal. Over Europe, no consistent weekly cycles exist in the occurrence frequencies of any of the circulation types from the cost733cat database (Beck, 2012). This is important to know because any observed weekly cycle therefore has to be related to human influence.

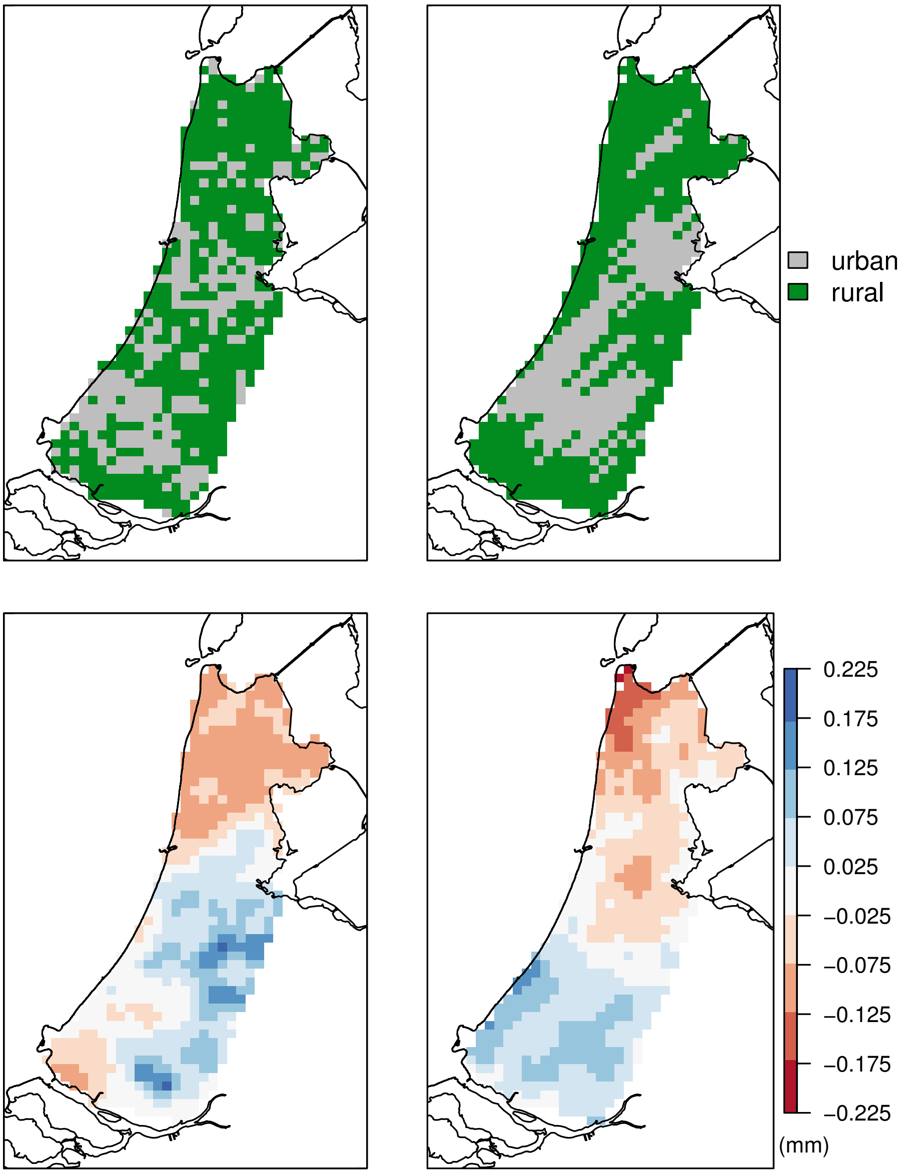

Figure 6.1 Top: Urban (grey) and rural (green) areas in the Dutch West coast (left) and area downwind of cities (grey; right). Bottom: mean precipitation bias (mm/hr) over the same area calculated with radar data over the 14 summer cases used in Chapter 5 (left) and derived from the modelled cases (right).

We tested the time series of all precipitation stations with daily available data in the Netherlands over the 1951-2010 period. The data was divided into seven groups (giving six degrees of freedom); one for each day of the week, and tested for equality of population medians among groups, following Barmet et al. (2009). We did not find a significant ($p<0.05$) weekly cycle. In addition, we investigated the spectral density plot (i.e. periodogram) of precipitation stations in the Randstad classified as "urban" based on the upwind fraction for all of the weather types utilized in Chapter 3. The periodogram did not show a peak either at 1/7 day (or the multiples of it) for any of the selections, or for the whole country mean. We therefore conclude that no weekly cycle in precipitation exists in the Netherlands. This could be because of the high background pollution levels over Europe (Rosenfeld, 2000). Our findings agree with other studies over (parts of) Europe that also failed to find evidence of weekly cycles (Laux and Kunstmann, 2008; Stjern, 2011).

6.3 Effects of land cover changes

In the Netherlands, the most important land cover changes in the last century were the conversion of large heather areas into agriculture or grassland and expansion of urban areas (Feranec et al., 2010; Verburg et al., 2004). In addition, almost 1650 km^2 of land was reclaimed in the former Zuiderzee, now called Lake Yssel (Hoeksema, 2007). In the Netherlands urban areas have increased from about 2% in 1900, to 13% in 2000, and are projected to increase to 24% in 2040 (Dekkers et al., 2012). Consequenlty, in the model simulations in Chapter 4, urban extents of 0, 2, 13 and 24% were used. In Chapter 5, we use similar values, but do not have an experiment without urban areas. In Chapter 4, the only difference between the simulations is the extent of urban areas and the expansion of urban areas is simulated with a simple function. The expanded urban areas might therefore not be realistically located. In Chapter 5 actual land cover maps are used, so the changes in urban areas are realistic and changes in other land use types are also included.

Using observations it is practically impossible to formally attribute changes in precipitation to the expansion of urban areas or other land cover changes. From the analysis in Chapter 2 we can infer that changes in external factors, like SST and circulation, had more effect on changes in precipitation in the last half century than land cover changes had.

This was found by establishing correlations between land surface properties and observed precipitation trends. A model, on the other hand, can be used for attribution, because the effects of changing only one variable, in this case the land surface, can be investigated in a controlled environment. Any difference between the simulations can then automatically be attributed to the imposed changes. In both Chapter 4 and 5 over the Netherlands an average decrease of precipitation was simulated after expansion of urban areas, despite increases directly over and downwind of cities in the West Coast as discussed above. We find the effects of urban areas are twofold: they increase precipitation locally, while they reduce precipitation in the country as a whole. Urban areas in the model differ from other land cover types because they have a much lower fraction of vegetation and therefore lower rates of evapotranspiration. When expanding urban areas in the simulations, moisture is therefore reduced. This reduction of moisture seems to outdo the increase of precipitation occurring due to enhanced triggering of precipitation over/nearby urban areas. This can be explained with the strength of the soil moisture-precipitation feedback that was explained in Chapter 1 and quantified for the spring case study in Chapter 4.

In Chapter 4 we quantify the soil moisture-precipitation feedback strength using the ratio of evapotranspiration to precipitation. The ratio of evapotranspiration to precipitation, unlike the recycling ratio, combines precipitation that truly originates from the region of interest with precipitation that originates from the sea but is triggered by moist conditions over land (e.g. Bisselink and Dolman, 2009). The source of moisture for continental precipitation often originates from the sea, in the neighborhood of continents (van der Ent and Savenije, 2011). This is likely true for the Netherlands as well, considering the dominance of coastal effects over land surface effects that was illustrated in Chapter 2. Other studies have also shown that apparent soil moisture-precipitation feedbacks can often as well or even better be attributed to the influence of SST on precipitation (Orlowsky and Seneviratne, 2010). In addition, Goessling and Reick (2011) demonstrated that moisture recycling estimates do not necessarily mirror the consequences of land-use change for precipitation. Likewise, in Chapter 4 we find urban expansion leads to smaller precipitation reduction than expected on basis of the change in the strength of the soil moisture-precipitation feedback. This relatively low precipitation response is generated because the reduction of moisture is partly cancelled by the enhanced triggering. This behavior is more often found (e.g. Collow et al., 2014) and could explain the difference found between the local and countrywide sign of precipitation changes after urban expansion.

The precipitation response in both Chapter 4 and 5 was spatially variable and regions of precipitation increases as well as decreases were simulated. This seems to be a common feature of mesoscale models. In itself this is not inappropriate, because an increase of precipitation downwind of urban areas, as was simulated in Chapter 5 and found in observations in Chapter 3, should lead to a decrease in precipitation elsewhere. However, precipitation was also reduced upwind of urban areas in the simulations. So apparently the changes in land use cause a widespread disturbance to the atmosphere that displays itself differently in various areas. This might suggest, similar to Li et al. (2013), that land use change and urbanization play an important role in modifying not only local, but also regional precipitation patterns.

6.4 Climate change context

Climate change (also referred to as global warming) is a scientifically well accepted phenomena that receives a lot of attention (IPCC, 2013). On the one hand the impacts of the increase in CO_2 and other greenhouse gasses, that (simply put) result in global warming, are investigated. On the other hand the impacts of climate change on local weather are investigated, like we do in Chapter 5 of this thesis. These local changes are important to investigate because they are responsible for societally important issues such as droughts (Trnka et al., 2010), floods (Mahmood et al., 2010), heat waves (Fischer et al., 2007), etc. On a global scale, changes are generally investigated using earth system/climate models (GCM) ranging from scales of 25 to several hundreds of kilometers. This resolution is too coarse to investigate local changes. Therefore regional models (RCMs), like WRF, are used. The resolution of RCMs spans a range from around 500 meters to that of the finest GCMs. For studies into small areas or one country, it is important to use a mesoscale model, because future weather is expected to change due to a combination of large scale changes (e.g. greenhouse gas increases, circulation changes) and local conditions, that can only be properly represented by a model with sufficiently high resolution. Using such a model can assist in land use and management decisions, and identifying opportunities and limitations for managing climate change (for both mitigation and adaptation strategies) (Hibbard et al., 2010).

The difference in resolution of climate models and local scale processes has brought considerable problems for the impact assessment of climate change (e.g Fowler et al., 2007). Regional models are commonly "fed" with output of a GCM to predict future conditions. This is called dynamical downscaling. Several studies (e.g. Leung et al., 2004) have illustrated how dynamical downscaling provides 'added value' to climate change impact studies. In general, more accurate variability and extreme event statistics are simulated by higher spatial and temporal resolution models (e.g. Frei et al., 2006). However, the model skill of regional models used in dynamical downscaling depends strongly on biases inherited from the driving GCM and the presence and strength of regional scale forcings (Fowler et al., 2007). Conversely, the initialization of land surface and soil conditions are essential to make accurate seasonal predictions with climate models (Prodhomme et al., 2015). Land surface changes are shown to cause significant differences on a regional scale (Pitman et al., 2009). Areas where the land surface has significant impact on precipitation have for example been identified in the GLACE project (Koster et al., 2006). Under climate change, a new transitional climate zone with strong land-atmosphere coupling is predicted to establish in central and eastern Europe (Seneviratne et al., 2006). For (coastal) western Europe, future climate predictions are probably underestimated because of misrepresentations of the North Atlantic Current, atmospheric circulation, soil moisture and cloud cover in climate models (van Oldenborgh et al., 2009). It is therefore unknown whether land surface interactions will become more important under future climate conditions in the Netherlands as well.

Typical RCM projection have a resolution of 11 km over Europe (Jones et al., 2011). This resolution is still too coarse for many impact studies. One way to deduce higher resolution scenarios, also widely employed in the Netherlands, is pattern scaling. This methods assumes small scale spatial patterns in weather will remain unchanged and the magnitude can be scaled with global warming. A high resolution future climate map can therefore be produced by simply applying a delta change to the present pattern. In the introduction and Chapter 2 of this thesis, we question the validity of such an approach. Our and earlier work shows that (some of the) persistent rainfall patterns are related to land use and urbanization (and coastal SST). The KNMI'14 climate scenarios for the Netherlands use a change in circulation patterns as one of the main change drivers. The position of spatial (precipitation) anomalies may change with such circulation changes. Simply reasoned for urban effects: rainfall enhancement downwind of cities presently occurs mostly northeast of cities (with SW winds), and as more easterly winds are expected in the future (summers) this enhancement may shift more to the West of cities. The amount of precipitation that falls under easterly winds is quite low however (see Chapter 3), so the effect on the year-round patterns will be small. In addition, precipitation patterns might change because of a change in the frequency distribution of precipitation. In Chapter 5 of this thesis we show the effects of land cover change and climate change can be of comparable size. For mean summer precipitation an increase of 7-8% is found for a +1°C climate change scenario, while a reduction of 2-5% is found for projected land use changes in the future. Precipitation extremes in summer increase with more than 20% in summer in the imposed climate scenario, but land use changes complete negate this.

The linking of severe weather events to climate change, along with a number of recent demonstrations of societal vulnerability to severe weather, has led to significant media and scientific attention (e.g. Hazeleger et al., 2015; O'Hare, 2013; Pall et al., 2011). Information on a range of possible future weather extremes would be of great value to society (Kunreuther et al., 2013). To encourage this, Hazeleger et al. (2015) propose an alternative to dynamical downscaling that deduces high-impact weather events. The methodology we use in Chapter 5 can be used to select such a high-impact weather event by incorporating the important characteristics for such an event into the clustering procedure. With a simple surrogate climate change scenario these events can then be simulated for future conditions. Other such examples for the Netherlands can be found in Attema et al. (2014) and Lenderink et al. (2012). Such examples can have considerable value to users: they are vivid, can be related to relevant past weather analogues and linked to the everyday experience of users. Relating information on extremes to everyday experiences is a statistically significant determinant of higher levels of concern about extreme weather (Vasileiadou et al., 2014). This translation is important for decision-making on climate adaption.

Better prediction of extreme weather can for example be valuable for urban water management (van Luijtelaar, 2014) and the agricultural sector (Schaap et al., 2011; van Oort et al., 2012). The intensification of especially convective summer precipitation can cause difficulties in urban water management. Sewers for example are not made to deal with precipitation amounts over 30 mm/hr and heavy precipitation events can cause temporary flooding of infrastructure and cellars (McAlpine et al., 2010). In Chapter 5 we show precipitation extremes could increase by 10-20% under a temperature increase of 1°C. However, changes in land cover could negate this increase in summer precipitation extremes completely. This information could be valuable for spatial planners and water boards for example, because it shows the influence of the land surface. The WRF model could be used in a similar way to that done in this thesis, to identify management options that help reduce high-impact weather risks. Vegetation can for example be designed in such a way that it helps generate atmospheric conditions conducive to precipitation (Ryan et al., 2010). Using this knowledge, one could try to influence the location of convective precipitation to be outside of high value areas and reduce subsequent damage.

6.5 Reflection on methods and implications for future research

The chapters in this thesis are difficult to compare to one another because they employ different methodologies and focus on different time periods. Chapters 2 and 3 make use of daily precipitation data in the 1951-2010 time period, while Chapters 4 and 5 make use of the WRF mesoscale model to investigate between 4 to 19 days. Precipitation displays a large natural variability in both time and space, which makes it difficult to prove statistical significance with such short simulations. Conducting sensitivity experiments with the model for a longer time period would therefore be desirable. This requires a large computational effort however.

In Chapter 4 and 5 a synoptic circulation classification system was used to select case studies with similar synoptical situations. From this we hoped to create a "composite event" like one that was utilized in Mahoney et al. (2012). For a composite simulation, all available fields (e.g. temperature, moisture and wind at all available levels) are averaged together. These fields are then used as initial and boundary conditions for new WRF simulations. Mahoney et al. (2012) were able to use the composite events to show the same changes in hail and flood risk that were also occurring in the ten separate events that the composite was based on. This approach has the potential to substantially reduce computational effort, because simulating the individual events would no longer be needed.

We tried to apply this approach to our WRF simulations in Chapter 4, and an earlier selection of cases for Chapter 5. In Figure 6.2 and Figure 6.3 we show the performance of the composite made from 24 one-day events in the 1998-2012 period. The composite case yields rather realistic spatial fields of precipitation with the highest precipitation amounts in the western part of the country (Figure 6.2). However, the time evolution during the day is far off (Figure 6.3). Precipitation clearly falls in two events, in the afternoon and night, while the average radar data over the 24 days does not show this behavior, nor does the WRF average of the individual events (not shown here). In the

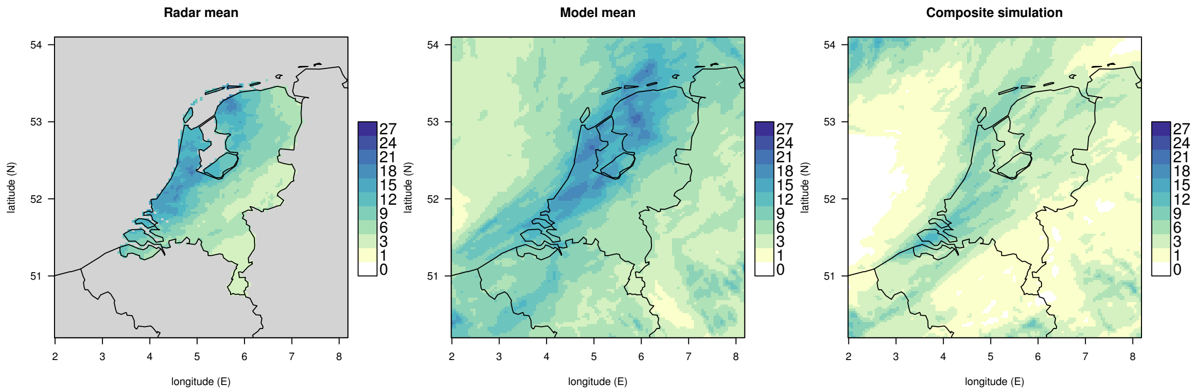

Figure 6.2 Spatial distribution of precipitation in the Netherlands as observed by radar (left) and simulated by the WRF model (middle) averaged over 24 cases, and precipitation as simulated by the composite of the 24 cases (right).

individual events there are several days that have a clear precipitation peak in afternoon or night however. These days seem to have had too much influence on the composite. We also perturbed soil moisture in the composite simulation, and expanded urban areas, similar to Chapter 4. Here expansion of urban areas lead to an increase in precipitation, in contrast to the results shown in Chapter 4 and 5. This increase was not seen in the individual cases however. From this, and the wrong temporal evolution of precipitation, we conclude that the composite approach failed and might not be suitable for simulating land surface perturbations. Whether this is due to improper case selection or due to non-linear responses to small forcing differences is still unclear and could be investigated further.

In this thesis we made a selection of cases that were expected to have a large sensitivity to the land surface, but even for this selection the results were not clear and a large difference between the response of the different selected days was obtained. The selection of cases might have reduced representability of our results, however, and lowered comparability to observational evidence that intrinsically includes a wide range of conditions. The small analysis downwind of urban areas in the Randstad presented in Section 6.2 is inconclusive in this respect as well, because the model overestimates the precipitation enhancement within urban areas, but underestimates the downwind effect.

Observational data, such as the radar data and gauge measurements presented in this thesis, are generally considered the truth. These data are however also subject to uncertainties and measurement errors. Precipitation estimates by radar are hampered by a variety of errors. Overeem et al. (2009) specify the most important error sources

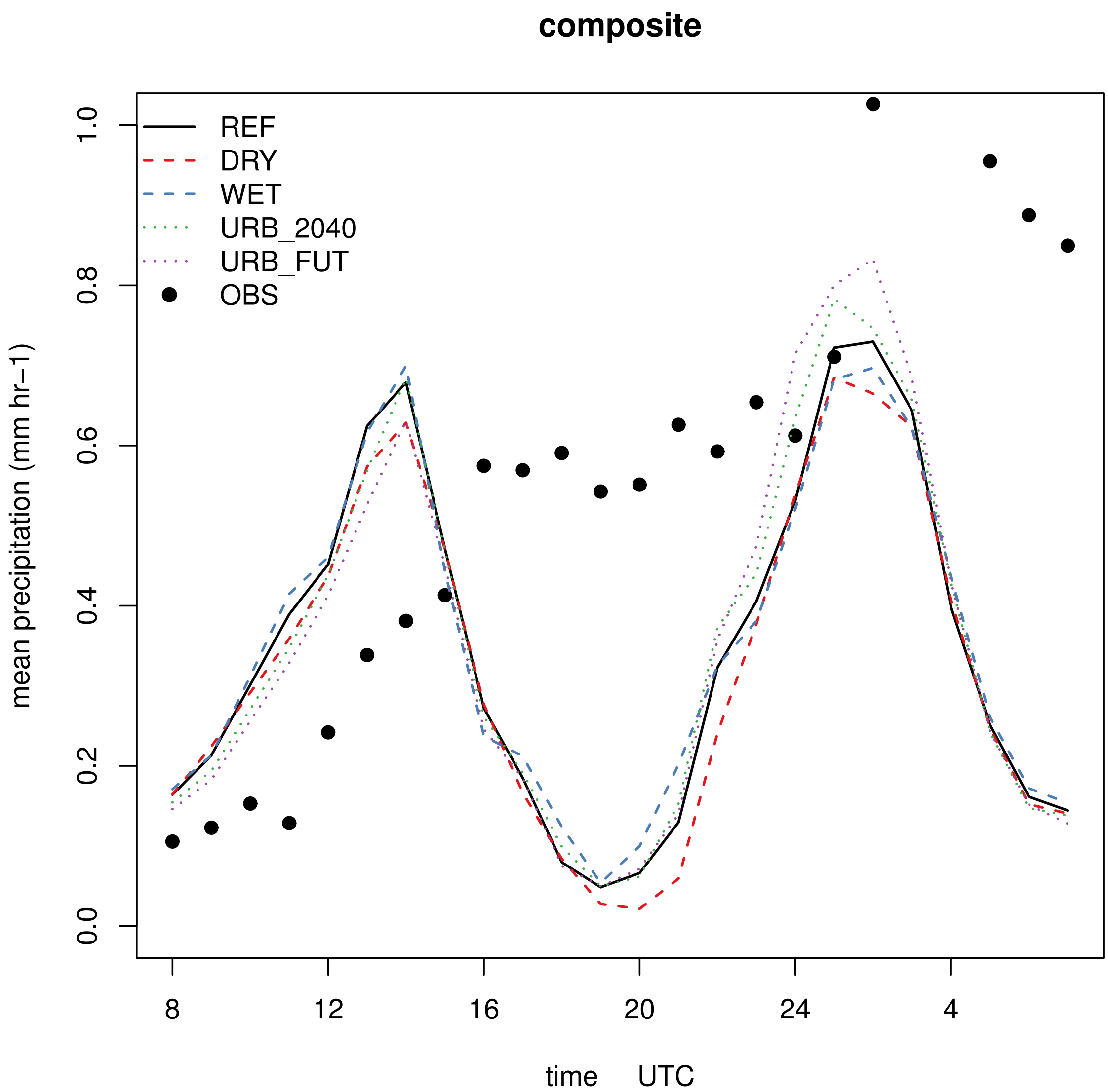

Figure 6.3 Diurnal cycle of mean precipitation over the Netherlands simulated from composite boundary and initial conditions for the reference simulation (REF), a simulation with soil moisture initialized at wilting point (DRY) and saturation (WET), and simulations with urban areas in the Netherlands expanded to 12% (URB-2040) and 24% percent (URB-FUT) like in Chapter 4. Dots indicate the average precipitation observed by radar from the 24 cases that the composite is based on.

for the utilized C-band radars in the Netherlands. These are: (1) attenuation of the radar beam as a result of strong precipitation or a wet radome, (2) a nonuniform vertical profile of reflectivity, (3) variability of the drop size distribution, and (4) incomplete beam filling or partial overshooting. Some other errors related to precipitation estimates with radar are occultation, brightband effects, hardware calibration errors, and anomalous propagation of ground clutter (Overeem et al., 2009). The radar data utilized in this thesis has been corrected for errors and spatially adjusted with rain gauge measurements, which considerably improves the quality. Gauge measurements, on the other hand, suffer from wind-induced undercatch, wetting and evaporation loss (e.g. Sieck et al., 2007). Although the Netherlands has a dense manual gauge network of approximately one station per 100 km^2, it is possible to achieve a larger spatial level of detail using radar data.

The WRF model used in Chapter 4 and 5 is a state-of-the-art atmospheric modelling system. It consists of mathematical representations of physical processes that for example simulate precipitation. Such a model is a valuable tool to use, because systematic (land surface) changes can be made and their effects evaluated. However, sub-grid scale processes and interactions need to be simplified in such a model. Land surface processes and variability, and convective cloud formation, are typically such small scale interactions, and are inherently difficult to represent in a model. In addition, some assumptions, e.g. regarding fluxes in the surface layer, are necessary to be able to solve the mathematical equations. The patchiness of the precipitation response to land surface changes (shown in Chapter 4 and 5) might be the result of oversensitivity to such parameterizations and not be representative of reality.

Many studies have investigated the sensitivity of the model to the choice of parameterization schemes and found substantial influence. The model design used in Chapter 4 and 5 is consequently only one version of reality. Many more simulations could be made, with different parametrization schemes. We hope, but cannot be certain, that the simulated sensitivity and sign of simulated changes remains the same in other model realities with a different choice of parameterization schemes. An additional cause of concern is the discrepancy between the modelled and observed precipitation in Chapter 4 and 5. The simulated precipitation in the reference run in Chapter 4 agreed reasonably well with observations. A spatial correlation of 0.8 between modelled and observed precipitation was achieved. This is comparable to other studies (Soares et al., 2012) and was deemed good enough. But in Chapter 5 the onset and intensification, as well as total amount of precipitation was distant from observations. The spatial correlation between modelled and observed precipitation was only 0.2 on average. This could be related to a poor choice of parameterization schemes, though both correlations are far from one, suggesting the model as a whole still requires improvement as well.

Something additional to consider in the development of mesoscale models is the representation of urban areas. The typically used resolution of several hundred meters to a few kilometers is still too coarse to resolve individual buildings and street canyons. Not properly resolving buildings and street canyons might have substantial effects on simulated temperature and wind in a grid cell because of shadow effects and preferential flow patterns. The urban scheme utilized in this thesis is the Urban Canopy Model (UCM) (Kusaka and Kimura, 2004; Kusaka et al., 2001). The UCM is a single layer model which has a simplified urban geometry, so all streets for example face the same direction. Included in the UCM are: shadowing from buildings, reflection of short and longwave radiation, wind profile in the canopy layer and multi-layer heat transfer equations for roof, wall and road surfaces. Nevertheless, local knowledge is indispensable because building styles and materials differ greatly from country to country and city to city. A potential approach toward the resolution of a true urban landscape is to nest a high-resolution large eddy simulation (LES) within WRF (e.g. Liu et al., 2011; Talbot et al., 2012). However, Mirocha et al. (2013) found that nesting a fine LES within a course LES gives better results than nesting it directly in a mesoscale model. In addition, little information exists about the conditions under which such a nesting approach is appropriate, and the results so far have not demonstrated enhanced model performance (Talbot et al., 2012).

In addition, a difference between urban areas in the model and in reality in the Netherlands could come from the modelled percentage of vegetation within urban areas. Even the centers of large Dutch cities, for example, could perhaps best be described as outskirts of metropoles as they occur in other countries, since they have a large share of vegetation and relatively low buildings. As such, the vegetated urban canopy model (Lee, 2011) might be able to make a better representation of cities in the Netherlands, hereby improving simulations on a regional scale. Observational evidence shows that Dutch cities have relatively high evaporation rates (Jacobs et al., 2015). The high evaporation originates from the large share of open water commonly present within cities and a building style (with flat roofs for example) that encourages interception reservoirs that are slow to dry.

Moisture availability from such sources is essential for accurate simulation of precipitation. Chapter 4 in this thesis shows that soil moisture is an important determinant in the amount of precipitation in spring. However, the initialization of soil moisture conditions is often done very coarsely and therefore homogeneous. While in reality soil moisture is known to have a large spatial variation, depending on local soil conditions. For accurate (real-time) predictions soil moisture should therefore be realistically initiated. While we did study the effects of realistic land cover changes in the Netherlands, we did not for example study the effects of large scale improved drainage and increased drinking water extraction. These measures were incorporated on a large scale in both the relatively high and the low lying areas of the Netherlands in the second half of the 20th century. The resulting low groundwater levels are known to have intensified (agricultural and ecological) droughts in the Netherlands (RWS, 1997). Drying of these areas could have affected precipitation, though the positive trend observed during this period does not suggest this.

On the other hand, the Netherlands hosts many polders where water levels are artificially kept at a certain level. Especially in the relatively low lying areas of the Netherlands, this means soil moisture can easily be replenished by groundwater and soils will never actually dry out. Since groundwater is not commonly taken into account in mesoscale models, the modelled soil moisture conditions can easily be too low in the Netherlands. This can be improved by always forcing wet conditions in the model or coupling with a hydrological model. Recently WRF-Hydro has become available, it is a coupling framework designed to link multi-scale process models of the atmosphere and terrestrial hydrology. WRF-Hydro makes use of the Noah land surface model within WRF and includes multi-scale (dis)aggregation, surface, subsurface and channel routing, and ponded water. However, it does not include a direct groundwater-surface water interaction, which would allow upward groundwater flow into the soil from below the currently implemented the free drainage condition at the lower boundary. Modelling fully coupled groundwater-surface water interactions with an interactive atmosphere in the Netherlands would be of great interest, as latent heat fluxes are shown to be sensitive to the groundwater table (Barlage et al., 2015; Maxwell et al., 2010; Seuffert et al., 2002).

From Chapter 2 and other research (e.g. Attema et al., 2014; Buishand and Velds, 1980) it is known that the North Sea strongly influences weather and precipitation patterns in the Netherlands. The North Sea is a relatively shallow water body and the temperature is more variable than deep ocean bodies. In addition, the temperature gradient near the coast can be quite steep and this is not captured well in climate reanalyses. As a reanalysis is used for the initial and boundary conditions of the WRF model, the SST (gradient) could also be unrealistic in the model. Improving this requires more observations and/or a water temperature model for the North Sea. Similarly, the water temperature in

Lake Yssel is likely not well captured by the model because it is such a shallow water body and this could also be improved with a water temperature model.

The imposed temperature perturbation used to simulate climate change in Chapter 5 has been used by others in combination with WRF as well (e.g. Gutmann et al., 2012; Lackmann, 2013; Rasmussen et al., 2011). The approach is called a surrogate climate change scenario (Schar et al., 1996). The approach is simple to apply, and takes advantage of the ability of GCMs to simulate trends compared to absolute climates (Solomon and IPCC., 2007). However, with this approach the effects of changes in large scale circulations are basically neglected, and it therefore does not provide a full picture of climate change. A different and more-often used approach is dynamical downscaling of multiple GCM/RCM combinations. This approach should be considered in further research on this topic, because it helps portray the sensitivity of land use changes in relation to the uncertainties inherent to climate change.

Chapter 7

Summary

In this thesis the effects of the land surface on precipitation were studied. Four research questions were defined in Chapter 1 and addressed for the Netherlands in Chapters 2–5. They are:

1. **Can observed trends in precipitation patterns be related to land surface characteristics?**

2. **Is there evidence of enhanced precipitation downwind of urban areas?**

3. **How does the land surface influence springtime precipitation?**

4. **What is the influence of historic and future land use changes on summertime precipitation?**

To answer the first two questions we made use of station observations of daily precipitation. The latter two questions were answered with the weather research and forecasting (WRF) mesoscale model. For the first question we looked at spatial precipitation trends in the Netherlands and tried to attribute these to differences in the land surface (Chapter 2). The second question focused on the West coast of the Netherlands, that hosts most of the major cities in the country. We studied differences in precipitation characteristics at stations downwind of urban areas compared to stations in the rest of the area (Chapter 3). To understand the underlying processes we use the WRF model for a multiple day case study (Chapter 4) and several single-day cases (Chapter 5). Both the third and fourth question involved making changes to the land cover maps, for example extending urban areas in the Netherlands. For the fourth question, high resolution land use maps were incorporated into WRF, with historical, present, and future land cover in respectively 1900, 2000 and 2040.

7.1 Precipitation patterns and trends

Mean annual precipitation in the Netherlands is currently about 850 mm and varies spatially from 675 to 925 mm. Higher than average precipitation amounts are observed in certain regions, such as the Veluwe and the southernmost, elevated, part of the country. In spring and autumn, a distinct, but reversed, difference between precipitation near the coast and precipitation further inland exists. In spring (autumn) rainfall is more abundant inland (along the coast). Over the period 1951-2009 precipitation has increased by almost 16%. The largest increases, up to 35%, occurred in spring and winter, while there was hardly any increase in summer. In Chapter 2 we try to link the coincidence of trends in precipitation patterns with specific land surface characteristics: soil type, topography and urbanization.

The Netherlands has four major soil types: sand, clay, loam and peat. Clay and loam are mainly present along the seacoast and the (former) courses of the major rivers: Rhine and Meuse. Peat has been excavated in major parts of the country, but is still present in the North and the West, while sandy soils are dominant in the East and South of the country. The soil information was combined with average precipitation and altitude data to create a map with distinct regions. However, correlations between precipitation trends and surface characteristics were found to be very small. Distance to the coast turned out to explain more of the variance in the dataset than any of the investigated surface characteristics. This suggests the increase of sea surface temperatures over the last decades had the largest influence on precipitation and the observed trends are not related to land surface characteristics. The largest differences between precipitation trends in various regions were observed from April to July, making this an interesting period for further investigation. This has been done with the WRF model in Chapter 4.

7.2 Observed urban effects

Urbanization was included in the analysis in Chapter 2 in a very simplified way by calculating the fraction of urban area within a 5 km radius around each station. No differences in trends were found between stations classified as urban or rural in this way. However, from literature it is known that urban effects mainly occur downwind of cities at a greater distance. Typical methods to investigate urban effects cannot be used in the Netherlands, because of the small size and mutual proximity of cities. Therefore, in Chapter 3 an innovative methodology investigating precipitation downwind of urban areas was developed and used for the West coast of the Netherlands. The methodology considers urban areas up to 20 km upwind of precipitation stations to distinguish the stations as urban or rural. We only did the analysis for the West coast because most of the major cities in the Netherlands are located there. In addition, it would have been inappropriate to investigate urban effects for the Netherlands as a whole, because the mean climatology as well as trends in precipitation show a large dependency on distance to the coast (Chapter 2).

The results show a very consistent, though not significant, picture of increased precipitation downwind of urban areas. This means there is a positive urban effect. Depending on wind direction and time period, enhancements of up to 20% are found. Only under easterly wind directions a negative urban effect is sometimes observed. Easterly winds occur relatively little however and the associated precipitation amounts are generally low, so this has limited influence on the mean. The average urban enhancement over the 1950-2010 period is about 7%, while the enhancement of extreme precipitation was about 10%. In all, considering the numbers here and the much larger trends observed (Chapter 2), it is unlikely that urban areas are a major cause of the observed increase in precipitation. Although they might have contributed to the high precipitation trends observed near the coast. Overall, the largest positive urban effects were found under light flow (no clear wind direction) and low wind speeds. These conditions were therefore sought after in the selection of case studies for the WRF model in Chapter 5.

7.3 Land-atmosphere interactions

Understanding the impact of the land surface on precipitation is easier with the use of a model than when analyzing data, because systematic changes can be made and their effects investigated. In Chapter 4 we use the WRF model to quantify the soil moisture-precipitation feedback in the Netherlands for a 4-day period in spring. Springtime was selected because of the apparent influence of the land surface on precipitation, and because the largest idfferences between trends in various regions were observed (Chapter 2). The influence of the land surface in spring is visible in the low amounts of coastal precipitation and higher amounts of inland precipitation. This spatial difference occurs because precipitation is only triggered after air has travelled over land for several kilometers and has sufficiently warmed.

Model simulations with five different soil moisture initializations were conducted, in addition to a simulation where all urban areas in the Netherlands were removed, and two where urban areas were expanded. A consistent soil moisture-precipitation feedback was found in the simulations. That is, wet (dry) soils increase (decrease) the amount of precipitation. Consistently, as urban areas are very dry in WRF, expansion of urban areas led to a decrease of precipitation. Changes in the spatial distribution of precipitation were too chaotic to derive any conclusions from regarding local urban effects.

The strength of the soil moisture-precipitation feedback was quantified with the ratio of evaporation to precipitation. With linear regression this ratio was estimated to be about 67% in the soil moisture experiments and 23% in the urbanization experiments. The ratio is smaller in the urbanization experiments because the temperature and sensible heat flux are relatively high in urban areas. This affects the overhead and downwind boundary layer, effectively increasing the potential for cloud formation and triggering of precipitation. As a result, the same change in evaporation gives a smaller precipitation reduction in the urbanization experiments and a lower feedback strength. In the experiments, the impact of soil moisture (availability) is larger than the impact of urban areas on precipitation. Overall, the land surface influences springtime precipitation amounts through evapotranspiration and influences the triggering of precipitation through changes in the atmospheric boundary layer.

7.4 Historic and future changes

In Chapter 5 a selection of 19 day-long cases was made to investigate historic and future land use changes in summer. The WRF model simulated a decrease in precipitation after conversion from historic to present land use, as well as from present to future land use. This is consistent with the reduction of precipitation found in Chapter 4 after expanding urban areas. The effects of urban areas seem to be twofold however, as both a local increase and a countrywide decrease are simulated. With observations it is shown that precipitation has increased by about 25% in the last century, but the trend in the summer months was only about 5% (Chapter 2). So the countrywide reduction of summer precipitation simulated with the WRF model might have taken place in reality and mitigated some of the externally forced increase in precipitation. Hence a small increase was observed in summer. No conclusive evidence was found for the consequences of land creation in Lake Yssel.

Future precipitation was simulated with a surrogate climate change scenario by imposing a +1°C temperature perturbation while keeping relative humidity constant. Without land use changes, a precipitation increase of 7-8% was simulated. This increase is consistent with the expected increase in near surface humidity of about 7% K^{-1} derived with the Clausius-Clapeyron equation. Hourly precipitation extremes were found to increase by 10-20%. When also considering land use changes, however, the precipitation increase was only 2-6% and no longer observed in extreme precipitation. The increase in extreme precipitation due to climate change was completely negated by the simulated changes in land use. So although the precipitation response to land use changes is smaller than the response to climate change, it is not negligible in the summer period in the Netherlands. This might be especially true for precipitation extremes and this requires further investigation.

Appendix A

Synoptic circulation classification

Several chapters of this thesis make use of a synoptic weather classification in order to make smart selections of cases and/or be able to generalize results. Classification of weather and atmospheric circulation states is a widely used tool for describing and analyzing weather and climate conditions. A classification algorithm transfers multivariate information, e.g. time series of daily pressure fields, to a univariate time series of a fixed number of weather types. The advantage of such a substantial information compression is the straightforward use of these weather types. A database of such classification catalogs and software package, called cost733class, have been developed (Philipp et al., 2010, 2014) and are utilized in this thesis. Philipp et al. (2014) find large dissimilarity between the methods which means that finding a suited classification for a certain purpose for practice in synoptic climatology may require a broad comparison of methods.

To find a suitable classification, a comparison was conducted using all 234 whole year, single day classifications in the cost733cat database for domain 00 (entire Europe i.e. 37°W to 56°E and 30 to 76°N). The cost733cat database is based on the ERA40 reanalysis dataset (Uppala et al., 2005) and is available for the period 09-1958 to 08-2002. A chi-squared test was conducted on all of the classifications for a range of minimum precipitation and the number of stations at which this precipitation is measured using the daily gauge measurements from 240 stations. The choice of the best classification turned out to be quite insensitive to the number of stations and more sensitive to the amount of precipitation. For the range of 1-38 stations and 10-37 mm precipitation, one classification scheme was consistently the best and it fell within the top five outside this range. The classification that was therefore chosen is the Jenkinson-Collison Types (JCT) classification scheme. This type of classification is more of an air mass classification than a weather classification, because it does not take individual stations surface based observations into account. The scheme was run for a domain centered around the Netherlands with ERA40 and ERA-Interim (Dee et al., 2011) data and the overlapping period was compared. The JTC scheme seems to be sensitive to the input dataset, because 20% of the days were classified differently with the other input data. To retain internal consistency different datasets are used as input for the classification scheme throughout this thesis.

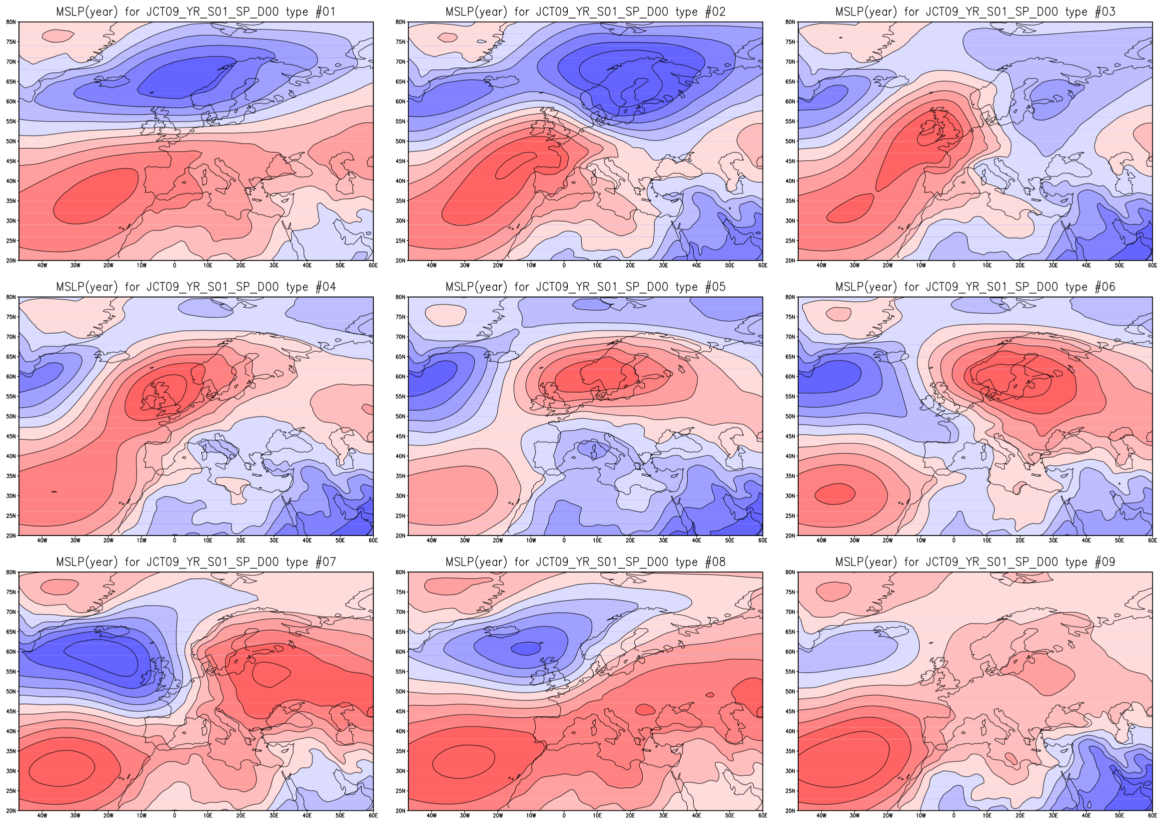

Figure A.1 Mean sea level pressure (MSLP) patterns for Jenkinson-Collison Types weather types 1-9.

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