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Climate change signal of future climate projections for Aachen, Germany, in terms of temperature and precipitation

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Abstract

A multi-model ensemble of regional climate projections is used to estimate the climate change signal in terms of temperature and precipitation for the city of Aachen, Germany, until the end of the current century. Since the combination of heat and high moisture content in the ambient air is assumed to adversely affect human health, the equivalent temperature is employed as an indicator for heat stress and applied to identify heat waves. As prolonged periods of high temperatures may also cause summer drought, summer precipitation and dry periods are analyzed as well.

The study refers to regional climate projections (A1B emission scenario) of the statistical climate models STARII and WETTREG and the dynamical climate models REMO and COSMO-CLM. The model outputs are compared a) with each other in order to assess discrepancies between them and b) with the 30-year baseline period of 1971–2000 in order to estimate future changes in heat load and precipitation patterns for the summer months of June, July and August.

Based on median realizations of the model runs, further warming of approximately 1–2 K is expected by the middle of the 21st century and 3–4 K by 2100. These changes will probably be accompanied by an increase in variance. Maximum temperature shows the greatest enhancement (+1.9 K 2031–2060 and 4.3 K 2071–2100, ensemble mean) causing almost a doubling of (extreme) hot days and a trebling of tropical nights as soon as the middle of the century. According to this temperature development heat waves are likely to last longer and occur more often in future whereas their intensity is not expected to change significantly.

An increasing number of heat waves is concurrent with a decreasing amount of rainfall in the summer months until 2100. All four climate projections indicate a decrease in precipitation in summer until 2100 with −17 % on average. The highest decrease is shown by COSMO-CLM with −30 % rainfall in June for the period of 2071–2100. Dry periods are expected to occur 3 times more often at the end of the current century and to last longer by 1 day (COSMO-CLM) to 3 days (WETTREG) compared to the period of 1971–2000.

Keywords: Climate Change, Air Temperature, Temperature Extremes, Precipitation, Aachen

1 Introduction

Since the end of the 19th century global warming has been detected by observational data (Folland et al., 2001). Global and regional climate projections indicate a continuation or even aggravation of rising temperatures in the 21st century (IPCC, 2007). As long-term observations have proven, annual mean temperatures rose by +0.9 K during the period of 1901–2006 in Germany (Müller-Westermeier, 2007) Almost the same temperature change (∼ +1 K) is projected for COSMO-CLM and REMO (A1B) simulations by the middle of the current century (baseline 1971–2000) (Wagner et al., 2013). A slightly higher increase (+1.68 K) was detected for North Rhine-Westphalia by Spekat et al. (2006) who examined climate scenarios from the model STAR for the period of 2046–2055 compared to 1951–2000. By the end of the century (baseline 1961–1990) a further temperature rise of +2.3 K (WETTREG, Spekat et al. (2007)) to +4 K (REMO, Jacob et al. (2008)) can be expected.

Rising mean temperatures are likely to be accompanied by an enhanced probability of extreme events (Mearns et al., 1984; Balling et al., 1990; Wigley, 2009). Particularly heat waves are a threat to human health and well-being since humans react more sensitively to prolonged exposure to heat than to isolated hot days (Tan et al., 2007; Gosling et al., 2009). Various studies show that heat waves are going to be intensified and last longer in future (Meehl and Tebaldi, 2004; Della-Marta et al., 2007). Especially high night temperatures that hamper relief at night may provoke cardiovascular diseases or fatalities. Urban residents are particularly vulnerable to heat since high temperatures are exacerbated by the urban heat island (Oke, 2001).

Keeping in mind the ongoing global urbanization trend – indicating a growing number of people living in urban areas – (United Nations Population Division, 2012), cities must play a major role in local mitigation and adaptation to climate change.

Previous investigations concerning the urban climate of Aachen (Havlik, 1981; Emonds, 1986; Ketzler,

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1997; Havlik and Ketzler, 2000; Havlik, 2002; Buttstädt et al., 2010a; Buttstädt et al., 2010b) were based on observations and aimed at investigating options for urban planning.

The present study addresses upper extremes to quantify unusually high temperature levels. In order to examine these events in more detail this study investigates the corresponding probability density functions and their possible changes in mean and variance. An analysis is made of the present and future development of temperature extremes – including the frequency, duration and intensity of heat waves – because of their relevance for societal impacts such as public health issues. Since heat waves may also have an impact on urban vegetation, agriculture and forestry (Ciais et al., 2005) an investigation on summer precipitation will take the relevance of summer drought incidences into account. Especially for Aachen where 41 % of the land is used for agriculture and 19 % is covered by forest (Stadt Aachen, 2010), it is not only knowledge about future temperature scenarios that is of great importance but also estimates on precipitation that may provide a crucial input for the redevelopment of cropgrowing strategies and the choice of tree species that will be planted in future.

Section 2 presents the study area and its meteorological characteristics. An overview of the data upon which this study is based as well as a comparison between observed data and the climate projections is given in section 3. Section 4 follows with a method description of the analysis of temperature and precipitation changes. In section 5 there are future estimates of air temperature and precipitation with regard to heat waves and dry periods. The study closes with a discussion and prospect for further research options.

2 Area of investigation

The city of Aachen is situated at the borders to Belgium and the Netherlands in North Rhine-Westphalia, Germany. With a size of approximately 160 km^2 and 250,000 residents (Stadt Aachen, 2010) the urban area stretches between a low mountain range in the south, the Eifel, and the German lowlands in the north. The basin location of Aachen with differences in altitude of up to 285 m poses a problematic situation for the city and its residents with regard to heat accumulation in the warm season during situations with low wind speed.

The prevailing wind direction is typically southwest, often causing foehn effects as in this case Aachen lies in the lee of the southern adjoining highlands. The air masses pass the low relief of Belgium and the Netherlands without significant modification so that the climate of Aachen is almost as maritime as the Dutch coast.

As described by Buttstädt et al. (2010a) for the period of 1980–2009, average annual rain- and snowfall amount to 908 mm with the highest precipitation in December (87 mm) and the lowest in April (63 mm). Highest mean air temperatures are reached in the summer months of July (18.5 °C) and August (18 °C). Buttstädt et al. (2010a) also report an increasing frequency of heat waves for the period of 1980–2009 whereas their duration and intensity have not changed significantly within the last 30 years.

3 Data

3.1 Climate observations

A reliable long-term set of observations is obtained from a weather station (WS) operated by the German Weather Service (*Deutscher Wetterdienst*, DWD) in order to analyze the present climate and to verify the accuracy of the regional climate models. Approximately 600 m northeast of the inner city of Aachen this station is situated on the lowest of three hills (50° 47′ N, 06° 5′ E, 202 m a.s.l.) within the Aachen basin. In the park-like surroundings there are no buildings in its vicinity. Although the choice of this station causes problems due to its location on the summit of a small hill with high trees nearby and encircling buildings 200 m away, this station is assumed to be representative for the climate of Aachen. Various meteorological data allow for an extensive evaluation of climate variability in the research area since the end of the 19^{th} century. Such a contiguous data set that is subject to regular controls of the quality standards of its measurements is a crucial precondition for the detection of changes in the frequency of extreme events (Della–Marta and Beniston, 2008).

3.2 Regional climate projections

Estimations of the climate development are based on simulations of regional climate models (RCMs). RCMs have already been applied since the beginning of numerical weather forecasts and have been established as a common method in climate research since the 1990s (Gobiet and Truhetz, 2008). Four German RCMs were available for this study, of which two are based on a statistical approach and two on a dynamical one (Tab. 1).

Statistical models are based on statistical coherencies between large- and small-scale atmospheric processes. They are based on the assumption that the climate characteristics and determined relations from past or present situations will not change significantly within the next decades. Thus, they do not necessarily represent the new extreme values in a changing future so that statistically generated future projections are subject to limitations (Murphy, 1998). Advantages of this model type are the relatively fast calculation times since only little processing power is required and hence, a larger number of model runs can be carried out (Kropp et al., 2009). The two statistical downscaling schemes used in this study are STARII (Orlowsky et al., 2008) and WETTREG (Spekat et al., 2007). Both models provide daily values of meteorological data as point information regarding the location of WS DWD. Projections for STARII are generated by recomposing observed annual means

Table 1: Regional climate models for the area of Aachen.

	Dynamical		Statistical	
	COSMO-CLM	**REMO**	**STARII**	**WETTREG_2010**
Domain	Extended „BALTEX"-region	Europe	Germany	Germany
Developer/operator	CLM community	MPI, Hamburg	PIK, Potsdam	CEC, Potsdam
Spatial resolution	0.167° × 0.167° (~18 km)	0.088° × 0.088° (~10 km)	station specific	station specific
Simulation period	Until 2100	Until 2100	Until 2060	Until 2100
GCM	ECHAM5/MPI-OM	ECHAM5/MPI-OM	ECHAM5/MPI-OM	ECHAM5/MPI-OM
Available scenarios	A1B, B1	A1B, A2, B1	A1B, A2, B1	A1B
Realizations	Median-realization elected out of 3 model runs. Data provided by the World Data Center for Climate (WDCC), http://www.mad.zmaw.de/wdc-for-climate	One out of 2 available model runs elected. Data provided by WDCC	Median-realization provided by PIK	Median-realization elected out of 10 model runs. Data provided by WDCC
Data	Lautenschlager et al. (2009)	Jacob & Mahrenholz (2006)	Gerstengarbe & Werner (2011)	Kreienkamp et al. (2010)

at WS DWD with regard to the future temperature trend derived from the global climate model ECHAM5/MPI-OM. The measured daily means are taken and the differences to the annual mean is calculated and assigned to the corresponding year of the simulation. Days with similar combinations of observed meteorological parameters are clustered and related to the same cluster type of the simulated time series and further to an ascertained day within this cluster. This approach allows all meteorological information of a single day to be transferred to the future simulation. Since the model results are aligned to the annual temperature trend, deviating seasonal trends cannot be determined (Werner and Gerstengarbe, 1997).

WETTREG is based on a resampling scheme that assembles and recombines present periods of distinct weather patterns and adapts them to the given frequency distribution of weather types for the future (derived from ECHAM5/MPI-OM). Thus, every day of the simulation is assigned to weather types of a certain temperature and humidity regime. Furthermore, weather types which could not or only seldom be observed in the past are considered so that the model is strongly adapted to the input of the global climate model. Outputs are prepared as daily values which are representative for one decade (Spekat et al., 2007).

Dynamical downscaling models incorporate the dynamics of physical and chemical atmospheric processes and are embedded in a GCM which provides the initial and boundary conditions (Murphy, 1998). Relevant physical processes are calculated dynamically. Subscale processes are computed by physical parameterizations. The smaller the mesh size the longer the computing time so that multiple realizations are often not feasible for regional scale. The two dynamical RCMs used for the area of Aachen can be characterized as follows:

REMO (Jacob et al., 2008) is based on a hydrostatic approach and covers a domain from 5.95/50.65 (lat/lon, lower left corner) to 6.25/50.85 (lat/lon, upper right corner) with a spatial resolution of 10 km. Data from the global climate model ECHAM5/MPI-OM are used as initial and boundary conditions for a model region with a horizontal resolution of 50 km. Outputs of this experiment are then used as initial and boundary conditions for a smaller model domain (spatial resolution of 10 km) comprising Germany, Austria and Switzerland.

The model domain of COSMO-CLM (CLM Community, 2011), which is based on a non-hydrostatic approach, was extracted from 5.8/50.6 (lat/lon, lower left corner) to 6.4/51.0 (lat/lon, upper right corner) with a spatial resolution of 18 km. Compared to REMO, the non-hydrostatic approach allows the consideration of vertical velocity of air masses and thus of convective processes.

Data for the dynamical models was averaged over a 4×3 grid around the WS DWD (Fig. 1). The selection of the grid points is based on findings by Kendon and Rowell (2007) who determined that a spatial pooling of 3×3 grid points is effective at reducing grid-box noise. With 4×3 grid points the model region was slightly enlarged in order to properly center the city of Aachen within that region. Daily temperature and precipitation values are provided as average amounts per grid box.

For this study the median realizations of all available model runs of the different RCMs for the emission scenario A1B are used for further evaluation (Tab. 1). Since for all RCMs a different number of model runs were available, the realization which represents the median

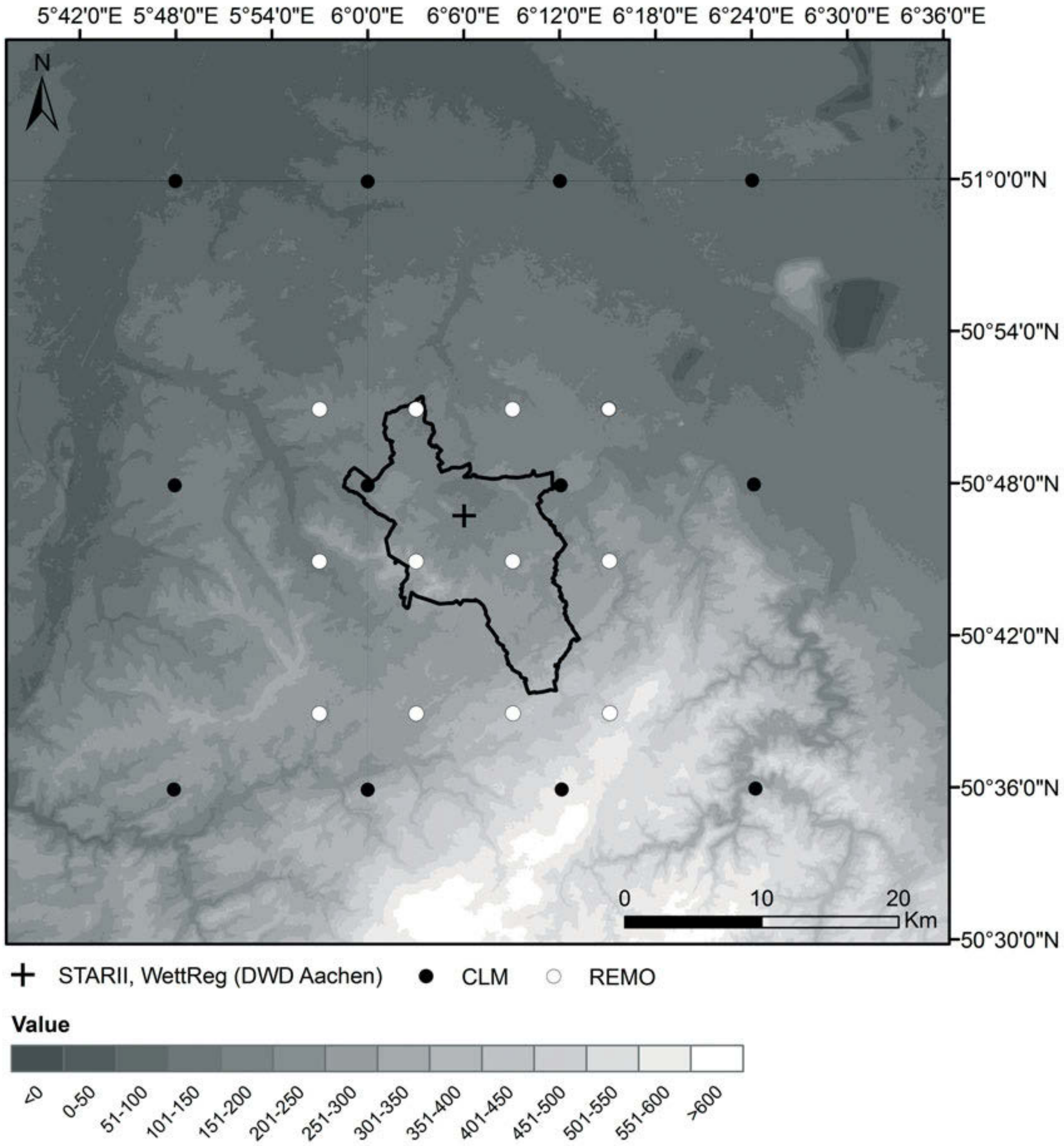

Figure 1: Domains of the regional climate models COSMO-CLM, REMO, STARII and WETTREG. The cross indicates the position of the DWD weather station within the urban area. Altitudes below sea level refer to open pit mines.

in terms of temperature change signal out of all available model runs of the respective model, was chosen. For STARII the median-realization for Aachen was provided by the Potsdam Institute for Climate Impact Research. The realizations for WETTREG, COSMO-CLM and REMO were downloaded from the world data center for climate. For WETTREG, 10 realizations were available from which the median was selected. For COSMO-CLM 3 realizations were available from which the median was selected. For REMO only 2 realizations were available so that we chose one of them.

3.3 Comparison of the RCMs with regard to temperature and precipitation

In order to assess future climate conditions, the RCMs were checked for their reproducibility of the current climate.

Average daily maximum (T_{max}), mean (T_{mean}) and minimum (T_{min}) summer temperature from temperature records (WS DWD) were compared to the climate projections for the period of 1971–2000 (Fig. 2, left). For daily T_{max}, T_{mean} and T_{min}, the dynamical models COSMO-CLM and REMO slightly underestimate the median value at WS DWD while the statistical models STARII and WETTREG are in good accordance with the observations. The latter can be ascribed to the fact that observations serve as input data for the statistical models. As indicated by the whiskers of the boxplots lower values of air temperature are generally overestimated by REMO and WETTREG while the other models show a rather good accordance except for the underestimated values of T_{max} computed by COSMO-CLM. The upper tail of the corresponding distribution is generally rather underestimated by REMO, COSMO-CLM (except T_{max}) and WETTREG. The length of the

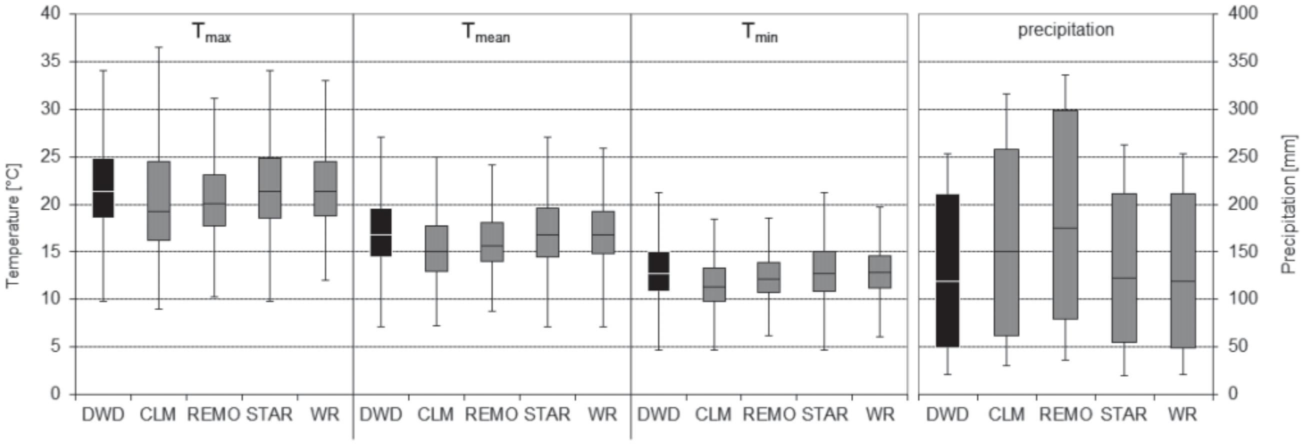

Figure 2: Comparison of daily T_{max}, T_{mean} T_{min} and precipitation sums between regional climate projections (COSMO-CLM, REMO, STAR II and WETTREG) and observations obtained from the WS DWD for the summer months (JJA) during the control period of 1971–2000. Boxes show the interquartile range (IQR), which is defined by the lower (Q_L) and upper quartile (Q_U) and include the median value of the data population. Whiskers extend to the adjacent value, which is the most extreme data value within a range of $Q_L - 1.5 * IQR$ and $Q_U + 1.5 * IQR$

whiskers and the interquartile range also provide an indication of dissimilarities in variance, namely a larger data spread for, for example, T_{max} obtained from COSMO-CLM and a slightly smaller one for all temperature parameters calculated by REMO.

Analog to the temperature analysis, observed daily precipitation sums at WS DWD were compared to the climate projections for the period of 1971–2000 (Fig. 2, right). The comparison of the RCMs for summer precipitation shows good accordance between the statistical models STARII and WETTREG and the observational data, whereas the dynamical models COSMO-CLM and REMO produce more rainfall.

Concerning the characteristics of a heat wave, the model estimates represent the observations quite well on average (WS DWD: heat wave duration: 3.6 days per year, frequency: 1 heat wave in 2 years, intensity: 59.3 K [T_{eq}]). Deviations of +0.2 days (COSMO-CLM) and −0.2 days (WETTREG) can be detected within the control run for the duration of a heat wave. The frequency is slightly underestimated by COSMO-CLM (−0.1 days per year) and slightly overestimated by WETTREG (+0.2 days per year) and the intensity differs from +1.1 K (WETTREG) to +2.7 K (COSMO-CLM).

Dry periods are calculated from observations at WS DWD for the period of 1971–2000 as follows: Dry periods last 15.6 consecutive days on average and occur 3 times every 2 years. For all regional climate models, except STARII, the occurrence of dry periods is considerably underestimated and ranges between −1.1 (REMO) and −0.9 (WETTREG) events per year between 1971 and 2000. The duration is underestimated as well – even though to a smaller degree (−2.5 (REMO) to −1.5 (COSMO-CLM) days).

4 Examination of the climate change signal

The general temperature trend for Aachen until the end of the current century is computed using the median realizations from the available data sets of the regional climate models STARII, WETTREG REMO and COSMO-CLM. The annual temperature is calculated as 30 year running averages for the period of 1960–2100 (Fig. 3).

Further temperature and precipitation assessment uses the summer months only. The data is examined with regard to the baseline period of 1971–2000, the medium time perspective (2031–2060) and the long term (2071–2100).

Temperature changes are further quantified by the frequency of special days until the end of the current century. Calculated are summer days ($T_{max} \geq 25$ °C), hot days ($T_{max} \geq 30$ °C), extreme hot days ($T_{max} \geq 35$ °C) and tropical nights ($T_{min} \geq 20$ °C).

In order to examine future temperature extremes for June, July and August the frequency distribution of the respective time series and its changes are analyzed in more detail. To attain independence from random features in the sample, a probability density function (PDF) that specifies the probability for certain values of the associated population (Jonas et al., 2005) is adjusted to the empirical frequency distribution of T_{max}. Given that the data do not represent a Gaussian normal distribution (tested by Kolmogorov-Smirnoff test and Lilliefors test (Wilks, 2011)) non-parametric distributions were fitted to the model data.

As changing mean temperatures and changes in variance affect the probability of extremes, prolonged periods of high summer temperatures are considered in terms of heat wave duration, frequency and intensity.

Although the term 'heat wave' is frequently used in the general population and in scientific discussion there is no universal definition that quantifies its duration and intensity in general. Even the parameters used to identify a heat wave are not standardized (Robinson, 2001).

Since the combination of heat and high moisture content in the ambient air is assumed to adversely affect human health (Havenith, 2005; D'Ippoliti et al., 2010) the equivalent temperature (T_{eq}) – a measure of relative discomfort – is employed in this study as an indicator for heat stress and further applied to identify heat waves (after Höppe, 1986)

$$t_{eq} \approx t + 2.5\mu \qquad (4.1)$$

where $10^3 * \mu$ (mixing ratio) is related to the vapor pressure (e) and pressure (p) by

$$\mu = 0.622\frac{e}{p-e} \qquad (4.2)$$

Furthermore, T_{min} is incorporated because high nighttime temperatures may pose a serious health risk especially for elderly people. Hence, a heat wave is defined as a sequence of at least 3 consecutive days during which the daily T_{eq} does not fall below 49 °C and T_{min} is not lower than 18 °C. The critical threshold of $T_{eq} = 49\,°C$ for sultriness was chosen according to Höppe (1986). Fixed values for T_{eq} and T_{min} are used as thresholds in order to ensure that events of a comparable intensity are examined.

Since increasing summer heat in combination with decreasing precipitation is likely to negatively affect agriculture and forestry, changes in summer precipitation are investigated additionally.

After the definition of Hänsel et al. (2005) sequences of at least 11 consecutive days with a daily amount of precipitation of less than 1 mm are regarded as dry periods. The calculation of the difference in the number of dry periods and average dry period duration was performed by taking the changes from the model runs and adding these to the number of dry periods and the duration of dry periods as observed in the control period at WS DWD.

5 Results

5.1 Temperature change and heat waves

The regional climate projections suggest a further warming of approximately 1–2 K by the middle of the 21st century and 3–4 K by 2100 with respect to 1971–2000 (trends are statistically significant; tested by Mann-Kendall test (Mann, 1945; Kendall, 1970)) (Fig. 3). The projections conform to future estimations for North Rhine-Westphalia and Germany, respectively (Spekat et al., 2006; Kropp et al., 2009). With regard to the climate model experiments in the scope of the PRUDENCE project (Christensen and Christensen, 2007), Aachen's temperature rise is equivalent to the central European average at least on the basis of the two dynamical RCMs COSMO-CLM and REMO.

In the following the focus is on summer temperatures only since exceptionally high temperatures are likely to pose a risk for human's well-being and consequently stress the urgency of detailed investigations on temperature extremes. The evaluation of the multi-model ensemble reveals a considerable temperature rise in T_{max}, T_{mean} and T_{min} (Tab. 2a). T_{max} shows the greatest enhancement (+1.9 K 2031–2060 and +4.3 K 2071–2100, ensemble mean) compared to 1971–2000 with highest values generated by WETTREG (+2.8 K 2031–2060 and +5.2 K 2071–2100). The outputs of REMO suggest the smallest temperature increase (+1.2 K 2031–2060 and +3.2 K 2071–2100).

T_{min} increases less than T_{max} with highest values produced by WETTREG for the medium-term perspective (+1.8 K 2031–2060). By the end of the century COSMO-CLM and WETTREG show the highest temperature increase (+3.1 K) compared to the control period.

Taking the median realizations of the model ensemble into consideration, a mean temperature rise of approximately +1.6 K (Tab. 2a) by 2031–2060 will probably lead to an increase in summer days which are expected to occur about 1.5 times more often than at the end of the last century (Tab. 2b) Hence, about 35 summer days are expected to occur in the medium-term perspective (WS DWD: 23 summer days per year between 1971 and 2000). The number of (extreme) hot days is likely to double and almost a trebling of tropical nights is expected. Until the end of the century the highest increase in summer days, hot days and tropical nights are projected by WETTREG while the lowest increase is generated by REMO.

An investigation of the monthly estimates of T_{mean} and T_{max} shows the highest temperature increase for WETTREG in summer (Fig. 4). For the medium term perspective (2031–2060) results from the statistical models STARII and WETTREG reveal that the highest temperature rise occurs in June and July for both, T_{mean} and T_{max}. The ouputs of REMO and COSMO-CLM suggests the highest increase to be most likely in August. By 2100, the projection for WETTREG shows the highest temperature increase in July while REMO and COSMO-CLM show the greatest rise in August.

The ongoing trend towards higher mean T_{max} (Tab. 2a) is displayed in terms of a probability density function which also indicates increased variance until the end of the 21st century in figure 5. The average maximum temperatures constantly rise for all model simulations until 2100. An accelerated temperature enhancement for the second half of the century is produced by COSMO-CLM. A shift in mean T_{max} to higher values entails pronounced changes in the frequency of extreme events (Mearns et al., 1984; Balling et al., 1990;

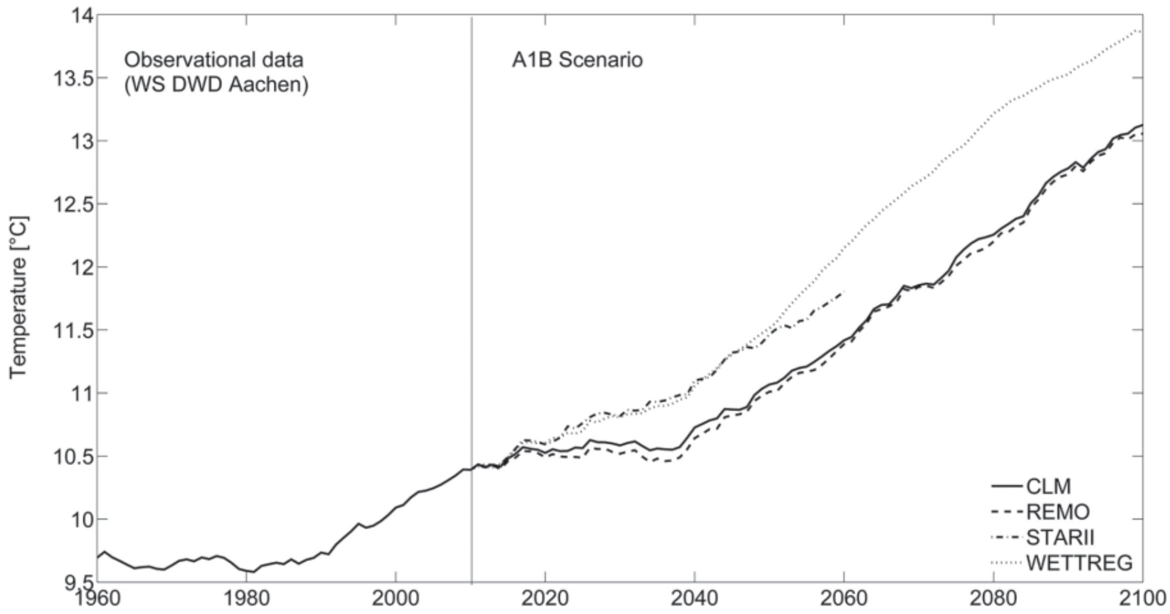

Figure 3: Development of the annual mean temperature for the period of 1960–2100 (30-year running average). Dashed and dotted lines present future scenarios analog to the IPCC SRES scenario A1B for the median realizations of the RCMs COSMO-CLM, REMO, STARII and WETTREG.

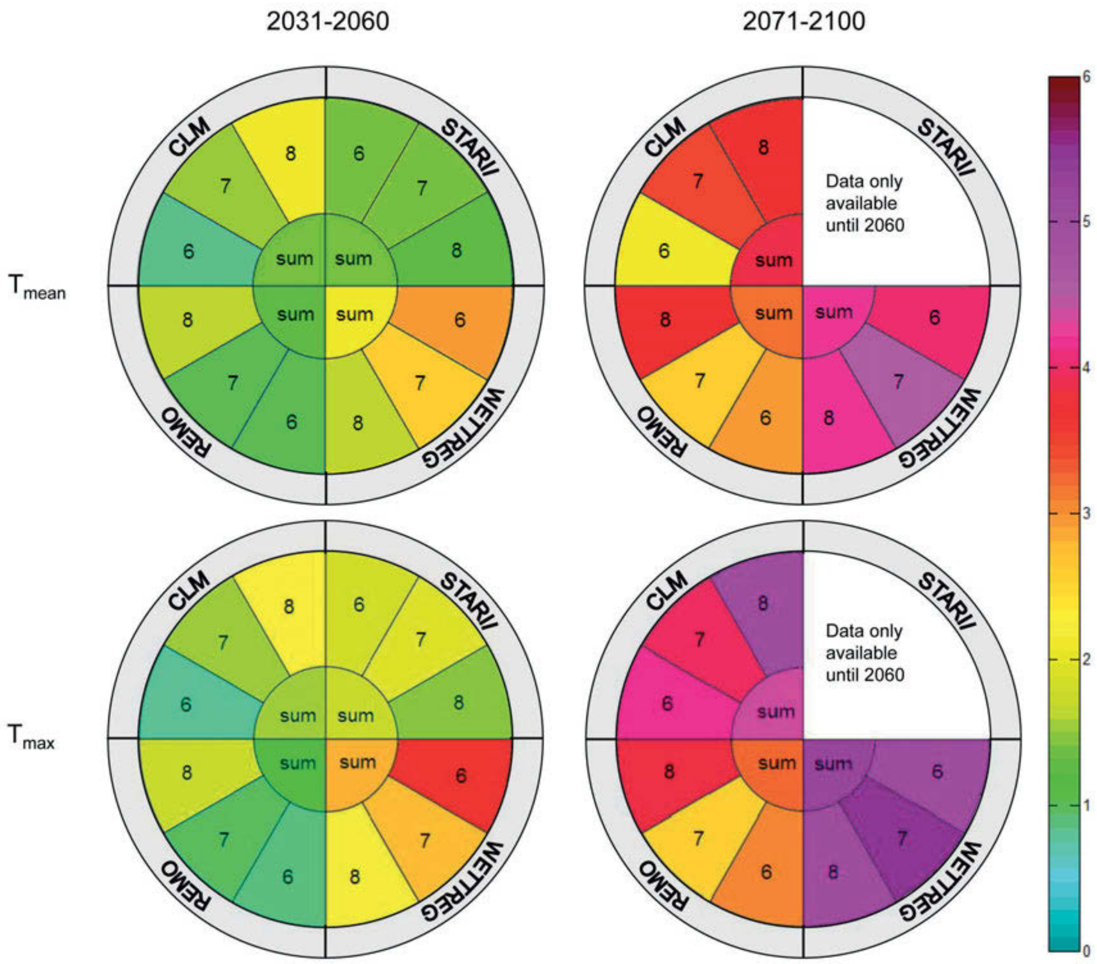

Figure 4: Changes in T_{max} (lower row) and T_{mean} (upper row) [K] for the months June (6), July (7) and August (8) of 2031–2060 (left column) and 2071–2100 (right column) each compared to 1971–2000.

Table 2: Calculated values for the summer months of June, July and August for the control period of 1971–2000 and the future periods of 2031–2060 and 2071–2100 based on the median realization of the different RCMs for the A1B scenario. Values in brackets indicate relative changes compared to the control period (1971–2000). The values of the ensemble mean for the control period show the mean values for all 4 RCMs and without the RCM STARII. The latter is also added to allow for an exact comparison for the future period of 2071–2100 for which no projection for STARII is available.

a) Present and future average values for T_{max}, T_{mean} and T_{min} [K]
b) Number of summer days, (extreme) hot days and tropical nights per year
c) Future estimates on duration (days per year), frequency (events per year) and intensity (K,T_{eq}) of heat waves for the projections of COSMO-CLM and WETTREG
d) Future estimates on duration (days per year) and frequency (events per year) of dry periods (at least 11 consecutive days with a daily amount of precipitation of at most 1 mm)

Period	**Parameter**	**COSMO-CLM**	**REMO**	**STARII**	**WETTREG**	**Ensemble**
a) Temperature change						
1971–2000	T_{max}	20.7	20.6	21.8	21.8	21.2/21.0
	T_{mean}	15.7	16.3	17.1	17.1	16.6/16.4
	T_{min}	11.6	12.5	12.9	12.9	12.5/12.3
2031–2060	T_{max}	22.3 (+1.6)	21.8 (+1.2)	23.5 (+1.7)	24.6 (+2.8)	23.1 (+1.9)
	T_{mean}	17.2 (+1.5)	17.5 (+1.2)	18.6 (+1.5)	19.5 (+2.4)	18.2 (+1.6)
	T_{min}	12.9 (+1.3)	13.8 (+1.3)	14.0 (+1.1)	14.7 (+1.8)	13.9 (+1.4)
2071–2100	T_{max}	25.1 (+4.4)	23.8 (+3.2)	–	27.0 (+5.2)	25.3 (+4.3)
	T_{mean}	19.5 (+3.8)	19.4 (+3.1)	–	21.4 (+4.3)	20.1 (+3.7)
	T_{min}	14.7 (+3.1)	15.5 (+3.0)	–	16.0 (+3.1)	15.4 (+3.1)
b) Special days						
1971–2000	Summer days	21.2	14.6	22.9	20.8	19.9/18.9
	Hot days	8.3	2.5	4.5	2.7	4.5/4.5
	Extreme hot days	1.7	0.1	0.2	0.1	0.5/0.6
	Tropical nights	0.4	0.8	1.0	0.8	0.8/0.7
2031–2060	Summer days	29.2 (+8.0)	21.2 (+6.6)	34.8 (+11.9)	43.1 (+22.3)	32.1 (+12.2)
	Hot days	12.1 (+3.8)	4.1 (+1.6)	9.0 (+4.5)	10.4 (+7.4)	8.9 (+4.4)
	Extreme hot days	3.2 (+1.5)	0.2 (+0.1)	0.7 (+0.5)	0.3 (+0.2)	1.1 (+0.6)
	Tropical nights	1.8 (+1.4)	2.2 (+1.4)	2.0 (+1.0)	4.5 (+3.7)	2.6 (+1.8)
2071–2100	Summer days	42.8 (+21.6)	32.2 (+17.6)	–	62.8 (+42.0)	45.9 (+27.0)
	Hot days	23.0 (+14.7)	10.0 (+7.5)	–	24.8 (+22.1)	19.3 (+14.8)
	Extreme hot days	8.4 (+8.0)	0.9 (+0.8)	–	2.3 (+2.2)	3.9 (+3.3)
	Tropical nights	6.9 (+6.5)	6.6 (+5.8)	–	9.0 (+8.2)	7.5 (+6.8)
c) Heat waves						
1971–2000	Duration	3.8	–	–	3.4	3.6
	Frequency	0.3	–	–	0.6	0.5
	Intensity	62.0	–	–	60.4	61.2
2031–2060	Duration	4.6 (+0.8)	–	–	5.3 (+2.1)	5.0 (+1.4)
	Frequency	0.8 (+0.5)	–	–	2.3 (+1.7)	1.6 (+1.1)
	Intensity	62.5 (+0.5)	–	–	59.5 (-0.9)	61.0 (-0.2)
2071–2100	Duration	4.4 (+0.6)	–	–	5.6 (+2.2)	5.0 (+1.4)
	Frequency	2.5 (+2.2)	–	–	5.3 (+4.7)	3.9 (+3.4)
	Intensity	63.9 (+1.9)	–	–	58.4 (-2.0)	61.2 (+0.0)
d) Dry periods						
1971–2000	Duration	14.1	13.1	15.6	13.4	14.1/13.5
	Frequency	0.4	0.3	1.4	0.5	0.7/0.4
2031–2060	Duration	14.5 (+0.4)	13.0 (-0.1)	15.1 (-0.5)	14.8 (+1.4)	14.4 (+0.3)
	Frequency	0.8 (+0.4)	0.4 (+0.1)	1.6 (+0.2)	1.1 (+0.6)	1.0 (+0.3)
2071–2100	Duration	15.0 (+0.9)	14.4 (+1.3)	–	16.2 (+2.8)	15.2 (+1.7)
	Frequency	1.4 (+1.0)	0.9 (+0.6)	–	1.5 (+1.0)	1.3 (+0.9)

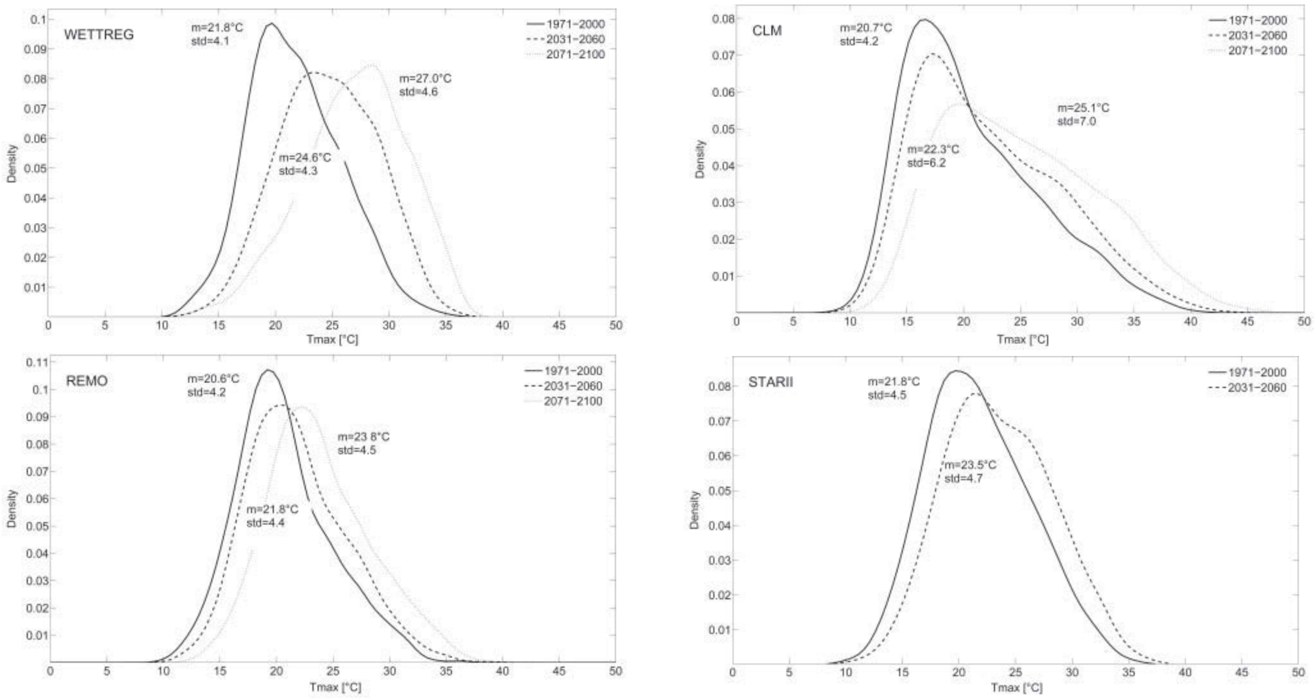

Figure 5: Changes in probability density functions for daily maximum summer (JJA) temperature; m: mean, std: standard deviation.

Wigley, 2009). A concurrent increase in variance – expressed by the standard deviation – indicates the probability of higher T_{max} in future. The change in variance is most pronounced for COSMO-CLM with an increased standard deviation of +2.0 (2031–2060) and +2.8 (2071–2100) compared to 1971–2000. For the other model simulations the standard deviation slightly changes between +0.1 and +0.5 for the 30 year periods analyzed in this study. These findings are consistent with a study by Schär et al.(2004) and Weisheimer and Palmer (2005) who also determined a substantial increase in variability in June, July and August over Europe.

For further analyses we worked with COSMO-CLM and WETTREG to detect future temperature changes and to show differences between dynamical and statistical RCMs. Based on observations at WS DWD, one heat wave occurred every two years with an average duration of 3.6 days and an intensity of $T_{eq} = 59.3$ K. From the data analyzed in this study it can be expected that in future there will be changes in the frequency and duration of heat wave events for the city of Aachen. By the middle of the century the number of heat waves may be twice as high (COSMO-CLM) or even four times higher (WETTREG) compared to 1971–2000. The duration is projected to increase by +0.8 days (COSMO-CLM)/+2.1 days (WETTREG) while a positive trend in terms of the heat wave intensity cannot be determined. The projection for COSMO-CLM (WETTREG) shows that $\sim 3(\sim 5)$ heat waves per year may be normal at the end of the century (Tab 2c). These heat waves are likely to last between $\sim$ 4 (COSMO-CLM) to $\sim$ 6 (WETTREG) days with an intensity of about 60 °C (T_{eq}). Irrespective of these calculations, isolated events can hardly indicate significant trends as demonstrated by Frei and Schär (2001).

5.2 Precipitation change and summer drought

Figure 6 shows estimates of monthly precipitation changes for the summer months of June, July and August until the middle of the century and until 2100. For June all models indicate the highest mean precipitation decrease in future with values up to −30 % (2071–2100 COSMO-CLM). In the medium-term the statistical models show the largest reduction for June and July while a temperature increase is projected for August. The opposite can be observed for July when the dynamical models COSMO-CLM and REMO show an increase in precipitation for the period of 2031–2060. For June and August, the dynamical models constantly compute decreasing precipitation. All in all, there is a consensual agreement between all RCMs used in this study that in the long run precipitation will decrease in summer (−17 % on average).

Based on precipitation measurements at WS DWD 42 dry periods occurred in the period of 1971–2000 with an average duration of 15.6 consecutive days. This means that on average 3 dry periods occurred every 2 years. The frequency of dry periods increases according to all four RCMs (Tab. 2d). The highest increase can be observed for COSMO-CLM and WETTREG (almost 2.5 events per year until 2100). The duration differs from −0.1 (REMO) to +1.4 (WETTREG) days for the medium-term perspective. For the period of 2071–2100 the duration is projected for the RCMs as follows: +0.9 (COSMO-CLM), +1.3 (REMO) and +2.8 consecutive days (WETTREG).

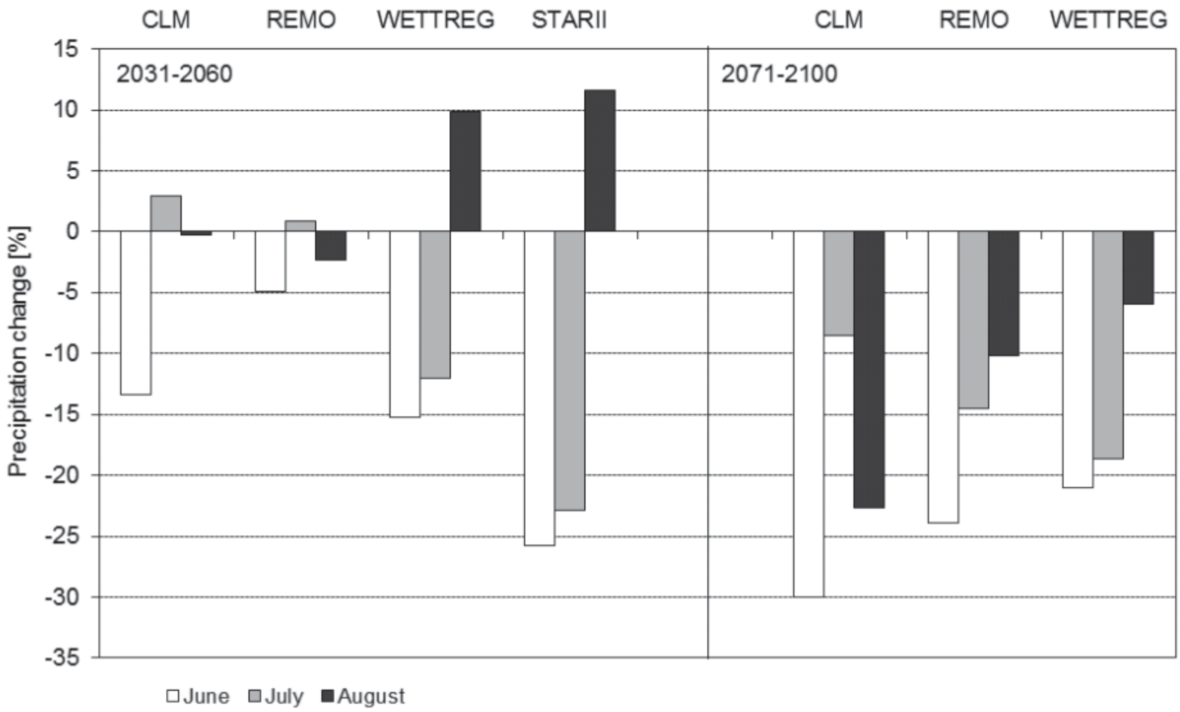

Figure 6: Monthly precipitation change for the summer months of June, July and August for the periods of 2031–2060 and 2071–2100 compared to the control period of 1971–2000.

6 Discussion and conclusion

This study investigates heat and drought in summer since the combination of both may have severe impacts on society. Daily data from four regional climate models and daily observations were gathered and analyzed statistically from 1971–2100. The temperature in Aachen has continuously increased since the middle of the 20th century. A further temperature increase of 1–2 K (2031–2060) and 3–4 K (2071–2100) can be expected according to evaluations of the outputs of the regional climate models known as COSMO-CLM, REMO, WETTREG and STARII. Although the trend towards higher temperatures within the summer months is most pronounced for T_{max}, an increase in T_{min} is of greater societal concern as high night temperatures may be a crucial factor to provoke cardiovascular diseases in vulnerable population groups (Kalkstein, 1993; Abenhaim, 2005).

The general temperature rise in summer can be explained by an increase in the frequency of anticyclonic weather regimes (Cassou and Terray, 2005) and a decrease in the strength of westerlies accompanied by an enhanced strengthening of easterly flow bringing warm and dry conditions to Europe (van Ulden et al., 2007).

The temperature rise can also be confirmed when special days are investigated. The number of (extreme) hot days is expected to double while the number of tropical nights is assumed to even triple under the A1B scenario by the middle of the current century. Since the statistical verifiability of significant trends for special days is difficult due to few exceedances over high thresholds, a significant trend could neither be determined for extreme hot days nor for tropical nights.

Heat wave situations and possible changes in the future were examined in order to assess the course of future impacts on public health and socio-ecologic systems. A heat wave was defined as the longest sequence of consecutive days at which the daily maximum mean equivalent temperature is $\geq 49\,°C$ on at least 3 consecutive days during which the minimum air temperature does not fall below 18 °C.

By means of this definition 3 to 5 heat waves which last 4 to 6 days may be normal by the end of the century. A positive trend in terms of the heat wave intensity cannot be determined.

However, the precise magnitude of these changes is uncertain due to uncertainties in the estimates of global greenhouse gas emissions and biases in GCMs/RCMs due to inadequate parametrizations of unresolved physical processes (e.g. clouding) (Della-Marta and Beniston, 2008).

Future work in terms of a more detailed investigation on heat stress should be an integrated biometeorological assessment. Such an approach would require the consideration of physiological and urban structural parameters such as the city's buildings and the human energy balance (e.g. Havenith, 2005; Matzarakis et al., 2009) which cannot be extracted solely from RCM data. Also the combination of high air temperatures and poor air quality may be important when considering health issues (Merbitz et al., 2012; Burkart et al., 2013).

Based on the analysis of projected precipitation, rainfall is likely to decrease by the end of the century. The highest decrease is computed by COSMO-CLM with a decrease of −30% in June. A further examination of dry periods indicated longer and more frequent periods with little or no rain in future. The increase in dry periods ranges from +0.6 (REMO) to +1 (WETTREG, COSMO-CLM) events per year for the period of 2071–2100.

A decreasing amount of rainfall in the summer months in combination with increasing temperatures and longer heat waves until 2100 affects the soil moisture conditions on land used for agricultural purposes or forestry and also in urban eco-systems. By this, higher air temperature contributes to summer drought which may result in failure of crops and the demand for irrigation both on agricultural fields and vegetation in cities. Drying soils impede an upward transfer of latent heat and foster sensible heat flux from the hot land surface which, in turn, promotes the occurrence of hot summer days (Fischer et al., 2007).

The present study is the first assessment of climate change signals of extreme temperature and precipitation calculated by climate change projections for the 21st century for the city of Aachen. The results are relevant for urban planning measures for the area under investigation and more generally as a case study. For this reason, the city of Aachen has incorporated the results from this study in its urban land use plan and attached importance to climatic concerns when taking administrative action in urban development (Ketzler et al., 2013).

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