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Extreme summer heat in Phoenix, Arizona (USA) under global climate change (2041-2070)

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Abstract

Summer extreme heat events in the arid Phoenix, Arizona (USA) metropolitan region for the period 2041-2070 are projected based on the ensemble of ten climate models from the North American Regional Climate Change Assessment Program for the SRES A2 greenhouse gas emissions scenario by the Intergovernmental Panel on Climate Change. Extreme heat events are identified by measures related to two thresholds of the maximum daily air temperature distribution for the historical reference period 1971-2000. Comparing this reference period to the model ensemble-mean, the frequency of extreme heat events is projected to increase by a factor of six to 1.9 events per summer and the average number of event days per year is projected to increase by a factor of 14. The inter-model range for the average number of EHE days per summer is larger for the projected climate, 10.6 to 42.2 days, than for simulations of the past climate simulations (1.5 to 2.4 days).

Zusammenfassung

Projektionen für extreme Hitzeereignisse in den Sommermonaten in Phoenix, Arizona (USA) wurden für den Zeitraum 2041-2070 unter der Annahme des SRES A2 Treibhausgasemissionsszenarios des Intergovernmental Panel on Climate Change erstellt. Dafür wurden Simulationsergebnisse eines Ensembles von zehn Klimamodellen ausgewertet, die im Rahmen des North American Regional Climate Change Assessment Programmes angewendet wurden. Die extremen Hitzeereignisse wurden mit Hilfe von Kriterien bestimmt, die auf Schwellenwerttemperaturen für die maximalen täglichen Lufttemperaturen für die Referenzperiode 1971-2000 beruhen. In der Zukunft versechsfacht sich im Ensemblemittel die Häufigkeit der Extremereignisse (~ 1.9 Ereignisse pro Sommer) im Vergleich zum Referenzzeitraum mit einer vierzehnfachen mittleren Anzahl der Hitzetage pro Sommer. Dabei vergrößert sich die Schwankungsbreite der Modelle bezüglich der mittleren Anzahl der Hitzetage pro Sommer in der Zukunft gegenüber der der Vergangenheit von 1.5-2.4 auf 10.6-42.2.

Keywords Extreme heat events; Phoenix, Arizona, USA; North American Regional Climate Change Assessment Program

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1. Introduction

This study investigates potential changes in summertime near-surface daily maximum air temperatures ($T_{\max}$) and extreme heat events (EHEs) under global climate change in the Phoenix, Arizona (USA) Metropolitan Area for the period 2041-2070 based on projections from the North American Regional Climate Change Assessment Program (NARCCAP; *Mearns* et al. 2009, 2012). EHEs are identified by means of three criteria that are related to exceedances of two thresholds of $T_{\max}$ (*Huth* et al. 2000; *Meehl* and *Tebaldi* 2004; cp. Section 2).

The Phoenix-Mesa-Scottsdale (abbrev. Phoenix) Metropolitan Area is located in the desert southwest of the United States and it is the 13th largest urban region of the country with a population of 4.3 million. The area experienced one of the largest population growth rates in the USA in the decades 1990-2000 (40 %) and 2000-2010 (24.6 %; US Census 2010). The climate is arid subtropical with summer (1 June – 31 August, JJA) average daily mean air temperatures of 33.9 °C for the period 1981-2010 (National Climatic Data Center). Understanding the effects of global climate change on episodes of extreme heat in this arid region is particularly important in order to enhance the adaptive capacity of a city that regularly experiences high summertime temperatures as well as rapid urban expansion. Investigations of heat and health for the Phoenix Metropolitan Area show that risks of mortality, morbidity and thermal discomfort are elevated during periods of above-normal summertime temperatures and during EHEs (*Harlan* et al. 2006, *Yip* et al. 2008, *Golden* et al. 2008, *Ruddell* et al. 2010, *Harlan* et al. 2014).

Several studies that are based on the analysis of global atmosphere-ocean general circulation model (AOGCM) simulations predict a likely increase in the frequency, duration and severity of EHEs in the western and southwestern United States due to global climate change (e.g. *Meehl* and *Tebaldi* 2004, *Seager* et al. 2007; *Diffenbaugh* et al. 2008). The spatial resolution of most global climate models used in the World Climate Research Program's Coupled Model Intercomparison Project (CMIP3; *Taylor* et al. 2012) is between one and four degrees (*Cattiaux* et al. 2013), and therefore important earth surface characteristics that may influence regional climate are not considered in the AOGCM simulations.

In order to enhance the global climate projections from CMIP3 with regional detail, the international NARCCAP program (http://www.narccap.ucar.edu) was undertaken. NARCCAP is currently the most comprehensive program for downscaling AOGCM results to the regional scale for North America. The aim of NARCCAP is to produce regional climate change projections for the future period 2041-2070 and the A2 greenhouse gas emissions scenario of the Special Report on Emissions Scenarios (SRES) by the Intergovernmental Panel on Climate Change (IPCC; *Nakićenović* and *Swart* 2000). The SRES A2 emissions scenario is one of the high IPCC emissions scenarios assumed in the Third and Fourth IPCC Assessment Reports. In order to investigate uncertainties in regional scale projections as well as societal impacts of future climate, NARCCAP provides model results from a set of regional climate models (RCMs) driven by a set of AOGCMs. The RCM domains cover the conterminous United States and most of Canada with a spatial resolution of about 50 km (*Mearns* et al. 2009, 2012). This so-called model ensemble is used to assess uncertainties in the climate projections due to uncertainties in the AOGCMs and RCMs that result, among other things, from choice of physical approaches, gaps in knowledge of atmospheric processes and data limitations.

Our reasoning for the applicability of the NARCCAP simulations for the investigation of projected changes for a particular urban region is twofold. First, we analyse $T_{\max}$ and choose EHE criteria that are based on observed and simulated maximum air temperatures. We use $T_{\max}$ because urban land use/land cover has a comparatively small influence on maximum daily air temperatures in this region (*Brazel* et al. 2000, *Grossman-Clark*e et al. 2010), whereas minimum air temperatures are strongly affected by urbanisation. This is an important distinction because local effects of urban land use/land cover on climate in the Phoenix Metropolitan Area are not captured by the NARCCAP simulations, due to the spatial resolution of 50 km and the accompanying fact that none of the RCMs considers urban land use. *Brazel* et al. (2000) found no significant increase in average maximum June daytime air temperatures after 1940 in the centre of the Phoenix urban area and on average slightly higher maximum daytime temperatures at a rural site southeast of the Phoenix Metropolitan Region. They also found that the average June minimum nighttime temperatures were on average 5 K (maximum up to 10 K) higher at the urban in comparison to the rural site. Using a different rural weather station than *Brazel* et al. (2000), *Ruddell* et al. (2013) showed an increase in misery days (T > 43.3 °C) in the urban area compared to rural over the 20th century, although the increase is considerably smaller than urban-rural nighttime temperature differences due to urbanisation. Additionally, the main use of the information acquired in this study is to assess potential health impacts under global climate change in the Phoenix region. Studies show that maximum air temperature is highly correlated with mortality rates (Centers for Disease Control 2005; *Anderson* and *Bell* 2011).

Second, we compare simulated present-day and projected future climate T_{max} in the Phoenix Metropolitan Area and the larger region of central-southern Arizona. The purpose is to ensure that the evaluation and projection results are not sensitive to local land use/land cover assigned by the models to the Phoenix Metropolitan Area. If both sets of results are similar, then the results for Phoenix can be interpreted in a larger context and support the application of the RCMs to the urban scale. Another benefit of this approach is the fact that the larger region can be resolved numerically by the RCMs where the spatial resolution is at least four times their grid size (*Pielke* 1991, *Walters* 2000, *Pielke* 2001).

2. Methodology

Within NARCCAP, modeling groups carry out simulations with several RCM/AOGCM model combinations for the future period 2041-2070 and also for the historical period 1971-2000. In this study, data are used from the ten RCM/AOGCM model combinations that are listed in *Table 1* along with the modeling groups that conducted the simulations. Simulated daily maximum air temperatures at 2 m above ground, T_{max}, for the time period 1 June – 31 August (JJA) for each simulated year are selected for the analysis. Subsequently, the data are elevation-corrected to the mean elevation of the Phoenix Metropolitan Area (346 m, *Fig. 1*) at their native model grid using terrain information of the corresponding RCMs. An average lapse rate of 0.0065 K/m is assumed. This lapse rate does not consider local conditions in terms of specific meteorological situations or surface conditions but is considered sufficient for climatological studies (*Kjellström* et al. 2007). Data for all model combinations are remapped to the WRFG model grid. Two regions with the following boundaries are selected for the analysis of summertime T_{max}: 113°W to 111°W, 33°N to 34°N and 115°W to 109°W, 32°N to 35°N. The smaller region represents the Phoenix Metropolitan Area while the larger one covers much of central-southern Arizona (*Fig. 1*).

Tab. 1 NARCCAP Regional Climate Models (RCMs) and Atmosphere-Ocean General Circulation Models (AOGCMs) used in combination for Extreme Heat Event analysis.

	Modeling group	Full model name	RCM/AOGCM combinations
RCMs			
CRCM	OURANOS / UQAM	Canadian Regional Climate Model	CRCM/ccsm CRCM/cgcm3
ECP2	UC San Diego / Scripps	Experimental Climate Prediction Center Regional Spectral Model 2	ECP2/gfdl
HRM3	Hadley Centre	Hadley Regional Model 3	HRM3/hadcm3
MM5I	Iowa State University	MM5 - PSU/NCAR mesoscale model	MM5I/ccsm MM5I/hadcm3
RCM3	UC Santa Cruz	Regional Climate Model version 3	RCM3/cgcm3 RCM3/gfdl
WRFG	Pacific Northwest National Lab	Weather Research & Forecasting model, Grell scheme	WRFG/ccsm WRFG/cgcm3
AOGCMs			
ccsm	NCAR	Community Climate System Model	
cgcm3	CCCMA	Third Generation Coupled Global Climate Model	
gfdl	NOAA	Geophysical Fluid Dynamics Laboratory GCM	
hadcm3	Hadley Centre	Hadley Centre Coupled Model, version 3	

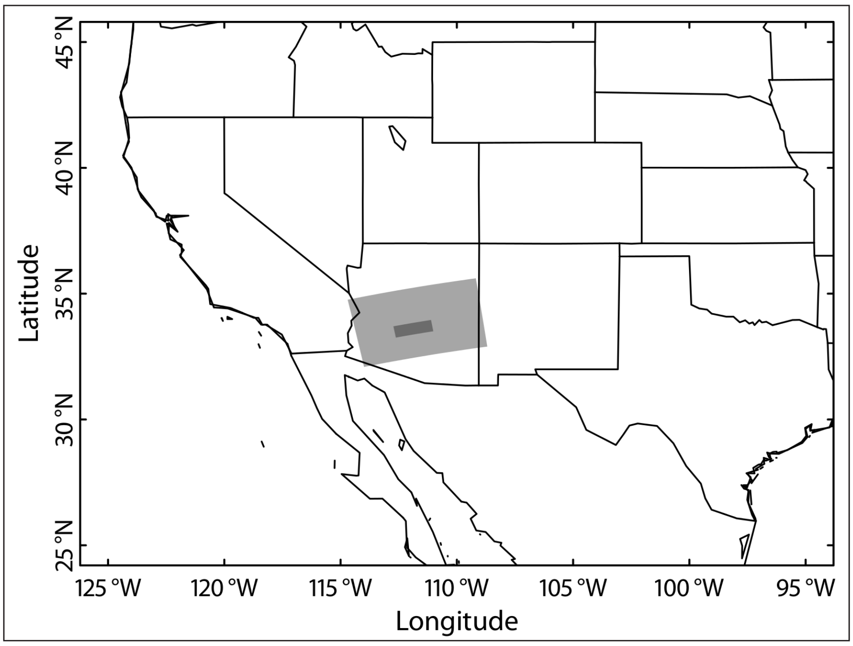

Fig. 1 Geographical regions for the analysis in this study: Phoenix Metropolitan Area (113°W to 111°W, 33°N to 34°N; small dark rectangle) and central-southern Arizona (115°W to 109°W, 32°N to 35°N; larger grey rectangle). Phoenix Metropolitan Area and central-southern Arizona are covered by 4 × 2 and 11 × 7 grid cells, respectively. Phoenix Metropolitan Area is located in the Salt River Valley, a broad, nearly flat plain, at a mean elevation of about 346 m above sea level.

Gridded observational data for daily T_{max} for the period 1971-2000 with a spatial resolution of 1/16 degree are obtained from a data set for North America (*Livneh* et al. 2014). The data set includes observations from approximately 20,000 stations that were obtained from the National Climatic Data Center and gridded to 211687 points. Elevation data with the same spatial resolution is provided with the meteorological data. The same procedure described for the simulated data is applied to adjust the observed T_{max} to the average elevation of the Phoenix Metropolitan Area. Subsequently, data are remapped to the grid of the WRFG model and extracted for the Phoenix and central-southern Arizona regions.

EHEs are identified based on the method by *Huth* et al. (2000) and *Meehl* and *Tebaldi* (2004) that uses two temperature thresholds T_1 and T_2, which are the 97.5th and 81st percentile of the T_{max} distribution for JJA between 1971 and 2000. Three threshold criteria characterise a continuous period as an EHE: (1) T_{max} must be above T_1 for at least three days, (2) the average T_{max} of the entire period must be above T_1, and (3) T_{max} must be above T_2 for every day of the entire period.

3. Results

3.1 NARCCAP model performance for present day (historical) climate

Before analysing the 2041-2070 projections of the RCM/AOGCM ensemble and conducting the analysis of extreme heat events, we first evaluate the simulated summer T_{max} for the historical climate runs (1971-2000) against gridded observations. The purpose is to diagnose how well the individual RCM/AOGCMs and the model ensemble-mean capture characteristics of the observed T_{max} (JJA) distribution. *Figure 2* includes boxplots for the T_{max} (JJA) distributions of the historical and future climate runs as conducted with each RCM/AOGCM combination listed in *Table 1* and for the gridded observations. All panels show results for both the Phoenix Metropolitan Area and the central-southern Arizona region. *Table 2* lists the corresponding numerical values of characteristics of the boxplots of *Figure 2*. In addition, the values for the model ensemble-means (mean of all values for all models) are given.

Gridded observations for the two analysed regions show similar values of 40.1 °C (central-southern Arizona) and 40.6 °C (Phoenix Metropolitan Area) for the median of T_{max} (JJA). For the historical climate the gridded observations are captured well by the RCM/AOGCM ensemble-mean of the T_{max} (JJA) medians. Values are 40.7 °C and 41.0 °C for central-southern Arizona and the Phoenix Metropolitan Area, with corresponding positive biases of 0.6 K and 0.5 K, respectively. The medians of the T_{max} distributions for individual model combinations are also similar for the two regions, with a tendency for Phoenix to be slightly warmer than central-southern Arizona (*Fig. 2* and *Tab. 2*). Also observations and simulations for both regions exhibit a relatively even spatial distribution of median T_{max} after elevation correction (not shown).

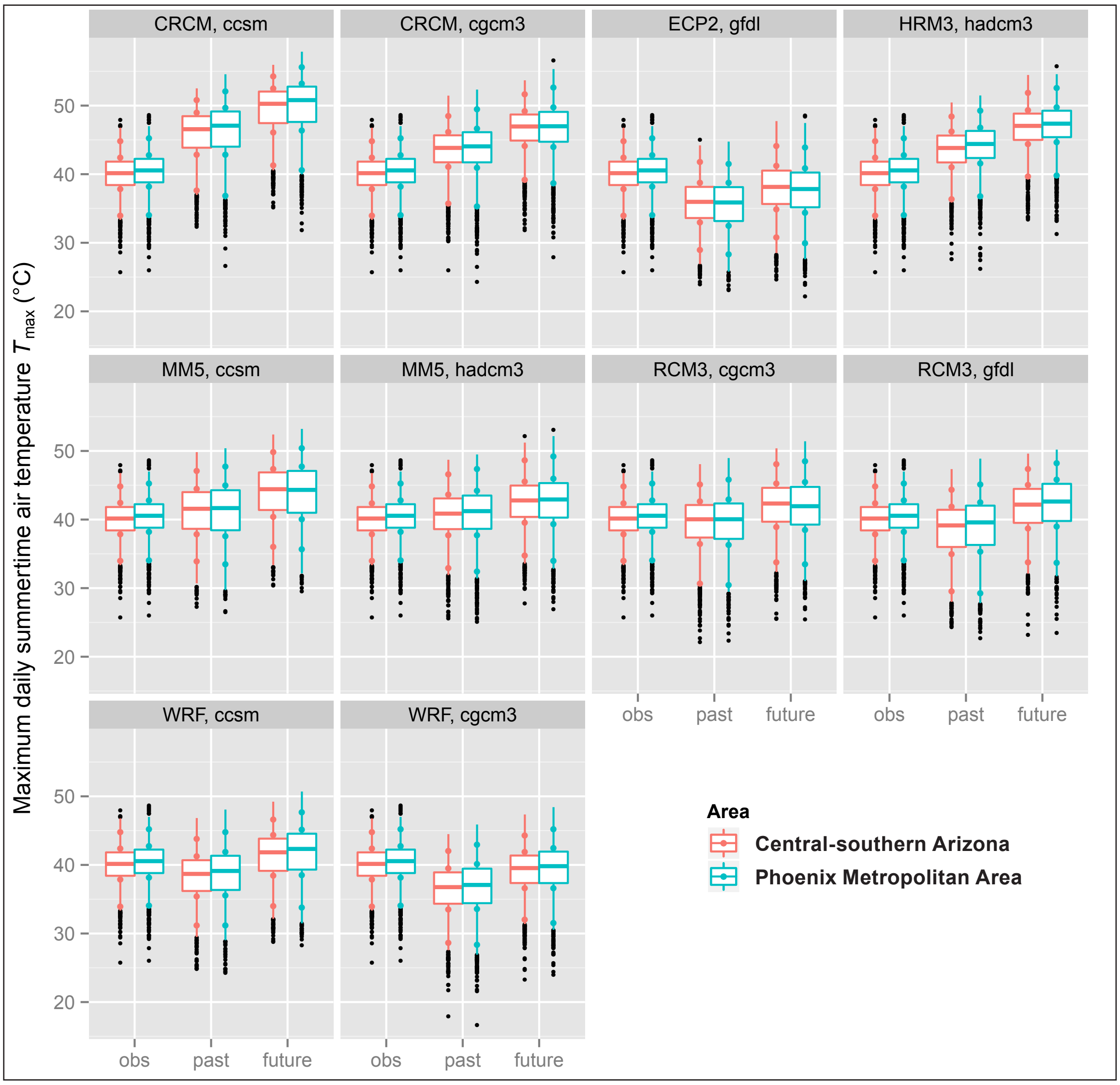

Fig. 2 *Boxplots of daily maximum air temperatures at 2 m above ground (T_{max}) for all summer seasons (JJA) for the central-southern Arizona (red) and the Phoenix Metropolitan Area (green) for each RCM/AOGCM combination; left hand side pairs of boxplots are observed (1971-2000), middle pairs of boxplots are simulated (1971-2000) and right hand side pairs of boxplots are simulated (2041-2070) data. Note that the runs for the present-day climate driven by the AOGCM ccsm include data to the end of 1999 only (center boxplots). Characteristics of the boxplots are: median (centre line); 25th and 75th percentiles are lower and upper bounds of the boxes with the vertical extent being the interquartile range (IQR); 2.5th, 19th, 81st and 97.5th percentiles (colored dots); length of the upper (lower) whiskers is the minimum of 1.5 × IQR or the upper (lower) values of the T_{max} distribution; black dots for T_{max} of individual extremely cold or warm days.*

In the following, results for the Phoenix Metropolitan Area are given in parenthesis following the values for central-southern Arizona. The median of T_{max} for the different RCM/AOGCMs range from 35.9 °C (36.0 °C) for ECP2/gfdl to 46.6 °C (47.1 °C) for CRCM/ccsm with corresponding biases of 6.4 K (6.5 K) and -4.2 K (-4.7 K), respectively. The smallest bias of individual models amounts to -0.1 K (0.5 K) for RCM3/cgcm3. Generally, the interquartile ranges (IQRs) are larger for the individual model combinations than the IQRs of the observations, i.e. within 4.0 K (4.4 K) and 5.4 K (5.9 K) vs. 3.4 K. The model ensemble-mean IQR and bias amount to 4.6 K (5.0 K) and 1.2 K (1.6 K).

Figure 2 also shows values of the 81st and 97.5th percentiles of the distributions that are used in our definition of EHEs. The latter represent extreme values of the distributions. The ranges among individual RCM/AOGCMs are 10.2 K (11.0 K) for the 81st percentile and 9.0 K (10.6 K) for the 97.5th percentile. This is somewhat smaller than

Tab. 2 Statistical characteristics corresponding to Fig. 2 of daily maximum air temperatures at 2 m above ground, T_{max}, for all summer (JJA) seasons for the central-southern Arizona region (grey background) and the Phoenix Metropolitan Area (white background) as simulated by means of each AGCM/RCM combination for the time period 1971-2000. Also included are model ensemble-means and values for gridded observations. Note that the runs for the present climate driven by the AOGCM ccsm include data to the end of 1999 only. The acronyms IQR and PCTL are used for interquartile range and percentile.

RCM	GCM	T_{max} median		IQR		81st PCTL;T_2		97.5th PCTL; T_1	
		(°C)	bias(K)	(°C)	bias(K)	(°C)	bias(K)	(°C)	bias(K)
CRCM	**ccsm**	46.6	6.4	4.6	1.2	49.0	6.6	50.8	6.0
		47.1	6.5	5.1	1.7	49.7	6.9	52.1	6.9
CRCM	**cgcm3**	43.8	3.7	3.9	0.5	46.2	3.8	48.5	3.6
		44.1	3.5	4.4	1.0	46.7	3.9	49.5	4.2
ECP2	**gfdl**	36.0	-4.2	4.5	1.1	38.8	-3.6	41.8	-3.0
		35.9	-4.7	4.9	1.5	38.7	-4.0	41.5	-3.7
HRM3	**hadcm3**	43.8	3.7	3.9	0.5	46.2	3.8	48.4	3.6
		44.4	3.9	3.9	0.5	46.8	4.0	49.2	4.0
MM5	**ccsm**	41.6	1.4	5.3	1.9	44.5	2.1	47.1	2.3
		41.7	1.1	5.8	2.4	45.0	2.2	47.7	2.5
MM5	**hadcm3**	40.9	0.7	4.5	1.1	43.6	1.2	46.6	1.8
		41.2	0.7	4.9	1.4	44.2	1.4	47.4	2.1
RCM3	**cgcm3**	40.0	-0.1	4.7	1.3	42.6	0.2	45.1	0.3
		40.0	-0.5	5.2	1.7	43.0	0.2	45.8	0.6
RCM3	**gfdl**	39.1	-1.0	5.4	2.0	41.9	-0.5	44.3	-0.5
		39.6	-1.0	5.7	2.3	42.5	-0.2	45.1	-0.1
WRF	**ccsm**	38.7	-1.5	4.5	1.1	41.2	-1.2	43.8	-1.0
		39.1	-1.4	5.0	1.6	41.9	-0.8	44.8	-0.5
WRF	**cgcm3**	36.8	-3.4	4.6	1.2	39.5	-2.9	42.1	-2.8
		37.1	-3.5	5.0	1.6	40.1	-2.6	43.0	-2.3
Ensemble-mean		40.7	0.6	4.6	1.2	43.4	0.9	45.9	1.0
		41.0	0.5	5.0	1.6	43.9	1.1	46.6	1.4
Observations		40.1		3.4		42.4		44.8	
		40.6		3.4		42.8		45.2	

the range for the medians of the T_{max} distributions of 10.7 K (11.1 K). As for the median, the temperatures for the two percentiles are slightly higher for the Phoenix Metropolitan Area than for central-southern Arizona, except in the case of ECP2/gfdl. The ensemble-mean bias of the 81st and 97.5th percentiles is about 1 K and therefore larger than for the median (~ 0.5 K). The extreme values will be discussed further in connection with extreme heat events in Section 3.2.

The deviations between characteristics of the T_{max} (JJA) distributions for central-southern Arizona and the Phoenix Metropolitan Area, as obtained from the historical climate simulations, and also the gridded observations, are relatively small. This supports the conclusion that the numerically resolved simulations for central-southern Arizona can be considered to represent also the Phoenix Metropolitan Area. Furthermore the results appear to be relatively independent from local land use/land cover in the models for this region.

3.2. NARCCAP projections for future climate and extreme heat events

The characteristics of the T_{max} (JJA) distributions from the individual RCM/AOGCM projections (2041-2070) and the model ensemble are shown for the central-southern Arizona and the Phoenix Metropolitan Area in *Figure 2* (right hand side boxplots in each panel). Numerical values for median, IQR and 81st and 97.5th percentiles are listed in *Table 3* along with the climate

Tab. 3 Corresponding to Figure 2, characteristics of the distributions of daily maximum air temperatures at 2 m above ground, T_{max} from all summers (JJA) of the projection period (2041-2070) for central-southern Arizona (grey background) and the Phoenix Metropolitan Area (white background) as simulated by RCM/AOGCM combinations. Also included are the ensemble-mean values. The climate change signals, Δ, are the differences between median, IQR, 81st and 97.5th percentile values, respectively, for the periods 2041-2070 and 1971-2000.

RCM	GCM	T_{max} median		IQR		81st PCTL		97.5th PCTL	
		(° C)	Δ (K)	(K)	Δ (K)	(° C)	Δ (K)	(° C)	Δ (K)
CRCM	**ccsm**	50.3	3.7	4.6	0.0	52.5	3.5	54.3	3.4
		50.8	3.7	5.2	0.0	53.2	3.5	55.6	3.5
CRCM	**cgcm3**	47.0	3.1	3.8	-0.1	49.2	3.0	51.7	3.2
		47.0	2.9	4.4	-0.0	49.8	3.1	52.6	3.2
ECP2	**gfdl**	38.1	2.2	4.9	0.3	41.2	2.4	44.1	2.3
		37.8	2.0	5.1	0.1	40.9	2.1	43.9	2.4
HRM3	**hadcm3**	47.0	3.2	3.8	-0.1	49.4	3.1	51.8	3.5
		47.4	3.0	3.9	-0.1	49.7	2.9	52.6	3.3
MM5	**ccsm**	44.4	2.9	5.5	0.1	47.4	2.9	49.9	2.7
		44.3	2.7	6.1	0.3	47.7	2.8	50.4	2.7
MM5	**hadcm3**	42.8	1.9	4.6	0.1	45.5	1.9	48.6	2.0
		42.9	1.7	5.0	0.2	45.9	1.8	49.2	1.8
RCM3	**cgcm3**	42.3	2.3	4.9	0.2	45.3	2.6	48.0	2.9
		41.9	1.9	5.5	0.3	45.5	2.5	48.5	2.7
RCM3	**gfdl**	42.2	3.0	5.0	-0.5	45.0	3.2	47.4	3.0
		42.6	3.0	5.4	-0.3	45.8	3.3	48.2	3.1
WRF	**ccsm**	41.8	3.1	4.7	0.2	44.3	3.1	46.6	2.8
		42.3	3.2	5.2	0.2	45.1	3.2	47.7	2.9
WRF	**cgcm3**	39.5	2.8	4.0	-0.6	41.9	2.4	44.3	2.3
		39.8	2.7	4.6	-0.4	42.5	2.4	45.2	2.2
Ensemble-mean		43.5	2.8	4.6	-0.0	46.2	2.8	48.7	2.8
		43.7	2.7	5.0	0.0	46.6	2.8	49.4	2.8

change signals in terms of the differences in the values between the periods 2041-2070 and 1971-2000. The model ensemble-means are also given.

As for the simulations for the historical period, the median of the T_{max} (JJA) distributions as simulated by ECP2/gfdl and CRCM/ccsm are the coolest and warmest, respectively, and amount to 38.1 °C (37.8 °C) and 50.3 °C (50.8 °C). The range of median values increases from 10.7 K (11.1 K) for the historical period to 12.2 K (13.0 K) for the future period. The ensemble-mean median is 43.5 K (43.7 K) with a climate change signal of 2.8 K (2.7 K). The smallest and largest climate change signals of 1.9 K (1.7 K) and 3.7 K (3.7 K) were determined for MM5/hadcm3 and CRCM/ccsm. The range in the climate change signal among the RCM/AOGCM combinations is much smaller than the above-mentioned spread of median values of individual models. This indicates systematic model errors, so-called model biases (*Maurer* et al. 2010).

The IQR range of the model ensemble increases slightly between the historical simulations and climate projections, while the change in the ensemble-mean IQR is negligible. The climate change signal of the ensemble-mean 81st and 97.5th percentiles on the other hand is similar to that of the median 2.8 K (2.8 K) and deviates by less than 0.6 K for individual models from the ensemble-mean. The results indicate a shift in the T_{max} (JJA) distributions towards higher temperatures rather than a strong change in shape.

The EHE criteria described in section 2 were then applied to the gridded observations and historical climate runs of each RCM/AOGCM combination in order to identify past EHEs. The resulting temperature thresholds T_1 (97.5th percentile) and T_2 (81st percentile) were also used with the T_{max} (JJA) distributions of the future climate runs in order to detect the projected change in the occurrence, duration and intensity of potential future EHEs. T_1 and T_2 are listed in *Table 2*, while the average number of EHEs per summer, their average duration and average T_{max} for the historical and projection periods are given in *Table 4.* Data for the model ensemble-mean are also included.

As an observed reference we also analysed EHE characteristics that were identified for the prominent National Weather Service's Sky Harbor Airport station located in the centre of the Phoenix urban region. The threshold temperatures there were determined to be 45.6 °C and 43.3 °C. For comparison, T_1 and T_2 amount to 45.3 °C and 42.8 °C for the gridded observations for the Phoenix Metropolitan Area as defined in the previous section. Six EHEs were identified at the station for the 30-year period 1971-2000, with an average duration of about 8 days. The highest daytime temperature of 50.0 °C was recorded on 26 June 1990. The EHE characteristics for the gridded observations for the Phoenix Metropolitan Area (*Tab. 4*) are similar to those obtained from the observations at Sky Harbor Airport, i.e. an average EHE duration for the latter of 10.5 days with an average number of 0.20 EHEs per summer. The gridded observations for the central-southern Arizona region indicate slightly more frequent and shorter EHEs (0.33 and 8.4 days). The model ensemble-means amount to 0.30 (0.32) and 6.9 days (6.3 days) for the average frequency and duration per summer for the

Tab. 4 Characteristics of historical and projected future Extreme Heat Events (EHEs) as derived from historical (1971-2000) and future (2041-2070) climate simulations for RCM/AOGCM combinations, observed gridded data (1971-2000) and recorded data at the National Weather Service (NWS) Sky Harbor Airport station for central-southern Arizona (grey background) and the Phoenix Metropolitan Area (white background). Listed are threshold temperatures T_1 (97.5th percentile), T_2 (81st percentile) of the T_{max} distributions for summer (JJA), average number and duration of EHEs per summer.

RCM	**GCM**	**EHEs (1971-2000)**				**EHEs (2041-2070)**			
		Average number per year	Average EHE duration (days)	Average EHE days per year	T_{max} (°C)	Average number per year	Average EHE duration (days)	Average EHE days per year	T_{max} (°C)
CRCM	**ccsm**	0.28	8.6	2.4	50.9	1.73	28.0	48.6	51.7
		0.24	8.1	2.0	52.2	2.30	18.3	42.2	52.8
CRCM	**cgcm3**	0.30	6.2	1.9	48.8	1.87	19.5	36.4	49.0
		0.30	5.6	1.7	49.7	2.13	12.3	26.2	50.1
ECP2	**gfdl**	0.37	6.0	2.2	41.9	1.37	13.6	18.6	42.1
		0.37	5.3	1.9	41.8	1.77	9.4	16.7	41.9
HRM3	**hadcm3**	0.30	5.2	1.6	48.6	2.70	13.9	37.4	49.0
		0.27	5.5	1.5	49.5	2.80	10.8	30.2	49.8
MM5	**ccsm**	0.28	8.4	2.3	47.3	1.70	17.7	30.1	47.5
		0.28	8.4	2.3	47.9	1.90	12.5	23.7	48.2
MM5	**hadcm3**	0.23	6.6	1.5	46.8	1.13	12.0	13.6	46.9
		0.33	5.4	1.8	47.6	1.20	8.8	10.6	47.7
RCM3	**cgcm3**	0.27	6.4	1.7	45.3	1.80	13.9	25.0	45.7
		0.33	6.8	2.3	46.0	1.67	11.6	19.4	46.3
RCM3	**gfdl**	0.33	6.6	2.2	44.5	2.07	16.6	34.3	44.8
		0.37	5.4	2.0	45.4	2.20	14.5	32.0	45.7
WRF	**ccsm**	0.34	7.0	2.4	44.0	1.83	18.4	33.8	44.2
		0.38	6.4	2.4	45.0	1.77	16.5	29.1	45.2
WRF	**cgcm3**	0.27	7.9	2.1	42.3	1.80	11.7	21.1	42.3
		0.33	6.3	2.1	43.2	1.63	11.0	17.9	43.2
Ensemble-mean		0.30	6.9	2.0	46.0	1.80	16.5	29.8	46.3
		0.32	6.3	2.0	46.8	1.94	12.6	24.4	47.1
Observations		0.33	8.4	2.8	45.0				
		0.20	10.5	2.1	45.4				

historical period, with a range for individual models between 0.23 (0.24) and 0.37 (0.38) for frequency and 5.2 days (5.5 days) for duration. The simulated average T_{max} during EHEs is 46.0 °C (46.8 °C) with a range of 41.9 °C and 50.9 °C (41.8 °C and 52.2 °C).

Based on the current heat wave criteria the ensemble-mean of the EHE frequency is projected to increase by a factor of six to 1.80 (1.94) per summer accompanied by an extended average duration of 16.5 (12.6) days per EHE. This amounts to a fourteenfold increase of the ensemble-mean average number of EHE days per year (*Tab. 4*). The intermodel range for the average number of EHE days per year is larger for the projected climate, 13.6 (10.6) to 48.6 (42.2) days, than for the past climate simulations, 1.5 (1.5) to 2.4 (2.4), days resulting in a six- to twentyfold range in the increase of the average number of EHE days per year.

The increase in average T_{max} of 0.3 K (0.3 K) between simulated historical and projected EHEs is relatively small. This is due to the use of the same threshold temperatures, T_1 and T_2, for both time periods. The ensemble-mean EHE events would be similarly rare as for the historical period and characterised by average T_{max} of at least 2.8 K higher if T_1 and T_2 as determined from the simulated T_{max} (JJA) distribution for the period 2041-2070 had been used in the EHE identification. This is due to the climate change signal in the 97.5th (T_1) and 81st (T_2) percentiles of 2.8 K (*Tab. 3*).

As for the historical observations and simulations, the results for the projection period in terms of median, IQR, 97.5th and 81st percentiles and EHE characteristics as well as the climate change signals are generally similar for the Phoenix Metropolitan Area and the central-southern Arizona region. This supports further the applicability of the NARCCAP data to the Phoenix Region for the particular purpose of this study.

4. Discussion and outlook

The NARCCAP simulations project a large change in extreme summer conditions for the Phoenix Metropolitan Area under the SRES A2 emissions scenario. Although this study is limited to only one greenhouse gas emissions scenario, the results support the "Assessment Report of Climate Change in the Southwest United States" (*Garfin* et al. 2013). This report evaluates projected climate change in the Southwest USA by using CMIP3 AOGCMs for the SRES A2 emissions scenario as well as for the SRES B1 low emissions scenario. The assessment report does not specify projections for changes in EHE characteristics for the Phoenix region but rather for the entire Southwest, i.e. an increase of EHEs "at an accelerating rate with nighttime heat waves projected to increase at a faster rate than daytime heat waves" and the "observed 100 year-return period of heat waves becomes a 10 year or even shorter return period during the last half of the twenty-first century" (*Gershunov* et al. 2013). The climate projections for the two emissions scenarios are similar for the first half of the century but increasingly diverge beginning in the middle of the century due to the SRES A2 emissions being considerably higher at that time than the B2 greenhouse gas emissions. The report states that the projected amount of annual warming for the low-emissions scenario ranges between 0.6 °C and 2.2 °C for the period 2041-2070 and between 1.1 °C and 3.3 °C for 2041-2070 for the high-emissions scenario. For the projection period, the average temperature change simulated by the NARCCAP models is 2.5 °C, which is close to the mean of the CMIP3 AOGCMs for the high-emissions scenario with larger temperature increases in the summer (*Cayan* et al. 2013).

Another potential indicator of an EHE (other than T_{max} used in this study) is the number of consecutive days characterised by high nighttime temperatures (*Karl* and *Knight* 1997). Recent EHEs identified from the recorded temperatures at the Phoenix Sky Harbor Airport station are also distinguished by exceptionally high nighttime temperatures (*Grossman-Clarke* et al. 2010). The threshold temperatures T_1 and T_2 for the minimum nighttime temperatures are calculated to be 32.9 °C and 30.7 °C, respectively, for the period 1971-2000 at the Phoenix Sky Harbor International Airport weather station. Generally the events with extremely high minimum temperature lasted longer than the EHEs based on T_{max} (*Grossman-Clarke* et al. 2010). Due to the lack of urban land use/land cover effects on the atmosphere in the NARCCAP simulations, neither projected changes in minimum air temperatures nor effects of urban development scenarios can be addressed in this study. *Georgescu* et al. (2012) showed that projections for urban expansion provided by the Maricopa Association of Governments (a government council that provides regional planning for the Phoenix Metropolitan Area; http://www.azmag.gov) have an influence on air temperatures that is comparable with projected changes due to the regional expression of global climate change. Questions about how global and urban influences interact with each other to affect regional climate need to be addressed in future higher resolution RCM applications.

Gershunov et al. (2009, 2012) showed that EHEs in California, USA, are becoming more humid and are therefore characterised by elevated nighttime temperatures ('humid heat waves'). Synoptic circulations, such as the North American Monsoon (NAM), that transport hot humid air to the Southwest United States are the reason for this trend. The NAM is characterised by the transport of moisture from the Gulf of Mexico and the tropical eastern North Pacific into northern Mexico and southern and central Arizona, leading to widespread thunderstorm activity (*Adams* and *Comrie* 1997). It is beyond this study to investigate changes in the NAM circulation and its effects on the occurrence of EHEs due to global climate change. Generally, in order to resolve the NAM as a distinct meteorological feature in climate models, a high spatial resolution is required (*Cayan* et al. 2013). AOGCMs cannot resolve the typical NAM circulation. Also there is little consensus among NARCCAP models regarding projected changes in the NAM circulation under climate change, which expresses the challenge of representing the NAM in climate models (*Garfin* et al. 2013, *Cayan* et al. 2013). However, four of the six EHEs identified from the Phoenix Sky Harbor Airport data for the period 1971-2000 occurred in June, while four more recent EHEs during the period 2000-2007 all occurred during NAM July and August (*Grossman-Clarke* et al. 2010, their *Tab. 1*). *Grossman-Clarke* et al. (2010) showed that during each EHE the NAM was temporarily suppressed because of a change in the position of the Bermuda high from its typical location (their *Fig. 2*). Nevertheless, the air moisture content is generally higher than during the early dry parts of the summer (June). This contributes to higher nighttime temperatures by increasing the downward flux of longwave radiation compared to the generally drier June atmosphere. A more comprehensive analysis is necessary but beyond the scope of this study to investigate if this change in the occurrence of EHEs during the NAM is significant.

5. Conclusions

This study investigates potential extreme heat events under climate change in the Phoenix Metropolitan Area for the period 2041-2070 based on the NARCCAP climate model ensemble under the SRES A2 emissions scenario. The NARCCAP simulations project a large change in extreme summer conditions in comparison to the last thirty years of the twentieth century. Specifically, based on current heat wave criteria the EHE frequency is projected to increase about sixfold to 1.94 events per summer accompanied by an extended average duration of 12.6 days per EHE for the model ensemble-mean. In comparison, the simulated ensemble-mean (observed) historical EHE frequency during the period 1971-2000 amounted to 0.32 (0.20) events per summer with an average duration of 6.3 days (10.5 days). The projected inter-model range for the average EHE frequencies per summer is 1.2 to 2.8 with maximum and minimum average durations of 18 days and 8.8 days. The increase in average $T_{\max}$ of 0.3 K (0.3 K) between simulated historical and projected EHEs is relatively small. This is due to the application of threshold temperatures that were derived from the historical simulations to identify future EHEs. The projected EHEs would be similarly rare as for the historical period and characterised by an average $T_{\max}$ of at least 2.8 K higher if T_1 and T_2 were determined from the simulated $T_{\max}$ (JJA) distribution for the period 2041-2070. This is due to the climate change signal in the 97.5th (T_1) and 81st (T_2) percentiles of 2.8 K.

The results of this study show a large uncertainty in the projected EHEs because of the range in the RCM/AOGCM projections. The uncertainties of the projections here even might be underestimated due to the limited number of RCM/AOGCM combinations in the model ensemble.

There are limitations to this study that arise from the lack of urban land use/land cover effects in the NARCCAP simulations. Further high-resolution downscaling of the NARCCAP results would be necessary in order to account for urban effects on the atmosphere in the simulations. Such downscaling would allow to assess effects of the city on nighttime air temperatures and also to include the response to urban development scenarios.

Another limitation is that NARCCAP simulations were only carried out for one greenhouse gas emissions scenario, and therefore we cannot assess uncertainty in the projections due to variation in scenarios. However, according to the CMIP3 AOGCMs, deviations in projected warming between lower (SRES B2) and higher emissions scenarios (SRES A2) are not as pronounced for the period 2041-2070 as they will be at the end of the century. Although the changes in EHEs discussed here are at the high end of projections, they might be representative of a larger range of emissions scenarios.

In the twentieth century, extreme heat contributed to the deaths of more people in the United States and Australia than any other weather disaster, such as floods, tornadoes, lightening and winter storms (*Kovats* and *Koppe* 2005). In a comprehensive evaluation of EHEs in 43 of the largest U.S. cities, including Phoenix, *Anderson* and *Bell* (2011) found that the intensity, duration and timing of heat waves (defined according to the community's long-term weather history) independently increased mortality compared to non-heat wave days for the period 1987-2005. One 2003 heat wave in Europe caused mortality excess rates between 28,000 (*Schär* et al. 2004) and 70,000 (*Robine* et al. 2008). Utilisation of health care services is many times larger than the number of deaths during heat waves (*Knowlton* et al. 2009; *Semenza* et al. 1999). For example, in the July 13-19, 1995 Chicago heat wave, *Semenza* and colleagues attributed 700 excess deaths to high temperatures but during the same period they identified several thousand excess hospital admissions for primary and secondary (comorbid) diagnoses (*Semenza* et al. 1996; *Semenza* et al. 1999).

The projected increase in extreme heat events and maximum daily air temperatures in Arizona, as shown in this study, may have large social implications for this arid region due to the negative impacts of extreme heat on human health (*Harlan* et al. 2014). We would also expect increased demand for energy use for air conditioning, and potential degradation in air quality by increased ozone production (*Nowak* et al. 2000). The projections of increasing EHEs in future central Arizona summers, viewed in the context of a large body of international research on the health effects of heat waves, suggest that there may be high costs in human life and utilisation of health care and emergency services in the Phoenix Metropolitan Area.

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