PROJECTED CHANGES OF HEAT WAVE CHARACTERISTICS IN THE EASTERN MEDITERRANEAN AND THE MIDDLE EAST

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Abstract According to climate projections and observations, the region that encompasses the eastern Mediterranean and the Middle East is identified as one of the most prominent climate change hot spots. In this part of the world where summers can be very hot, additional warming might have disproportional impacts. This includes human health effects and premature mortality, crop failures, and energy and water shortages that can be amplified during prolonged heat spells. The severity of such events can be expressed in various ways depending on societal aspects. Peak temperatures are critical for the agricultural sector. For energy planning and heat related health effects the duration of such events is also important. We present a comprehensive climatology of heat waves in the eastern Mediterranean and the Middle East region based on regional climate model simulations (HadRM3P), downscaling from a global climate model. We investigated to what extent may change in future. To cover a range of possible future climates we used an ensemble of three SRES emission scenarios. According to our simulations, all indices that characterize heat wave severity will increase.

Key words: Heat waves, Climate change, Eastern Mediterranean – Middle East, Regional climate modeling

1. Introduction

Based on observational data, the Intergovernmental Panel on Climate Change suggests that the warming of the climate system is unequivocal [1]. The report highlights that human influence has contributed to observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century, and has more than doubled the probability of occurrence of heat waves in some locations. Similar findings regarding the increased risk of heat extremes due to anthropogenic activities are presented in a number of studies [2-4]. In the likely scenario of a 2°C warmer world, almost every future summer will be as hot or hotter than the hottest that people have experienced in the recent past [5]. Increasingly, large-scale events such as the recent European heat waves of 2003 and 2007, in Russia in 2010 and in the USA in 2012 come to support these findings. Especially the 2003 and 2010 cases are characterized as “mega-heatwaves” [6] as they likely broke the 500-year seasonal temperature records over approximately 50% of Europe.

The occurrence and intensity of heat waves are mostly related to large-scale general circulation patterns and certain atmospheric flow anomalies. Such features include adiabatic heating, warm air advection and positive radiation anomalies as a result of reduced cloudiness [7-11]. Factors that may amplify extreme heat events can also include soil moisture-atmosphere interactions related to dry conditions [12-16].

In the already environmentally stressed eastern Mediterranean and Middle East (*EMME*) region, significant positive trends of temperature extremes are indicated by a number of observation-based studies [17-21]. Global and regional climate projections suggest that in this region heat stress intensification is very likely to continue throughout the 21st century [22-27].

Despite that heat waves sometimes occur without significant consequences, their effects may be more widespread than other severe weather phenomena or natural disasters [28]. For the rapidly increasing *EMME* population the occurrence of such extreme events might have tremendous impacts. Increased hospital admissions and human mortality, failure of crops, higher water and energy consumption, are examples. In addition, the increasing urbanization [29-30] and the associated locally produced or transported air pollution [31-32] or the urban heat island effect [33-34], might amplify these negative effects. Each of the societal aspects mentioned before can be differently affected by heat waves. For example, a short but extremely strong warm spell can dramatically reduce the quantity and quality of crop yields [35]. On the other hand, a relatively cooler but prolonged heat wave can increase human discomfort and mortality numbers. Moreover, long events that are usually connected with dry spells that increase water demand and forest fire risk [36].

In this study we present a comprehensive climatology of heat waves in the *EMME* region using data from a regional climate model. We calculated indices that describe the severity and persistence of such events. In order to explore potential changes over heat wave characteristics we repeated the analysis for a period covering the end of the 21st century when the signal of the warming is strongest. Finally, we try to explain why these changes are expected to occur.

2. Data

Since the coarse information derived from global models is not sufficient for impact studies and in most of the cases not representative for the complex *EMME* terrain (Fig. 1), we used a regional climate model (HadRM3P). HadRM3P [37] was developed by the Hadley Centre of UK's MetOffice. In our simulations, the model has a horizontal resolution of 0.22° (≈25km) and is driven by the HadCM3Q0 or HadAM3P General Circulation Models. To estimate a range of future possible climates we have created an ensemble of three *SRES* emission scenarios [38]. The selected scenarios cover a range of projected greenhouse gases emissions (Table 1), from an optimistic (*B2*) and an intermediate (*A1B*) to a more pessimistic estimation (*A2*). Daily maximum (*TX*) and minimum (*TN*) temperatures are used in order to identify summer heat extremes. Geopotential heights of the 500 hPa levels, derived from the model are used in order to explore the synoptic conditions during heat waves. Extended evaluation of the HadRM3P performance over the *EMME* region can be found in Lelieveld et al. [20,27]. Daily *ECA&D* [39] station data are used for testing. Four stations were selected based on availability of time consistent datasets for the 1961-1990 30-year period and the spread of the stations across *EMME*. These stations are the Athens (Hellinikon) station in Greece, Sivas station in Turkey, Eilat in Israel and Kerman station in Iran. The location of the stations is presented in Fig. 1. A large part of the *EMME*, especially in the Middle East part, may not be adequately covered from this selection of stations. This is due to the fact that consistent daily *TX* and *TN* observations in the region are either not publicly available or they do not exist at all throughout the period of study.

Table 1. Description of the global simulations and emissions scenarios

Global model	Emission scenario	Cumulative CO_2 - GtC (1990-2100)	2100 Population (Billion)	2100 Global surface warming (°C)
HadAM3P	A2	1862	15.1	3.4
HadCM3Q0	A1B	1499	7.1	2.8
HadAM3P	B2	1164	10.4	2.4

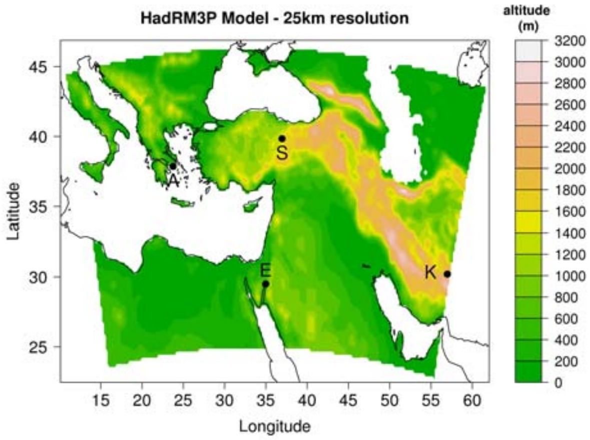

Fig. 1. Topography of the eastern Mediterranean and the Middle East region as represented in the HadRM3P model. The black dots indicate the location of the four stations used for the validation of the heat wave indices (A: Athens, S: Sivas, E: Eilat, K: Kerman)

3. Methods

3.1 Definition of heat waves

Even for a regional study it is not adequate to select a universal definition of heat waves. This is related to the complex orography, the distribution of land and major water bodies and the different climatic zones that are found in this atmospheric circulation crossroads. Therefore we used a percentage-based definition. Following the WMO guidelines on analysis of extremes [40], we defined warm spells as the number of days in a period of at least six days where *TX* > *TX* 90th percentile (*TX90*). *TX90* is calculated for a five-day window centered on each calendar day of the control period (*CTL*: 1961-1990). We considered as heat wave any warm spell that occurs in the extended summer season (May to September). A similar definition is used in Fischer and Schär [25]. For the future period (*SCN*: 2071-2099) we identified events according to the thresholds in the control period threshold. Hence, this represents the present-day understanding of heat waves.

3.2 Synoptic conditions

In order to identify the synoptic conditions related to extreme heat events, we created maps of the 500 hPa geopotential height averaged for the heat wave occurrence days and over the four selected *ECA&D* stations. Anticyclones that favor heat waves can have a radius of more than 1000 km, hence, these four stations are approximately representative of a domain of that magnitude. The Athens station characterizes conditions in Greece and the Balkan Peninsula, Sivas station represents the Asia Minor region, Eilat the conditions over the Levant and northern Arabian Peninsula and finally Kerman signifies the southwestern-most part of the *EMME*. The 500 hPa maps were created for both the *CTL* and *SCN* periods to investigate potential changes in synoptic conditions and try to connect circulation changes with heat wave characteristics.

3.3 Heat wave characteristics

Following Fischer and Schär [25] we calculated a range of indices characterizing the persistence and severity of heat wave events. These indices are: the average annual frequency of days (*HWF90*) meeting the heat wave criterion described in section 3.1, the average number of heat waves per summer (*HWN90*), the average peak temperature of the hottest heat wave per summer (*HWA90*) and finally, the average duration of the longest heat wave per summer (*HWD90*). Years without heat waves were excluded from the *HWA* and *HWD* calculations. Discomfort during heat waves is to a large degree attributed to high nighttime temperatures. During nighttime the human body should recover from the heat stress of the previous day. For non air-conditioned households, high nighttime temperatures can be critical for the health especially of vulnerable individuals. This category includes elderly people, infants, people exposed in outdoor activities and in general socially or physically isolated individuals. Hence, in addition to the aforementioned heat waves properties, we calculated the average number of combined hot days and tropical nights (*CHT*). These are considered summer days with a maximum temperature exceeding 35°C and a minimum nighttime temperature higher than 25°C. Often tropical nights are considered to be those with a minimum temperature over 20°C. Since this part of the world is already warm and these nighttime temperatures are common during summer, we used the 25°C threshold. Heat wave occurrences and all related indices are calculated for each of the three different scenario simulations and then averaged.

4. Results

4.1 Climate change in the EMME

Some general information from the climate change projections in the region is presented in Fig. 2. We focused on changes for the extended summer (May to September), averaged for the three greenhouse gas emission scenarios discussed in the data section 2. Changes in mean temperature between the *FTR* and *CTL* periods are depicted in the left panel of Fig 2. By the end of the century, the entire *EMME* region will experience a summertime warming ranging from 3 to 6° C. According to our simulations, this warming is not uniform across the region but is strongest in the northern part of the domain. In general, much of the region will experience a drying varying from 5 to 30% of the precipitation of the control period (Fig. 2 – right panel). The increase in precipitation projected over the southeast part of *EMME* is a robust result of climate change modeling studies. It can be attributed to a northward expansion of moist tropical weather influences [20] and is consistent with observed recent rainfall trends [21]. These increases might be large in percentage, however, they are small in absolute amounts.

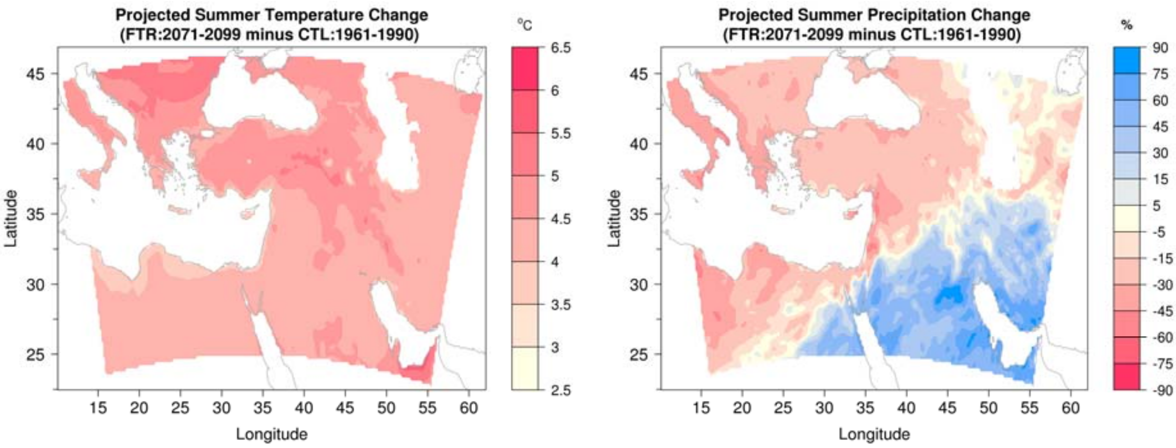

Fig. 2. Projected changes of summer (May to September) mean temperature (left) and precipitation (right) based on HadRM3P model results, averaged over the *A1B*, *B2*, and *A2* emission scenarios.

4.2. Synoptic conditions

As mentioned in the introduction section, extreme heat events are usually connected with large-scale anticyclonic weather systems. Fig. 3 depicts the mean synoptic conditions (500 hPa geopotential height) for heat wave occurrence days in four locations over the *EMME* for the *CTL* period.

For all cases, heat waves are connected with high 500 hPa geopotential heights. For Athens, according to our simulations, heat waves occur when a ridge in approximately north-south direction is developed to the west part of the domain. This structure brings hotter air from Africa into the region. The upper air circulation patterns during heat wave occurrences in Athens are in agreement with the atmospheric conditions during specific heat events case studies, described by Balafoutis and Makrogiannis [41] and Founda and Giannakopoulos

[42]. The heat wave pattern is similar for the Sivas station while the ridge of high geopotential height is located more to the east. In these two cases hot air advection is the key mechanism for the occurrence of heat waves. For the Kerman and Eilat stations, during heat wave days, the center of high geopotential heights is located directly overhead. Besides advection, adiabatic heating due to subsidence can also contribute importantly. During the *SCN* period, the region is projected to experience enhanced anticyclonic conditions during summer but the circulation patterns are more or less similar to the *CTL* period (not shown).

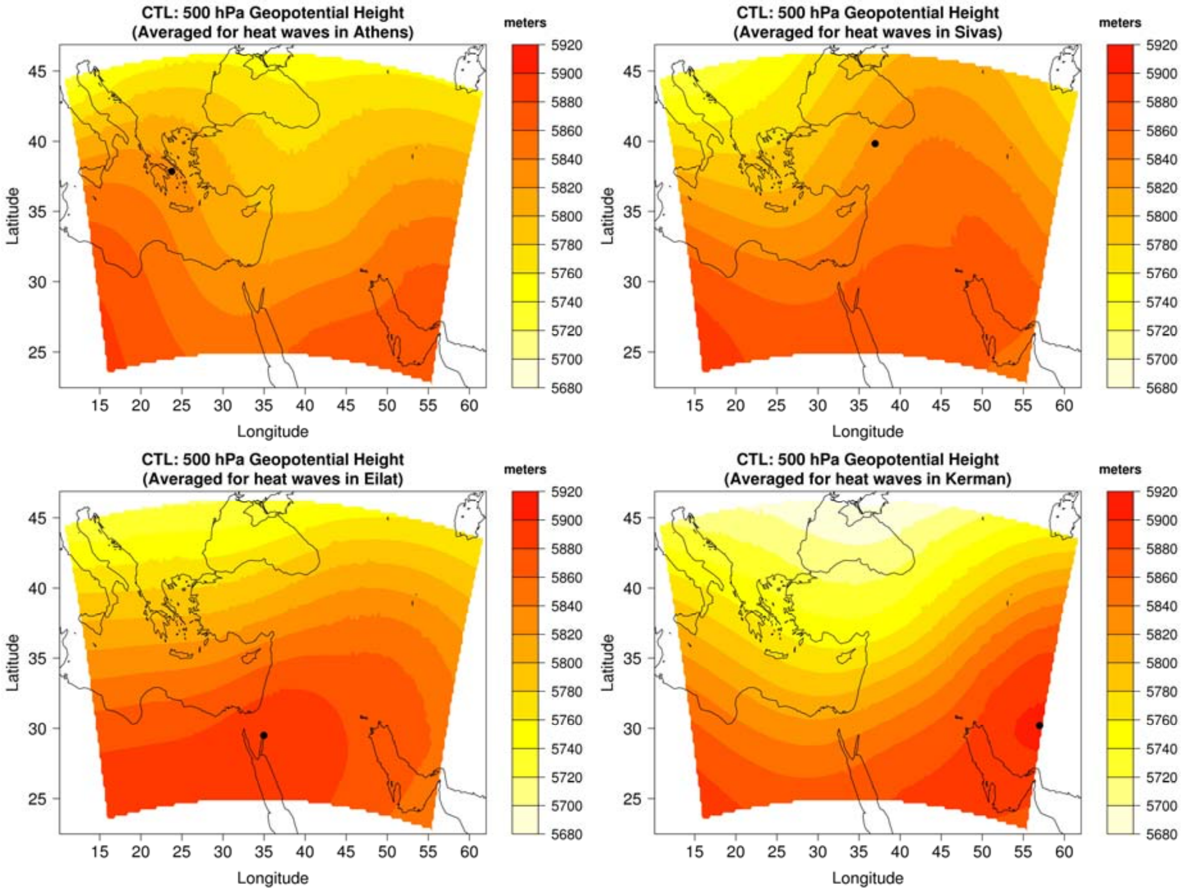

Fig. 3. Geopotential height of the 500 hPa level averaged for the heat wave occurrence days over (a) Athens, (b) Sivas, (c) Eilat and (d) Kerman during the *CTL* (1961-1990) period.

4.3 Comparison with observations

In order to explore how well the regional model represents the heat wave characteristics that were discussed in the methods section, a comparison with station data was performed. The four selected stations cover a range of climatic zones ranging from desert climate (Eilat) to a Mediterranean (Athens) or more continental type (Sivas, Kerman). The results of this comparison are presented in table 2.

In general, the HadRM3P model seems to reproduce the heat wave properties for the *CTL* period and the selected stations reasonably well. The frequency (*HWF*) of heat wave occurrence days per summer and the annual average number of events (*HWN*) are in the range of the observations. However, a general overestimation of these two indices is identified. Likewise, HadRM3P overestimates the duration of events (*HWD*) by 1-2 days. Peak temperatures (*HWA*) are underestimated for Athens and Kerman. This can be attributed to the fact that model grid points for the specific stations are at higher elevation than in reality. Finally, the combined hot days and tropical nights are reasonably well reproduced for all stations except Eilat. This difference between the observed number of *CHT* days is probably again a result of the elevation overestimation related to the resolution of the model. More detailed evaluation of the model for both mean climate variables and extremes can be found in Lelieveld et al.[20,27].

Table 2. Heat wave indices comparison between four *ECA&D* stations and the HadRM3P ensemble output for the control period (*CTL*: 1961-1990). *HGT*: height, *HWF*: heat wave frequency, *HWN*: heat wave number, *HWD*: heat wave duration, *HWA*: heat wave amplitude, *CHT*: Combined hot days-tropical nights.

	Units	Athens		Sivas		Eilat		Kerman	
		ECA&D	MODEL	ECA&D	MODEL	ECA&D	MODEL	ECA&D	MODEL
HGT	meters	10	159	1285	1503	12	516	1754	2093
HWF	days/summer	2	3.1	2.2	3.2	2	2.4	2.1	5.2
HWN	events/summer	0.3	0.4	0.3	0.4	0.3	0.3	0.3	0.7
HWD	days/event	6.5	9.1	6.8	8.9	6.8	7.8	8.3	8.9
HWA	°C	33.4	31.8	31	31.4	43.3	43.4	38.6	36.2
CHT	days/summer	2.6	3.4	0	0	54	2.6	0.1	0

4.4 Heat Wave Characteristics

The left panel of Fig. 4 depicts the recent past (1961-1990) climatology of the *HWF* index. The mean annual frequency of days that meet the heat wave criteria in most areas does not exceed four or five days. Two *HWF* maxima over the *EMME* region are identified. One is located over south Iran and one over the Balkan region. The right panel of the same figure depicts the changes for the scenario period (2071-2099) averaged for three *SRES* emission scenarios and calculated using the control period threshold. The mean frequency of heat wave days per year will be dramatically increased in the whole of *EMME* region. According to our simulations, these increases will range from approximately 20 to 130 days per year and will be most pronounced over the Arabian Peninsula and the Gulf region.

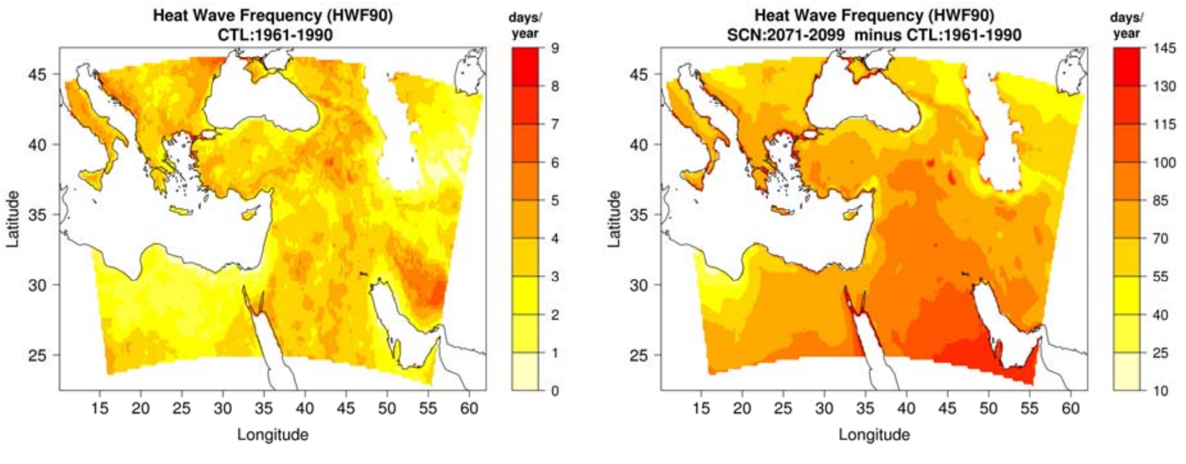

Fig. 4. Recent climatology (left panel) and future changes of the heat wave frequency (*HWF90*) index (3 scenarios ensemble)

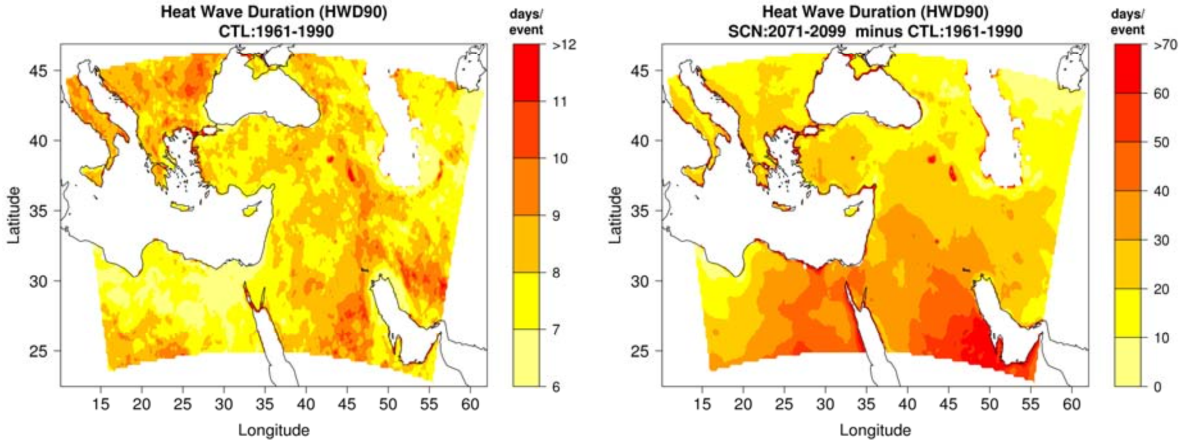

Fig. 5. Same as figure 4 for the heat wave duration index (*HWD90*).

The index that describes the duration of summer extreme events is presented in Fig. 5. For the control period (left panel), according to HadRM3P simulations, heat waves in the region have an average length that varies from 6 to 12 days. By the end of the century these heat events will be several weeks up to months longer. The changes are again stronger over the southern part of our domain and the Arabian Peninsula.

The strong increases of the *HWF* and *HWD* indices over the southern part of the domain and especially the Arabian Peninsula can be illustrated using the probability density function of *TX* over these regions and the percentage-based definition of heat waves we used. In the aforementioned areas the 90th quantile is closer to the median and mean values (Fig. 6). Therefore, under warmer climate conditions it is more likely to exceed the heat wave definition threshold (section 3.1). In contrast, in the northern part of the domain, although the summertime warming is relatively stronger (Fig. 2), the 90th quantile is more distant from the median and mean *TX* values. As a result, the heat wave threshold is less likely to be exceeded in the *SCN* period resulting in relatively smaller changes of the *HWF* and *HWD* indices over the northern *EMME*. Therefore a larger projected change in heat wave properties over certain geographical areas may not only be a direct response to mean warming but also related to the kurtosis of the respective *TX* probability distribution.

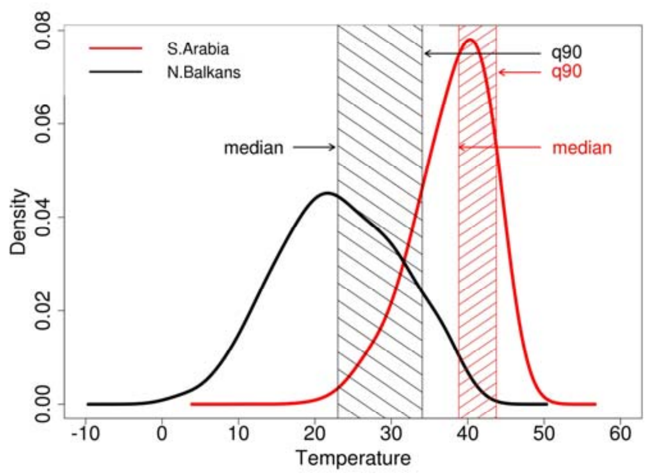

Fig. 6. Probability distribution of maximum temperature for the *CTL* (1961-1990) period and two grid points, one in Saudi Arabia (red curve) and one in northern Balkans (black curve)

Heat wave events in the EMME region are expected to become a more frequent weather phenomenon. The right panel of Fig. 7 depicts the changes in the average number of events per year (*HWN*). Up to 8 more occurrences per year are projected. The changes are larger for the northern part of the domain. This index is connected with the duration index (*HWD*). According to our simulations, in the southern part of the domain heat waves will occur in a few but very long events. On the other hand, in the northern part, heat waves are expected to be higher in number but of relatively shorter duration comparing to the southern part of the domain.

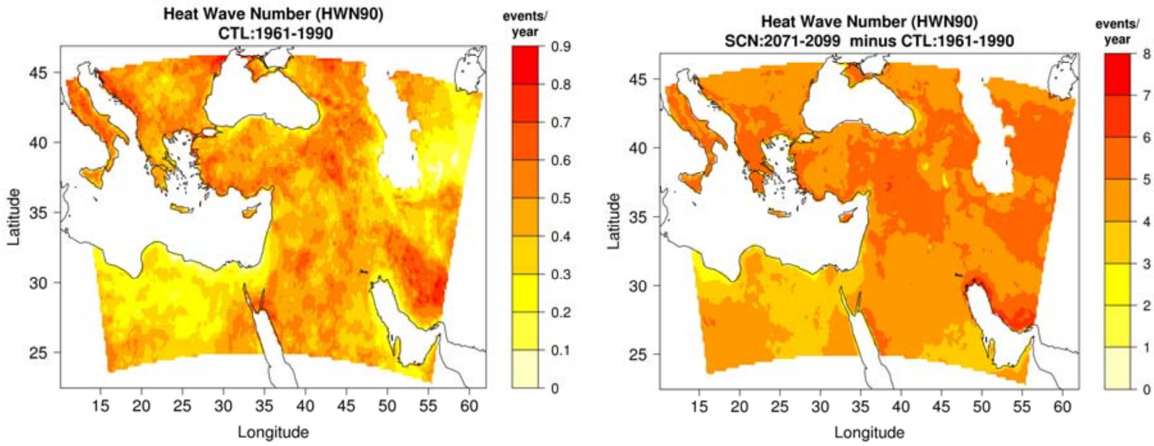

Fig. 7. Same as figure 4 for the heat wave number index (*HWN90*).

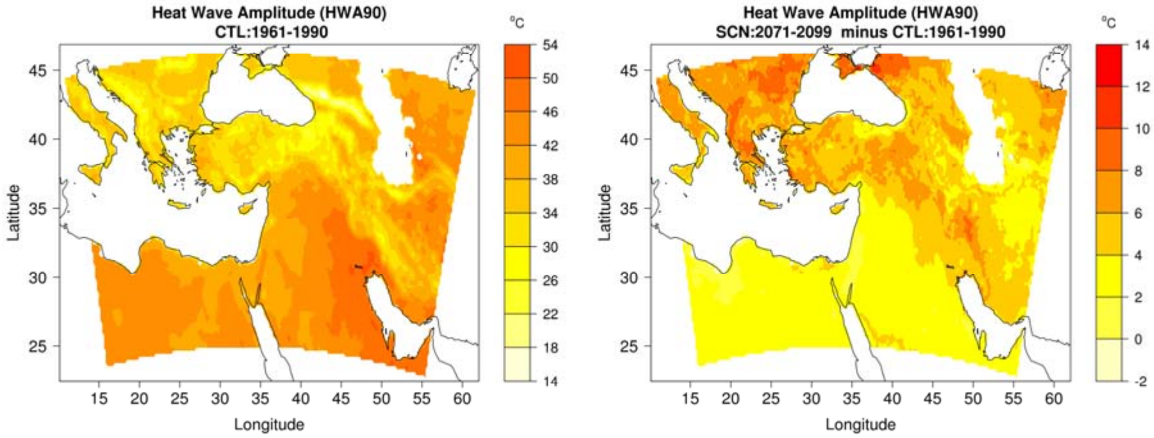

Fig. 8. Same as figure 4 for the heat wave amplitude index (*HWA90*)

The heat wave negative impacts in some sectors are proportional to the peak temperatures. The heat wave amplitude index describes the average peak temperature of the hottest event per year. *HWA* for the control period is depicted in the left panel of Fig. 8. As expected, peak temperature follows the orography and also depends on the latitude of each location. For the future scenario period the increases in peak temperatures are larger in the northern part of the domain and especially the Balkan Peninsula (Fig. 8 – right panel). This is in agreement with the projected changes in summer temperatures over the region depicted in Fig. 1 and also identified in Lelieveld et al. [21] and Zittis et al. [16]. During the summer season the warming is not uniformly distributed and is stronger in the northernmost *EMME*. This can be explained by the combined intense drying over this part of the domain (Fig. 2 – right panel). In the already dry southern part, sensible heat fluxes prevail, and therefore evaporative cooling is negligible both in the control and future periods. However, in the northern *EMME* evapotranspiration, being a key cooling mechanism, will be reduced under the projected drier conditions [16]. For some locations, especially in the northern part of the domain, the increase in heat wave peak temperatures is much stronger than the mean summer temperature change, presented in fig. 2 (left panel).

4.5 Combined hot days and tropical nights

The *CHT* index, which describes the combination of hot days and tropical nights, is presented in Fig. 9. In most of the *EMME* region the number of *CHT* days is limited to less than two weeks in total per summer or year (Fig. 9 – left panel). Higher *CHT* numbers are found in the Mesopotamia region. This region differs from the surrounding non-vegetated areas where radiative cooling during the night reduces minimum temperatures to less than 25°C. This number is projected to dramatically change by the end of the 21st century. In the entire *EMME* region *CHT* is expected to become more frequent with larger increases projected for the southern and hotter part. These increases are stronger in the southern part of the domain where up to 100 additional *CHT* days are projected. Exceptions are the mountainous areas including the Dinaric Alps, Taurus, Caucasus and Zagros mountains. Despite the projected warming, nighttime temperatures over the aforementioned regions will not often exceed 25°C and therefore the increases in the number of *CHT* are relatively small. Besides human health, these changes can be of great importance for the energy sector. Since air conditioning during nighttime will probably be an essential need, energy demand profiles are likely to change.

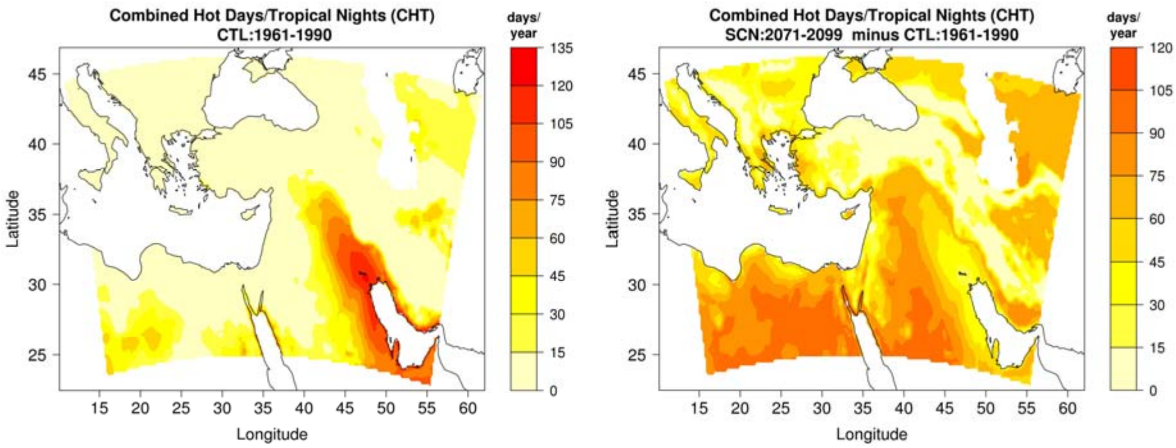

Fig. 9. Same as figure 4 for the heat wave number index (*CHT*)

5. Discussion and Conclusions

This study aims to detect and attribute climate warming-related changes in heat wave characteristics in order to inform policy makers in the *EMME* region and motivate mitigation measures and development of adaptation strategies. According to our projections heat waves in the *EMME* are expected to change from events with a return period of about 2 years on average to a common phenomenon with multiple occurrences per year. All indices that describe the frequency, persistence and severity of these extreme events are projected to increase strongly.

Heat waves, as defined by present-day standards, will have extraordinary duration of several weeks to months. In addition, much hotter heat events are expected by the end of the century. Changes in severity of heat waves in terms of peak temperatures will probably exceed by far the projected mean summer temperatures increases. Besides the general global warming, these changes of heat wave peaks can be attributed to the stronger summer anticyclonic conditions projected for *EMME*, resulting in stronger advection of warm air masses from lower latitudes in the northern locations, and more pronounced adiabatic heating due to increased subsidence in the southern locations. The number of tropical nights is also projected to increase in the whole *EMME* region. This climate change feature will probably increase human discomfort and energy demand, and may have serious health impacts.

Changes in the discussed properties of heat waves will not be uniformly distributed over the domain. Alterations in frequency and duration related indices are expected to be most pronounced in the southern part of our domain and especially over the Arabian Peninsula. This is related to the percentage-based definition of heat waves we use in this study and the leptokurtic nature of the probability distribution of *TX* in the aforementioned regions. On the other hand, changes in characteristics related with number of events and peak temperatures will be stronger in the northern part of *EMME*. Changes in the number of events is connected with the relevant changes in duration. The north-south gradient in peak temperatures is consistent with the changes in mean temperature and is related to the stronger drying over the northern part of the domain, which reduces summer evapotranspiration and the associated cooling.

The current fossil fuel-based energy production in the *EMME* region will probably become more intense in order to provide the essential space cooling and refrigeration needs. This can be translated into more greenhouse gases emissions, which as a vicious circle problem, enhancing the greenhouse effect and leading to even higher temperatures. Switching to cleaner or renewable energy sources, implementation of energy efficiency techniques and proper environmental education in the region can contribute, at least partially, to mitigation of the problem.

Since future summer conditions might be hotter than the hottest the region ever experienced, the timely design and implementation of adaptation strategies in sectors like agriculture, water supply, energy production, food security, human health, tourism and biodiversity is highly recommended. In addition, side effects of these devastating changes may include possible human displacement (UNHCR, 2009), which has to be seriously considered.

The modeling results derive from a three-simulations ensemble. However, uncertainties related to initial and boundary conditions, physics of the model and greenhouse gas emissions cannot be neglected. Since most of the region of interested is not included in the large European projects that dealt with these uncertainties we had to base our study on the presented in-house produced simulations. With the consideration of two global models and three emission scenarios we somehow covered, at least a partly, some uncertainty in regional climate modeling. However, analysis with future results from current and planned multi-model projects that consider the *EMME* region (e.g. the CORDEX experiment[1]) can make the results more robust.

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