Reduced impacts of heat extremes from limiting global warming to under 1.5 °C or 2 °C over Mediterranean regions

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Abstract

Heat extremes have a serious impact on humans and on agriculture around the world. As one of the prominent climate change ‘hot spots,’ the Mediterranean area, especially the eastern portion, is expected to be more vulnerable to heat exposure than other regions due to its high population density and urbanization rate. The Paris Agreement includes the goal of ‘holding the increase in the global average temperature to well below 2 °C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above preindustrial levels.’ It is interesting to study how heat extremes would change in the Mediterranean area in a +1.5 °C and +2 °C global warming world and how they would impact humans and agriculture. Based on high resolution climate scenario data from Coordinated Regional Downscaling Experiment Mediterranean, we calculate several heat extreme indices to study heat extreme changes in the future. We found that in most Mediterranean areas, both daytime and nighttime heat wave intensity and frequency will have a robust increase in the 21st century compared with that of the historical period, with the most prominent areas located in northwest Africa, the Iberian Peninsula, Italy and Middle East. Meanwhile, nighttime heat waves should be garnering more attention because more moderate and extreme events happen in nighttime than in daytime. If the global warming level is limited to 2 °C or even 1.5 °C, the percentage of population exposed to dangerous events (especially one-in-20 year events) and yield loss from maize harvested areas may be much less in the future than the percentage affected during 3 °C warming period. Moreover, limiting global warming to 1.5 °C instead of 2 °C would result in an additional 20%–25% reduction of exposure.

1. Introduction

Heat extremes have become more intense, frequent and longer-lasting in Asia (Chen and Li 2017, Miao et al 2020), Australia, (King et al 2017), America (Smith et al 2013,) and Europe (Russo et al 2014, Christidis et al 2015, Russo et al 2015, King and Karoly 2017, Liu et al 2020) during recent years. Exposure to extreme heat could possibly cause sudden cardiovascular illness and cerebrovascular diseases (Huang et al 2010) leading to increased mortality (D’Ippoliti et al 2010, Mitchell et al 2016), particularly for vulnerable people above 65 years old. In America, heat extremes cause more deaths than other extreme events (Jones et al 2015). In Europe, more than 70 000 additional deaths occurred during the summer of 2003 (Robine et al 2008). Heat extremes also have a serious impact on agriculture and the ecosystem (Ciais et al 2005). Maize is a major food crop that is very sensitive to heat extremes (Lobell et al 2013, 2014). During the heatwave of 2003, the maize yield had a 20% loss compared...
with previous years and resulted in an overall loss of € 4 billion to the agricultural sector in France (van der Velde et al 2010, 2012). Studies show that extreme degree days (EDDs) have a strong negative effect on maize yield (Zhang et al 2015). In Africa, each EDD reduces the maize yield by 1% (Lobell et al 2011).

The Mediterranean is expected to be one of the most prominent and vulnerable climate change ‘hot-spots’ of the 21st century due to its complex coastlines and topography (Giorgi 2006). From the middle of the 20th century, the mean temperature over the Mediterranean is increasing higher than the global average, and observed heat waves have become more frequent and intense, especially in its eastern part (Kuglitsch et al 2010). Meanwhile, due to its ageing population, high rates of urbanization, and high prevalence of cardiovascular and respiratory diseases, the Mediterranean is one of the most vulnerable regions to heat exposure (Watts et al 2019). Research shows that total mortality increases by 21.8% during heat wave days over the Mediterranean (D’Ippoliti et al 2010). In addition, extreme heat has a serious impact on maize and wheat yields over Mediterranean countries, which influences the whole of Europe’s food security (van der Velde et al 2012). According to the target to limit global warming to well below 2 °C and pursue efforts to limit the temperature increase to 1.5 °C above preindustrial levels in the 2015 Paris Agreement, Dosio and Fischer (2018) found that the number of hot days and nights in the Mediterranean area will increase more than in other parts of Europe in the 1.5 °C and 2 °C warmer scenarios. Hot summer events will become more persistent in a 2 °C world in the Mediterranean, which is probably due to weakening summer storm tracks (Pfleiderer et al 2019). Jacob et al (2018) found that one-in-20 years heat waves will become common over the Mediterranean in a 1.5 °C warming world. Seldom has research considered the exposure of nighttime events although they have been proven to be a risk to people’s health as well (Weisskopf et al 2002, Bumbaco et al 2013). Heat extremes also have been found to impact crop yields (Bouras et al 2019, Hawkins et al 2013), but most studies have been limited to one country only. Two of the top five maize-producing countries (France and Romania) are located in the Mediterranean (Feng and Hao 2020); therefore, it is meaningful to study how different daytime and nighttime heat extremes might change in the Mediterranean and how they might impact the population and maize yield in different warming scenarios.

We calculate several heat extreme indices (five indices related to heat waves, one related to maize yield) to study heat extreme changes in future. Three major questions we want to address are as follows: (a) How will the intensity, duration, frequency and other aspects of daytime and nighttime heat waves change in the 21st century especially in a +1.5 °C and +2 °C warmer world? (b) How many people will be exposed to dangerous events and which country will contribute the most? and (c) What percentage of maize harvest areas will be exposed to the risk of maize loss? We show evidence that the robust increase of daytime and nighttime heat extremes will cause a serious impact on population and agriculture, however, the situation can still be controlled in a +1.5 °C and +2 °C warmer world. Therefore, our findings may call out society attention and provide a reference for policy makers.

The remainder of this paper is organized as follows: section 2 will discuss the data used and define several indices. Section 3 will first present results of characteristics of heat waves for the Mediterranean, then present the heat extreme impacts on population and agriculture. Finally, we present a discussion and conclusions in section 4.

2. Data and methods

2.1. Data

2.1.1. Observation data

In this study, daily 2 m maximum, minimum and average temperature data were obtained from E-OBS (https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php) and ERA5 (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form). The original E-OBS data (1971–2016) were obtained through interpolating more than 7300 meteorological stations records over Europe, the Middle East and North Africa to a spatial resolution of 0.25° × 0.25° gridded data (Haylock et al 2008). The latest version of E-OBS used an improved interpolation method which calculated a 100-member ensemble mean value to reduce uncertainty compared to its old version (Gornes et al 2018, Raymond et al 2019), which is widely used for bias adjustment and evaluation of regional climate models (RCMs) (Panthou et al 2016, Jacob et al 2018). ERA5 data from 1979 to 2016 are used as a supplement in our study. Different from E-OBS, ERA5 is an hourly reanalysis data with a spatial resolution of 0.25° × 0.25°, and it served as an updated version of ERA-Interim.

2.1.2. Regional climate models (RCMs) data

The World Climate Research Programme (WCRP) launched Coordinated Regional Downscaling Experiment (CORDEX; Giorgi et al 2009) to build a framework for providing high resolution climate data and evaluating some uncertainties affecting regional climate projections. Here, we use MED-CORDEX, which is a unique framework designed to study the Mediterranean using different global climate models (GCMs) and RCMs (Vautard et al 2013, Ruti et al 2016). Five climate models from MED-CORDEX which contain historical data (1971–2005), RCP 4.5 and RCP 8.5 data (2006–2099) with a spatial resolution of approximately 50 km (MED-44) are used in
this study. The 2 m maximum, minimum and average temperature data values can be downloaded from (www.medcordex.eu). Detailed information about the selected models and their driven GCMs are shown in table 1.

2.1.3. Future population data
Assuming that the population is mainly affected by fertility, mortality, and migration, we use a new dataset which uses different combinations of the above three factors referring to different developing conditions (SSP1: sustainability, SSP2: middle of the road, SSP3: regional rivalry, SSP4: inequality, SSP5: fossil-fuel development) (Jones and O’Neill 2016). This global spatial population projection data contains urban and rural population at a resolution of 1/8° (Gao 2017). Based year (2000) population data and projection population data under different SSPs (SSP1–5) were obtained from (www.cgd.ucar.edu/iam/modeling/spatial-population-scenarios.html). These data allow us to estimate the population exposure to extreme heat waves consistent with different patterns of development.

2.1.4. Maize yield data
The latest version of the global dataset of historical yields provides historical yields from 1981 to 2016 for four major crops with a spatial resolution of 0.5° × 0.5°. This dataset uses a United Nations statistical database (FAOSTAT) and other remote sensing data to estimate grid-cell yield (Iizumi and Sakai 2020). The yearly maize yield data contained in this dataset were obtained from (https://doi.pangaea.de/10.1594/PANGAEA.909132). The aligned version v1.2 + v1.3 results not only agree with other datasets (Ray et al 2012), which just contain crop yield from 1995 to 2005, but they also include 2016 data to meet the latest scientific demand. A dataset containing harvested area and yield for 175 crops (Monfreda et al 2008) were used in our study to calculate a weighted average heat extreme index (see in methods). The area fraction of maize harvested data can be downloaded from (www.earthstat.org/harvested-area-yield-175-crops/).

2.2. Methods
2.2.1. Definition of warming levels
In our study, we use the ‘Time sampling’ method to define global warming levels (GWLs) which has been widely used in previous research (James et al 2017, Maüre et al 2018, Ge et al 2019). According to IPCC AR5, 1986–2005 is 0.61 °C (HadCRUT4) warmer than 1850–1900 (defined as ‘an approximation of preindustrial levels’) (Stocker et al 2013). We define 1986–2005, 1850–1900 as reference period and pre-industrial (PI) period respectively.

Assuming that RCMs are driven by their original GCMs, when a 20 year period moving averaged global temperature is 0.89 °C/1.39 °C/2.39 °C above its reference period for the first time, we define this 20 year period as 1.5 °C/2 °C/3 °C warming period. Five models used in our study all have RCP 4.5 and RCP 8.5 scenario data, so we have a ten-member (1.5 °C/2 °C GWLs) or seven-member (3 °C GWL) ensemble dataset (table 1). Although there is a little difference in the time-sampling step (e.g. different PI and reference period), it does not affect the results (Maüre et al 2018)). Time sampling is easier for calculation compared with other methods and it allows us to reduce the model’s uncertainty.

2.2.2. Bias correction
Due to the inadequate parametrizations of physical processes, complex topography and other factors, climate simulations may contain some systematic errors compared to the observation data (Jacob et al 2018). Thus, we use the CDF-t (cumulative distribution function transform, Michelangeli et al 2009) method, which is widely used in previous studies (Yang et al 2018, Guo et al 2020) to do bias correction.

2.2.3. Heat extreme indices
Although there are no unified standards, two types of indices (absolute indices and relative indices) are used to evaluate heatwaves (Qiu and Yan 2020). Expert Team on Climate Change Detection and Indices (ETCCDI) which contain both absolute indices and relative indices have been widely used in previous studies (Dosio et al 2018, Yang et al 2018). However, the ETCCDI indices (SU, TR, TXx, TNx, TX90p, and TN90p) may not be able to describe the detailed characteristics of a heatwave event. Furthermore, some indices are based on absolute thresholds (SU and TR), which may be not suitable in some regions (Perkins and Alexander 2013). Thus, we use the heatwave framework constructed by Perkins and Alexander (2013) to study different aspects of heat waves. The framework is based on Fischer and Schär (2010), and includes HWN (the total number of events), HWF (the total number of heat waves days), HWA (the peak temperature of the hottest event), and HWM (the average peak temperature of yearly events). Considering that HWA refers to the peak temperature of the hottest heat wave, it may be not exactly appropriate for evaluating heat wave intensity in our study, since Africa-Mediterranean (AM) regions have higher $T_{\text{max}}$ than other Mediterranean regions in Europe. Thus, we use the Heat-wave magnitude index daily (HWMD) defined by Russo et al (2015). It combines the magnitude and duration of heatwave events which enables us to assess the severity of an event more clearly.

In our work, we study daytime and nighttime heat waves from May to September, where a daytime/nighttime heat wave is defined as a spell in
which at least six consecutive day maximum/minimum temperatures (\(T_{\text{max}}/T_{\text{min}}\)) are higher than a daily threshold. The daily threshold is calculated as the 90th percentile of \(T_{\text{max}}/T_{\text{min}}\) for 1971–2000 based on the surrounding 15 d (7 d before and after). The Mediterranean regions (28–48 N, 9.5 W–38.5 E) defined by Giorgi and Lionello (2008) is shown in figure 1.

EDD, the sum of growing degree days above 30 °C, which was defined by Lobell et al (2011), is used to evaluate the impact of heat extremes on maize yield. Then, to define the degree that EDD departs from its mean state, we use the z-score to calculate each year’s standard score for each grid (equation (1)).

\[
Z = \frac{P_i - \bar{P}}{\sigma}
\]  

(1)

\(P_i\) denotes maize’s EDD in a given year \(i\). \(\bar{P}\) denotes the mean EDD from 1971 to 2000 and can be seen as the climate mean state, and \(\sigma\) denotes the standard deviation. Since there are too many missing values existing in AM, we do not compare subregional changes. The fraction of land harvested data from Monfreda et al (2008) for maize is used to calculate historical and future weighted area average EDD for the whole Mediterranean, similar to Hawkins et al (2013).

2.2.4. Estimated impacts

In our study, we use the percentage of population and maize harvest area exposed to dangerous events to represent the impact of heat extremes. Different levels of dangerous heat waves are defined as HWMId exceeds the 10- or 20 year return values, which are fitted by generalized extreme value distribution from the 1971 to 2000 base period (Kharin and Zwiers 2005). Similarly, we define the dangerous events in agriculture according to the relation between the EDD’s return values and maize yield change on each grid. Yield change is defined as the change between an extreme year and the expected year (equation (2)).

\[
\text{Yield change} = \frac{\text{Yield}_{(i)} - \text{Trend}_{(i)}}{\text{Trend}_{(i)}} \times 100\% \quad (2)
\]

Table 1. Information about the RCMs and their driving GCMs. The central year when RCMs reach 1.5 °C, 2 °C and 3 °C warming under different RCPs are shown respectively in the 4th–9th column.

| Institute | RCM        | Driving GCM     | 1.5 °C | 1.5 °C | 2 °C RCP | 2 °C RCP | 3 °C RCP | 3 °C RCP |
|-----------|------------|-----------------|-------|-------|----------|----------|----------|----------|
| ICTP      | RegCM4-3   | HadGEM2-ES      | 2023  | 2019  | 2039     | 2032     | 2070     | 2052     |
| LMD       | LMDZ4NEM   | IPSL-CM5A-MR    | 2025  | 2024  | 2045     | 2037     | NA       | 2055     |
| GUF       | CCLM4-8-18 | MPI-ESM-LR      | 2034  | 2029  | 2061     | 2045     | NA       | 2068     |
| ELU       | RegCM4-3   | HadGEM2-ES      | 2023  | 2019  | 2039     | 2032     | 2070     | 2052     |
| CMCC      | CCLM4-8-18 | CMCC-CM         | 2033  | 2030  | 2050     | 2042     | NA       | 2061     |

Here, Yield\(_{(i)}\) denotes the observed data in a certain year, and trend denotes the expected yield in a long-term period (estimated for the period 1981–2016). This index reflects the yield deviation from the long-term trend. By assuming that the crop yield change is mainly caused by climate variability, the index can be used as a measure to quantify the climate variability and extreme climate impact (Li et al 2019). In this study, we mainly focus on the high temperature’s influence on maize yield, and other factors (e.g. precipitation, drought) that have been shown to influence maize yield in the Mediterranean (Schleussner et al 2018, Schewe et al 2019) will be studied in future research.

To answer the question of what impacts of heat extremes can be avoided if we limit GWLs to 1.5 °C rather than 2 °C or 3 °C, we calculate the avoided impact (AI, Zhang et al 2018). C3, C2, and C1.5 refer to the changes at 3 °C, 2 °C or 1.5 °C warming levels relative to reference period, respectively.

\[
AI = \frac{C3(2) - C1.5}{C3(2)} \times 100\%
\]  

(3)

3. Results

3.1. Characteristics of heat waves

To study the performance of RCMs, we compare the difference of indices between models and observations. Models may have bias in simulating extreme events (Perkins 2011), but multi-model ensemble (MME) and bias correction could reduce the uncertainty and provide more reliable results than original data (figures S1, 2 available online at stacks.iop.org/ERL/16/014034/media).

Detailed information about the MED-CORDEX models used in this study are shown in table 1. The central years when an individual RCP reaches 1.5 °C, 2 °C, and 3 °C warming is obtained from ‘time sampling’ methods. The spatial patterns of HWN, HWA, and HWMId are shown in figures 2 and 3, patterns of HWF and HWM are shown in figures S3, 4. Areas which both satisfy the significance test and model agreement represents that robust change has occurred between two periods (Tebaldi et al 2011).
Almost all areas have a significant change during the 1.5 °C and 2 °C warming periods compared to the historical period for all daytime indices, and the changes are reliable except in some parts of Switzerland, Romania and Libya (figure 2, columns 1 and 2). During the 2 °C warming period, models show the same sign in more areas (figures 2(e) and (h)). African-Mediterranean has a larger change than European-Mediterranean compared to its reference period, and in the whole Mediterranean, the most prominent areas are northwest Africa, Iberian Peninsula, Italy and Middle East (figure 2, column 2), which is consistent with previous studies (Fischer and Schär 2010, Jacob et al 2018). In the above areas, the
yearly heat wave number (HWN) increases exceeding 2–3 times/annual, the hottest peak temperature of yearly events (HWA) increases 1–4 °C and HWMid increases 4–20 compared with the reference period (figures 2(b) and (e)). Comparing the difference between the 2 °C and 1.5 °C warming period, the models show agreement on the changes in most areas.

With respect to nighttime heat waves (figure 3), similar spatial patterns can be found, but the change in different indices between the 2 °C and 1.5 °C warming period are larger than the daytime indices.
e.g. for HWN, most areas’ increases exceed 1.5–3 times in the 2 °C period compared with the reference period (figure 3(b)). This is due to the faster and larger change of minimum temperature in some regions (Scorzini et al 2018). During the 3 °C warming period, both daytime and nighttime indices exhibit a greater increase (figures 2 and 3, column 3), however, if the GWL is reduced to 1.5 °C, the increment of HWN, HWA, and HWMId can be reduced by 0.5–1.5 times, 0.6–1.2 °C, and 4–8 respectively, which again emphasizes the importance of reducing GWLs by as much as possible.

3.2. Impact of heat extremes on the population

Previous research has proved that the return periods of extreme and moderate heat waves will largely decrease in the 1.5 °C and 2 °C global warming period (Russo et al 2019), which means current heat extremes will become more frequent and cause higher heat-related mortality in the future (King et al 2018, Mitchell et al 2018). Since the Mediterranean has been one of the most vulnerable regions because of its high percentage of ageing people in the historical period, people in the Mediterranean will be exposed to a higher risk of heat stress in the future (Rohat et al 2019). Assuming that the one-in-ten years events and one-in-20 years events will very likely increase the mortality of relevant diseases (Im et al 2017), we calculate the percentage of population exposed to different levels of events during different warming periods. As is shown in table 1, for most models, 1.5 °C and 2 °C GWLs will be reached before 2050, 3 °C level will be reached before 2100, so we use the population in 2050 and 2100 to make a comparison. We also select 12 main countries/regions to exhibit the sum of exposure in each country/region respectively during corresponding warming periods (figures 4 and 5). Here we only show population under SSP3 (assumes a high population growth, Dosio et al 2018), other SPPs are put in our supplement information (figures S9–S16). Location of countries and regions are shown in figure S8.

For different levels of both daytime and nighttime events, during 3 °C warming period, the increasing trend of exposure is obvious compared to other GWLs and reaches over 20/5 million persons in most countries (figures 4 and 5). To compared the reduced impacts of limiting global warming under the same level of population, we calculate the AI using the population in 2100 (figure 6). If global warming is limited to 1.5 °C, the exposure of different levels of events for daytime and nighttime will decrease 46.8% (48.4%) and 48.9% (50.5%), compared to 2 °C, and 76.2% (78.7%) and 76.6% (83.0%) compared to 3 °C (figure 6). Moreover, the AI of one-in-20 years is higher, which suggests that limiting GWLs helps to reduce the impacts of more dangerous events.

Population exposure to nighttime events (figure 5) is higher than daytime events (figure 4), especially in France and Egypt. The spatial difference of exposure is obvious, generally, Europe Mediterranean (EM) contributes to the larger percentage of exposure for both daytime and nighttime events. Among EM countries, Italy and Turkey contribute the most exposure for daytime events, and their north/east part has a larger proportion than
their other parts. However, Italy’s exposure will be exceeded by France and Balkans for nighttime events due to the higher growth of population and frequency of dangerous heat waves. Interestingly, Egypt shows a huge increase for the exposure of nighttime events in the future. Comparing daytime and nighttime events’ AI between different GWLs, we found that the regional averaged AI of nighttime events is 0.4%–12% higher than daytime’s (figure 6). This shows that although the high frequency of dangerous nighttime events will risk more people’s health especially for the low rate of using air conditioning (Kovats and Kristie 2006), we can also avoid more impacts from limiting global warming compare to daytime events.

3.3. Heat extreme impact on agriculture
Correlations between EDD and yield from 1981 to 2016 at the grid and regional level (figures 7(a) and (b)) suggest that most of the grids which are exposed to the one-in-five years events may experience yield loss 1%–9%, while the grids exposed to one-in-ten years or even one-in-20 years events will experience more maize yield loss. Considering that most grids will have a yield loss exceed 5% expose

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**Figure 6.** Avoided impact (AI, Unit: %) of different levels of daytime (a) and nighttime (b) events in 12 countries/regions. The row 1–12 represents each country/region respectively, and the row 13 represents the regional mean results.

**Figure 7.** The weighted extreme degree days (EDD) and yield change from 1981 to 2016. Grey dots represent the maize yield change under different levels of events. Vertical black lines indicate the interquartile range with the horizontal red lines indicating the median, the round dots showing the average results. Blue horizontal line indicates the yield change equal to 0 (a). Each grey/red bar represents yearly regional mean maize yield change more/less than 0 and the blue line represents yearly regional mean EDD (b).
to one-in-ten/20 years, we defined two levels of dangerous events as EDD exceeds the 10 or 20 year return values. Years with EDD above 0.5 $\sigma$ all experienced maize loss although some years’ values are relatively small (e.g. 1998). Years with EDD above $\sigma$ all experienced large maize loss (e.g. 2003 and 2007), (figure 7(b)). The spatial pattern shows differences and similarities between two typical events in 2003 and 2007 (figure 8). In 2003, the Mediterranean’s yield loss was mainly contributed by extreme heat waves in France, which made maize yield decrease by 15%–20% compared to its expected yield. However, in 2007 in the Balkan Peninsula, the heat waves caused a more than 20% yield loss. Both of the regions experienced an EDD of greater than $2\sigma$.

Percentage of maize harvest area which have a risk of maize yield loss are shown in figure 9. The exposure will largely increase during the 3 °C warming period.
and reach 49%/37% for different levels of events, while during the 1.5 °C warming period the exposure increases little (less than 10%) relative to the reference period. Comparing the AI between different GWLs, the results show that limiting global warming to 1.5 °C will reduce 93.8%/94.5% of the exposure relative to 3 °C, and 78.3%/81.7% of the exposure relative to 2 °C. With the growth of population and more maize harvest area exposure to the risk of yield loss, pursuing efforts to limit GWLs to an increase of less than 2 °C or 1.5 °C is prudent.

4. Conclusions and discussion

In this study, we used MED-CORDEX data to investigate how daytime and nighttime heat extremes will change and their impacts on population and agriculture in the Mediterranean area during a 1.5 °C, 2 °C and 3 °C global warming period. The major findings are summarized below:

First, we found that if global warming is limited to 1.5 °C and 2 °C, the intensity, frequency and duration of both daytime and nighttime heat waves are significantly higher than they are during the historical period in most areas in the Mediterranean. Among all regions, the most prominent areas are northwest Africa, the Iberian Peninsula, Italy and Middle East. In particular, the nighttime events become more frequent and longer than daytime events during the 1.5 °C and 2 °C warming periods.

Second, one-in-ten/20 year events in the historical period happen more frequently in the 21st century, which would risk more than half of the total population's health in the Mediterranean. EM has exhibited more exposure than AM during all warming periods. Among all countries, Italy and Turkey contribute the most exposure for daytime events, but they will be exceeded by Egypt for nighttime events. Limiting GWLs to 1.5 °C will reduce 76%–83% exposure compared to 3 °C.

Third, the different levels of events may cause a maximum 49%/37% of maize harvested area exposure to the risk of yield loss in the Mediterranean; nevertheless, limiting global warming to 1.5 °C will reduce 93.8%/94.5% of the exposure compared to 3 °C. Considering the growth of population, it is meaningful to pursue 0.5 °C less warming to ensure food security. Comparing the AIs of heat extremes on both population and agriculture, the exposure of one-in-20 year events can be reduced more from limiting global warming under 1.5 °C or 2 °C.

There are several points we have to mention: Bias adjustment cannot alter the time dependence of the original distribution (Dosio 2016), thus, some indices might be overestimated (Vautard et al 2013).

30-year windows are commonly used to identify GWLs (e.g. Vautard et al 2014). However, the temperature rises rapidly during these 30 years especially for the RCP8.5 scenario during the second half of the 21st century and the heat extremes might be quite different between the start and end of such 30-year periods as well. Our comparison of the heat indices during the start and end of different warming periods also implies that the extracting time periods by 30-year windows may produce index distributions that are wider than is intended, especially for the 3 °C period (figures S5, S6, column 3). This problem may be limited by using shorter windows (e.g. 20-year window, figure S7).

Previous research points out that due to the urban heat island (UHI) effect, heat stress in urban areas is particularly amplified for nighttime minimum temperatures (Fischer et al 2012) which will lead to more nighttime extreme heat events (Oleson et al 2013, Schatz and Kucharik 2015, Eunice Lo et al 2020). Also, rapid urbanization which is still taking place in North Africa and the Levant will further expand the impacts of UHI (Bahi et al 2016, Salameh et al 2019). We will study this point using the next phase’s MED-CORDEX data in our future research.

In this study, we mainly focus on the high temperature’s influence on maize yield, and other factors (e.g. precipitation, drought) could also be very important and will be considered together in future study to estimate the explicit maize loss values.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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