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2016 Environ. Res. Lett. 11 054016

(http://iopscience.iop.org/1748-9326/11/5/054016)

Environmental Research Letters

OPEN ACCESS

RECEIVED
8 February 2016

REVISED
22 April 2016

ACCEPTED FOR PUBLICATION
26 April 2016

PUBLISHED
12 May 2016

LETTER

When will unusual heat waves become normal in a warming Africa?

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Keywords: heat wave, temperature extremes, climate indices, cordex Africa, regional climate models

Supplementary material for this article is available online

Abstract

Africa is one of the most vulnerable continents to climate change. In the upcoming decades the occurrence of longer, hotter and more frequent heat waves could have a strong impact on human mortality and crop production. Here, by applying the heat wave magnitude index daily to temperature reanalysis data, we quantify the magnitude and the spatial extent of the most extreme heat waves experienced in Africa between 1979 and October 2015 across different seasons. Results show that in the recent years Africa experienced hotter, longer and more extent heat waves than in the last two decades of the 20th century. In the future, 50% of regional climateprojections suggest that heat waves that are unusual under present climate conditions will occur on a regular basis by 2040 under the most severe IPCC AR5 scenario (i.e. RCP8.5).

1. Introduction

An international climate agreement was signed in Paris on 12th December 2015 following negotiations between 195 countries during the 21st Conference of Parties (COP21) meeting. The agreement is designed to reduce greenhouse gas emissions and limit the average rise in global temperatures to well below 2 °C above pre-industrial times. Moreover, countries committed to raising $100 bn a year by 2020 to help poor countries adapt their economies, and accept a new goal of net zero emissions by later this century.

Africa is likely to pay a heavy price for global warming, despite having contributed little to its cause. It is one of the most vulnerable continents due to its high exposure and low adaptive capacity (IPCC 2014). In the past three decades Africa suffered 27% of the world's reported fatalities from natural catastrophes (614 250 people) and experienced 1560 weather-related catastrophes, such as drought, heatwaves, storms and floods (Munich Re 2011).

Near surface temperatures have increased by 0.5 °C or more during the last 50–100 years over most parts of Africa (Hulme *et al* 2001, Jones and Moberg 2003, Kruger and Shongwe 2004, Schreck and Semazzi 2004, New *et al* 2006, IPCC 2007, Rosenzweig *et al* 2007, Trenberth *et al* 2007, Christy *et al* 2009, Collins 2011, Grab and Craparo 2011, Hoffman *et al* 2011, Mohamed 2011, Stern *et al* 2011 Funk *et al* 2012, Nicholson *et al* 2013).

In northern Africa the northwestern Sahara experienced 40–50 hot days per year in the period 1989–2009 (Vizy and Cook 2012). In the last 15 years in South Africa, the probability of austral summer heat waves has increased with respect to the period 1961–1980. This is associated with deficient rainfall conditions that tend to occur during El Niño events (Lyon 2009). In analogy, in northern Africa there is a projected increase in number of hot days in the coming decades (Patricola and Cook 2010, Vizy and Cook 2012).

In a future warmer climate with increasing mean temperatures, African heat waves will not only become more frequent; their duration and intensity are very likely to increase as well (Min *et al* 2011, Coumou and Rahmstorf 2012, IPCC 2012), strongly challenging the adaptive capacity and resilience of the population. Longer, hotter and more frequent heat waves are very likely to have a strong impact on mortality, occurrence of wild fires and crop failure. In this study we use the heat wave magnitude index daily (HWMId) defined in Russo *et al* (2015), which takes into account the severity of temperature extremes as well as heat wave duration. The HWMId enables the comparison of heat wavesoccurring in different places and times. We focus on Africa and estimate the magnitude of seasonal extreme heat waves in the past 37 years (1980–2014) from gridded reanalysis data, and in the future until 2100 from13 CORDEX-Africa regional climate projections under two different representative concentration pathways (RCP4.5 and RCP8.5) scenarios. Thereby we investigate the area affected by heat waves at different level of magnitude in order to assess when a heat wave event that was rare in the present, such as the one that occurred in Russia in the summer 2010, will become normal (i.e. occurring every year) under different RCPs.

2. Materials and methods

2.1. HWMId

The Africa continent mainly spans the intertropical zone between the Tropic of Cancer and the Tropic of Capricorn. Only the northernmost and the southernmost fringes of the continent have a Mediterranean climate because they are not located under the tropics. Because of this geographical location, where solar radiation intensity is always high, heat waves can occur in any season in Africa. In contrast to Europe, where heat waves with the highest impacts predominately occur in summer (e.g. figure 1). For this reason, differently from Russo *et al* (2015) where the HWMId was defined as the maximum magnitude of the heat waves in a year, here we apply the HWMId to a moving block of three months in which the HWMId is defined as the maximum magnitude of the heat waves in each block.

In order not to split heat waves that start in a 3 month block and end in the consecutive 4th month not included in the block, the HWMId is calculated for 12 moving blocks of 3 month: January–February–March, February–March–April, …, December–January–February (DJF). As in Russo *et al* (2015) a heat wave is a period of at least three consecutive days with maximum temperature above the daily threshold for the reference period 1981–2010. The threshold is defined as the 90th percentile of daily maxima, centered on a 31 d window. The magnitude of a heat wave is calculated by summing up the magnitude of each hot day composing a heat wave as described in Russo *et al* (2015). Here, we calculate the HWMId on reanalysis data and CORDEX-AFRICA model outputs for the period 1979–2100 over the Africa domain. The HWMId calculation has been carried out using the HWMId function recently included in the R package called extRemes (Gilleland and Katz 2011).

2.2. Models and observations

Daily maximum temperature data from the ERA-Interim (ERA-I) reanalysis from the European Centre for medium-range weather forecasts (Dee *et al* 2011) are applied to study heatwaves in the present climate. The dataset has a 6-hourly time resolution and is available from 1979 to January 2016. The ERA-I is based on a T255 resolution (0.7°, ~79 km). The data are interpolated to the CORDEX-Africa (Coordinated regional downscaling experiment—African Domain) grid (0.44°, ~50 km) of the projected model data for comparison. The HWMId have been calculated on both interpolated and non-interpolated ERA-I datasets.

For historical and future projections (period 1979–2100) we used daily maximum temperature from 13 regional climate model (RCM) simulations of the CORDEX-Africa multi-model scenario experiment with a resolution of 0.44°. In the set of simulations, 4 RCMs are driven by 13 different general circulation models forced with two senarios, RCP4.5 and RCP8.5 adopted by the Intergovernmental Panel on Climate Change (IPCC) for its fifth Assessment Report (AR5, Christensen *et al* 2013). Equivalent climate simulations using the other RCPs (RCP2.6 and RCP6.0) were not available. For the comparison with the reanalysis we use historical simulations (Taylor *et al* 2012) for the period 1979–2005. In detail, the ensemble model output used in this study is composed of the following 13 simulations listed in table 1: eight RCA model simulations (Swedish Meteorological and Hydrological Institute) forced with eight global climate models (CCCma-CanESM2, CNRM-CERFACS-CNRM-CM5, ICHEC-EC-EARTH, IPSL-IPSL-CM5A-MR, MIROC-MIROC5, MPI-M-MPI-ESM-LR, NCC-NorESM1-M, NOAA-GFDL-GFDL-ESM2M); three CCLM simulations (CLM Community) driven by lateral boundary conditions of three global climate models (CNRM-CM5, EC-EARTH and MPI-ESM-LR); one simulation for RACMO (Royal Netherlands Meteorological Institute), and one for HIRHAM5 (Danish Meteorological Institute), driven by ICHEC-EC-EARTH global model. More information on these models and simulations may be found at http://cordex.org/index.php?option=com_content&view=article&id=242&Itemid=769.

2.3. Percentage of spatial area in heat wave

The percentage of land areain a specific season experiencing HWMId values greater than a given magnitude level (HWMId $\geqslant$ 3, 6, 9, 15, 24) as in figures 2–4 and table 2 is calculated with respect to the land area of the CORDEX-Africa domain (13761 grid points) for both model data and ERA-I reanalysis interpolated to the CORDEX-Africa grid (see section 2.2). For comparison, the magnitude of the heat wave that occurred in Russia in 2010 is also calculated with ERA-I reanalysis interpolated to a grid with a spatial resolution of 0.44°. The percentage of spatial areas at each HWMId level during the Russian

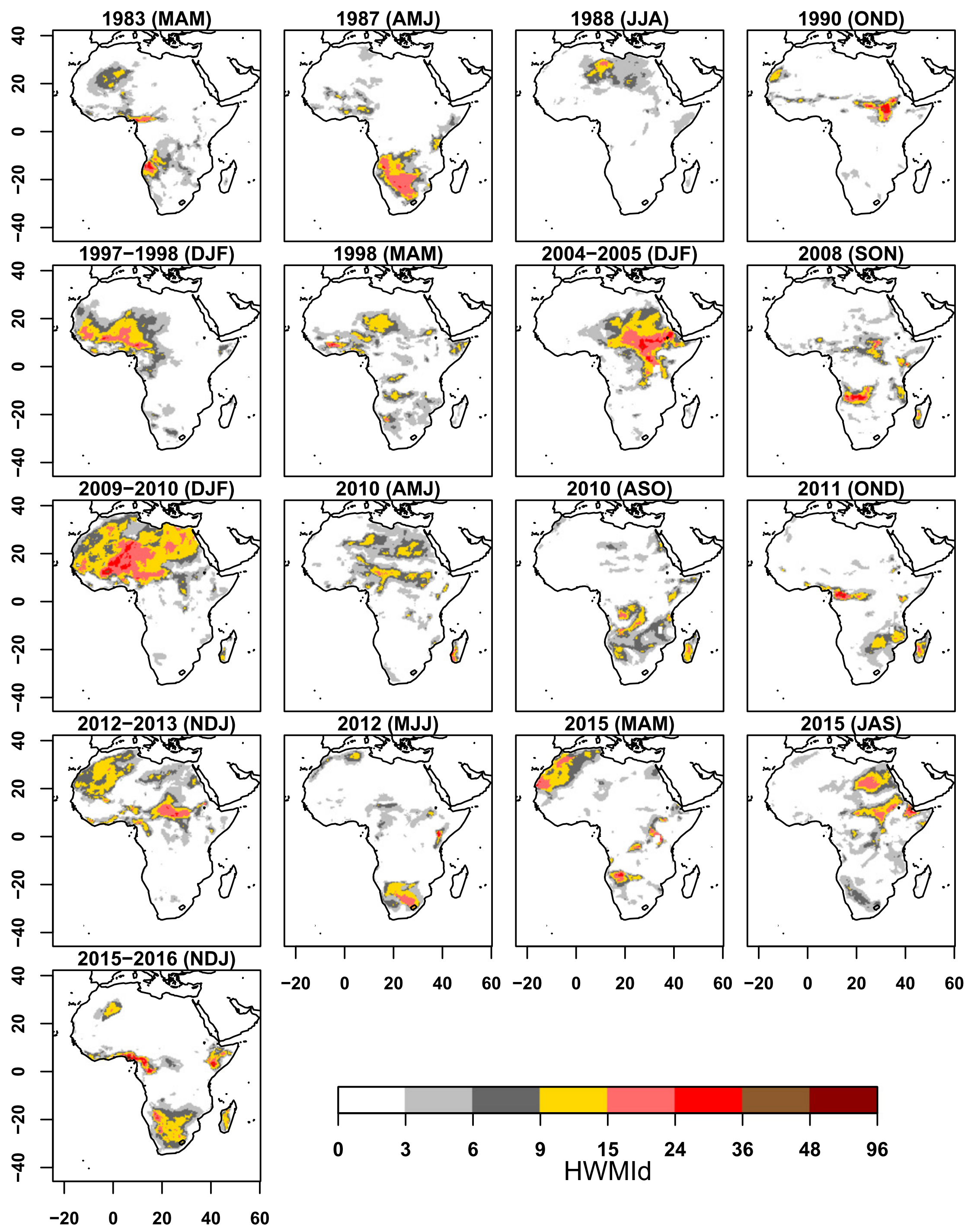

Figure 1. Spatial distribution of the HWMId with ERA-I reanalysis, interpolated to the Africa cordex domain, of the most severe heat waves since 1979. The HWMId values represent the seasonal maximum magnitude at each grid point.

heat wave are normalized with respect to the total number of grid points of the African domain. As done for the African heat waves the HWMId for the 2010 Russian heat wave is calculated at seasonal scale.

3. Extreme african heatwaves since 1979

Figures 1 and S1 show the geographical pattern of the HWMId for the most extreme events that occurred since 1979, calculated with ERA-I interpolated and non-interpolated reanalysis data, respectively (see section 2.2). Most of these events occurred during warm ENSO periods (WMO 2011). During the famous drought of 1982–1983 a heat wave affected many African regions. In particular this event had long persistence and severe magnitude in boreal spring season (MAM) in Burkina Faso, Nigeria, Cameroon, Angola, Namibia and South Africa. The highest HWMId values were experienced in Angola and in the Democratic Republic of Congo (figure 1). The spatial extent of this heat wave was not very large when

Table 1. List of the 13 CORDEX-AFRICA used models.

Model letter	Institute	RCM	Driving GCM
A	SMHI	RCA4	CCCma-CanESM2
B	SMHI	RCA4	CNRM-CM5
C	CLMcom	CCLM4-8-17	CNRM-CM5
D	CLMcom	CCLM4-8-17	EC-EARTH
E	SMHI	RCA4	ICHEC-EC-EARTH
F	KNMI	RACMO22E	ICHEC-EC-EARTH
G	DMI	HIRHAM5	ICHEC-EC-EARTH
H	SMHI	RCA4	IPSL-CM5A-MR
I	SMHI	RCA4	MIROC5
L	CLMcom	CCLM4-8-17	MPI-ESM-LR
M	SMHI	RCA4	MPI-ESM-LR
N	SMHI	RCA4	NCC-NorESM1-M
O	SMHI	RCA4	NOAA-GFDL-GFDL-ESM2M

compared with those of the most severe African heat waves of the recent years (table 2, figures 1, 2).

A similar heat wave to that of 1983 was recorded in the period 1987–1988 when South Africa was struck by another drought. This event had its heat center in South Africa in April–May–June (AMJ). It had a lower peak than that of the previous event in 1983 and a larger spatial extent at some magnitude level.

In the boreal summer (JJA) of 1988 temperatures were above normal over Algeria and Libya with HWMId peak equal to 19. This heat wave was not more severe than those in 1983 and in 1987 (see table 2). Another minor heat wave occurred in 1990, which covered mainly regions across the equator just after the equinox of 23rd September. This is when the solar terminator (the 'edge' between night and day) is perpendicular to the equator and the temperature reaches its maximum values at these latitudes.

In a recent study, Fontaine *et al* (2013) have shown that the occurrence of heat waves has clearly increased after 1996, except during the warm ENSO episodes of 1983 and 1987. This is confirmed by our data record split into two periods of 18 years: 1979–1996 (past) and 1997–2014 (present). Inparticular in the last years, Africa has experienced hotter, longer and more extent heat waves than in 1979–1996 (figure 2). In the present years, the percentage of land area experiencing a heat wave with magnitude greater than 3, 6 or 9 has increased on a seasonal basis by a factor of 2 with respect to the past (see figure 2). As an example, in the past only 5% of African land area experienced heat waves with magnitude equal to or greater than 3 on a seasonal basis, whereas in the present this magnitude of heat wave became very common across all seasons over12% of African continent (see figure 2(c)). Similar results are shown for the percentage of area covered by heat waves with magnitude greater than 6 and 9 (figure 2(c)). The most unusual heat waves of the past period that occurred in 1983 and 1987 had a comparable or even lower spatial extent than the heat wave events that occurred in 1998 in DJF and MAM. The two heat waves in 1998 hit a large part of The Sahel region (Burkina Faso, Benin and Southern Mali).

In the last decade starting from 2004, severe heat waves were recorded almost on an annual basis, not only during warm ENSO events (figures 1, 2, table 2). The heat center in 2005 was located in central East Africa, whereas in 2010 the heat wave was confined to central Sahel region. All other events had a strong impact in southern Africa and Madacascar. Finally, according to the WMO (2011) the global averagenear-surface temperature in 2015 was the warmest on record reaching approximately 1 °C above the 1850–1900 average. This is due to a combination of a strong*El Niño* and human-induced global warming (WMO 2015).

El Niño affects the global atmospheric circulation, altering weather patterns around the world and temporarily elevates global temperatures (Kenyon and Hegerl 2008, WMO 2015). Many extreme heat waves detected in this study occurred during an *El Niño* event. However, their magnitude seems more strictly depending on the regional mean temperatures than from the strength of *El Niño*.

For instance, during the very exceptionally *El Niño* of 1997–1998, the heat wave in DJF was much weaker than that in DJF 2009–2010 (see table 2) with regional temperature anomalies being much greater in 2009–2010 than in 1997–1998 (WMO 2015). According to ERA-I, the DJF temperature anomaly with respect to the 1980–1990 decadal average was 0.19 °C and 0.98 °C for 1997–1998 and 2009–2010, respectively, and the magnitudes of DJF heat waves rising steadily from 1997–1998, 2004–2005 and 2009–2010 (see table 2).

In 2015 heat waves affected Europe, northern Africa and the Middle East through the late spring and summer, with the heat center shifting from month to month and with many new temperature records set. The African continent observed its second warmest year, just after 2010 (WMO 2015), experiencing heat waves in almost every season (see figure 1). In May, high temperatures affected Burkina Faso, Niger and Morocco. The high temperatures persisted for many days in these regions in Spring (MAM) of 2015. At the same time a heat wave hit southern Africa where record high temperatures were exceeded on a regular basis. In the late summer of 2015 (JAS) consecutive hot days were recorded on the eastern coast of Africa with maximum HWMId values recorded in Egypt, Eritrea and Ethiopia (figure 1). During boreal spring of 2015 in South Africa, record high temperatures were exceeded on a regular basis. Finally, in NDJ 2015 a very extreme heat wave with a peak greater than that recorded in 2009–2010 affected this region (table 2, figure 1).

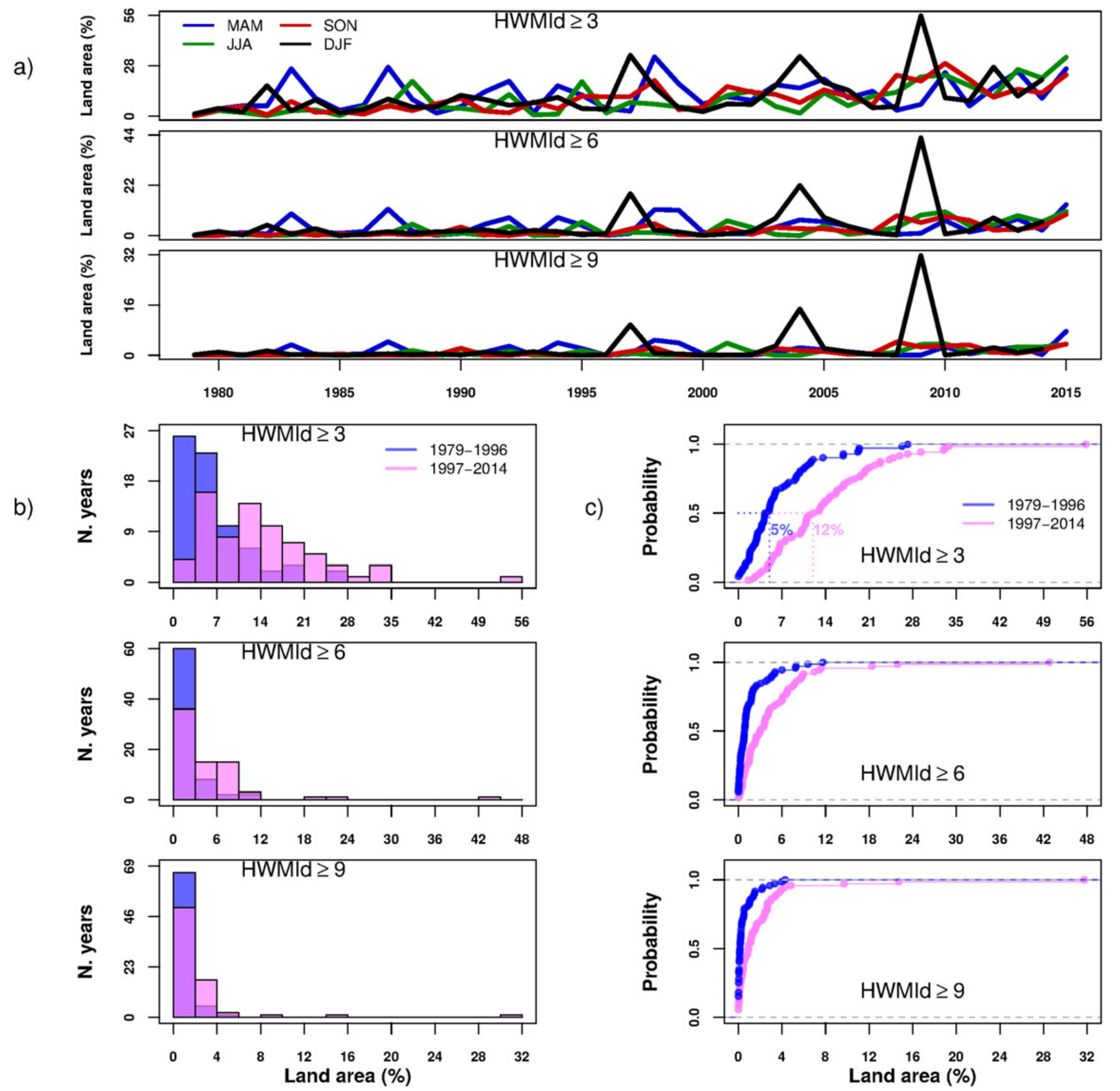

Figure 2. (a) Time evolution of percentage of EURO-CORDEX land area covered by HWMId seasonal maximum values greater than a given magnitude level (HWMId $\geqslant$ 3, 6, 9) with ERA-Interim data spanning the periods 1979–October 2015. Only the DJF season (black line) end in 2014. (b) Histograms of the percentage land area covered by grid points with seasonal HWMId values equal to or greater than 3, 6, 9 for two periods of eighteen years: 1979–1996 (blue), 1997–2014 (magenta). The bins in which the two histrograms overlap are represented in purple. The size of the data sample from which each histogram has been calculated is equal to 4 $\times$ 18 (seasons x years). (c) As (b) but for empirical cumulative density function.

3.1. Unusual heat waves (USWs)

Apart from the most extreme African heat wave of our data record that occurred in DJF 2009–2010, all other historical heat waves in Africa in the period between 1979 and January 2016 had lower spatial extent than the extreme heat wave of 2010 in Russia (table 2, figure 1). In particular, the 2010 Russian heat wave shows a spatial extent and a spatial HWMId maximum at least doublethat of the most severe African heat waves in the past37 years. As demonstrated by many studies (Barriopedro *et al* 2011, Russo *et al* 2014, Christidis *et al* 2015, Russo *et al* 2015, Zampieri *et al* 2016) the 2010 Russian heat wave was a very unusual event in Europe and across the entire globe. Russo *et al* (2015) estimated that the return period of the 2010 Russian heat wave was at least 66 years, which is the maximum length of the European climate assessment & data (Haylock *et al* 2008, ECA&D,www.ecad.eu spanning from 1950–September 2015. Considering the different climate conditions between Africa and Europe, the HWMId defined at seasonal scale enables us to compare African heat waves with the 2010 Russian heat wave, butonly on a physical basis. Of course, heat waves with similar magnitude and spatial extent can have different impacts in regions with different vulnerability and underlying climate conditions.

An UHW is defined here only from a physical point of view without considering its possible impact. In this study, a UHW is a rare event that has not occurred in Africa at least since 1979, with a spatial extent at each magnitude level equal to the greatest percentage of area of all the historical African heat waves reported in table 2. This heat wave, greater in magnitude and

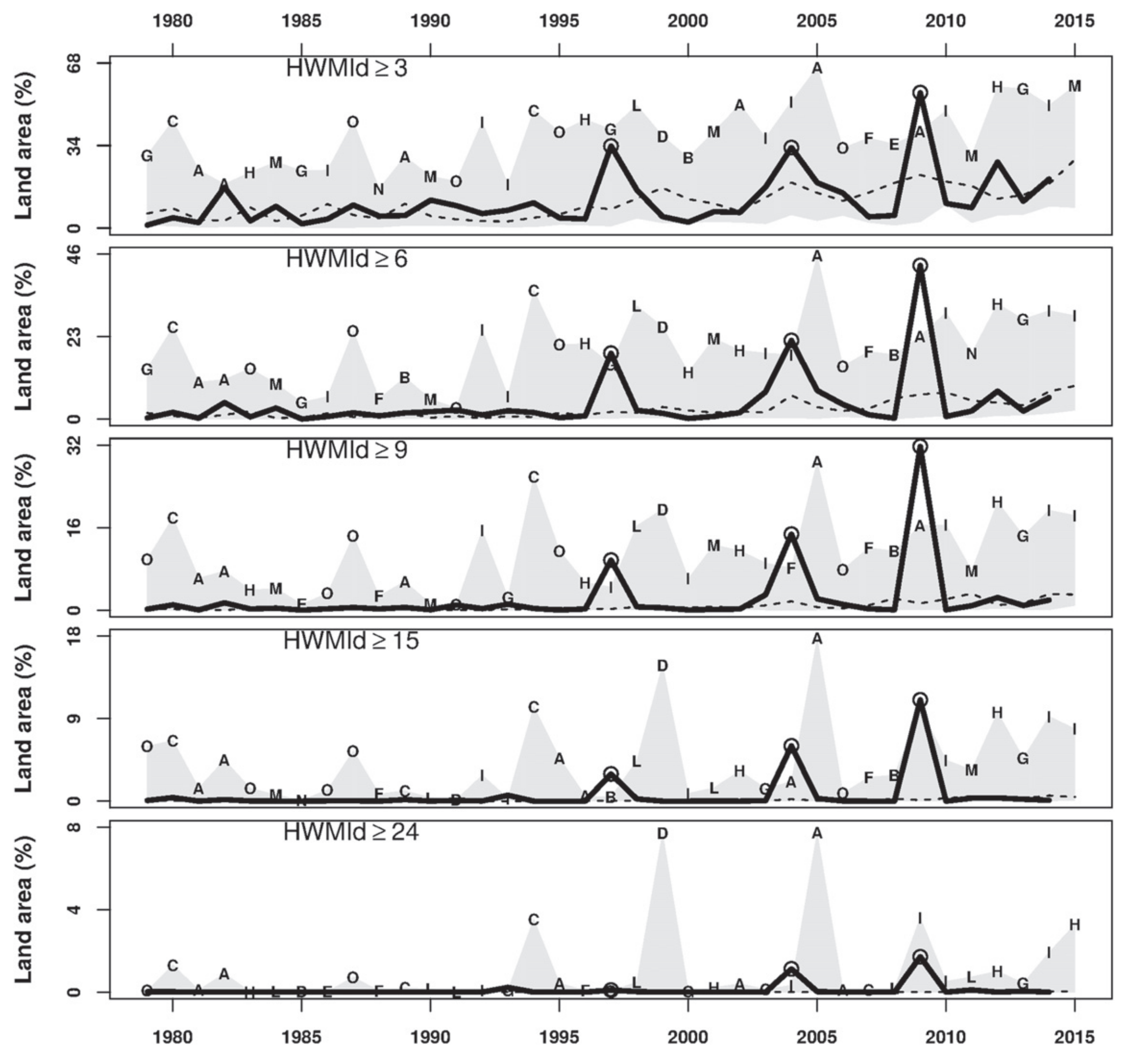

Figure 3. Time evolution of seasonal (DJF) percentage of Africa land fraction with HWMId greater than a given magnitude level (HWMId ⩾ 3,6, 9, 15, 24) calculated with ERA-Interim reanalysis (black lines) and CORDEX-Africa ensemble model median (dashed black lines). The black open circles represent the most severe heat waves that occurred in DJF with an HWMId spatial distribution represented in figure 1. The shaded gray areas denote the DJF HWMId's range (maximum–minimum) of all 13 simulations for the historical period (1979–2005) and the RCP4.5 scenario (2006–2015). Letters indicate the model retrieving the maximum values for each specific year. See table 1 for correspondence between letters and models.

spatial extent than the one in Africa in DJF 2009–2010, is used here as reference to assess when UHWs will become normal with increasing temperature in Africa. In this study a UHW (see table 2) is considered normal, within a given season, if it occurs with a frequency ofonce a year.

4. Model evaluation (1979–2015)

We use an ensemble of 13 RCMs (see section 2.2) to evaluate the simulated heat wave magnitude and extent against observations. Kim *et al* 2013 did an evaluation of T_{AVG}, T_{MAX}, T_{MIN} and other variables in the CORDEX-Africa hindcast, using a variety of reference datasets and comparison of outputs from multiple models against multiple observations. They show that RCM skill varies according to variables, regions and metrics. Models perform generally better for T_{AVG} and T_{MAX} than for T_{MIN} in both the spatial distribution and seasonal cycle. Our models evaluation is based on how realistically the ensemble models can reproduce the HWMId magnitude and extent for each single season. The simulated HWMId values for DJF in a 37 year period (1979–2015) representing present-day climate are shown in figure 3. The shaded areas in each panel denote the range from the minimum to the maximum percentage of area of all13 simulations for each model year and at each level of magnitude. The observation's spatial extent of each level is within the spread of the ensemble models for each year. The ensemble of all the models at different HWMId levels captures the general trend of the spatial area in heat waves in the period 1979–2015. According with a KS-test applied to each HWMId level, the null hypothesis (i.e. the ensemble model median is equal to the spatial area in a heat wave as simulated with ERA-I) is not rejected at 1% level of significance. The same results are

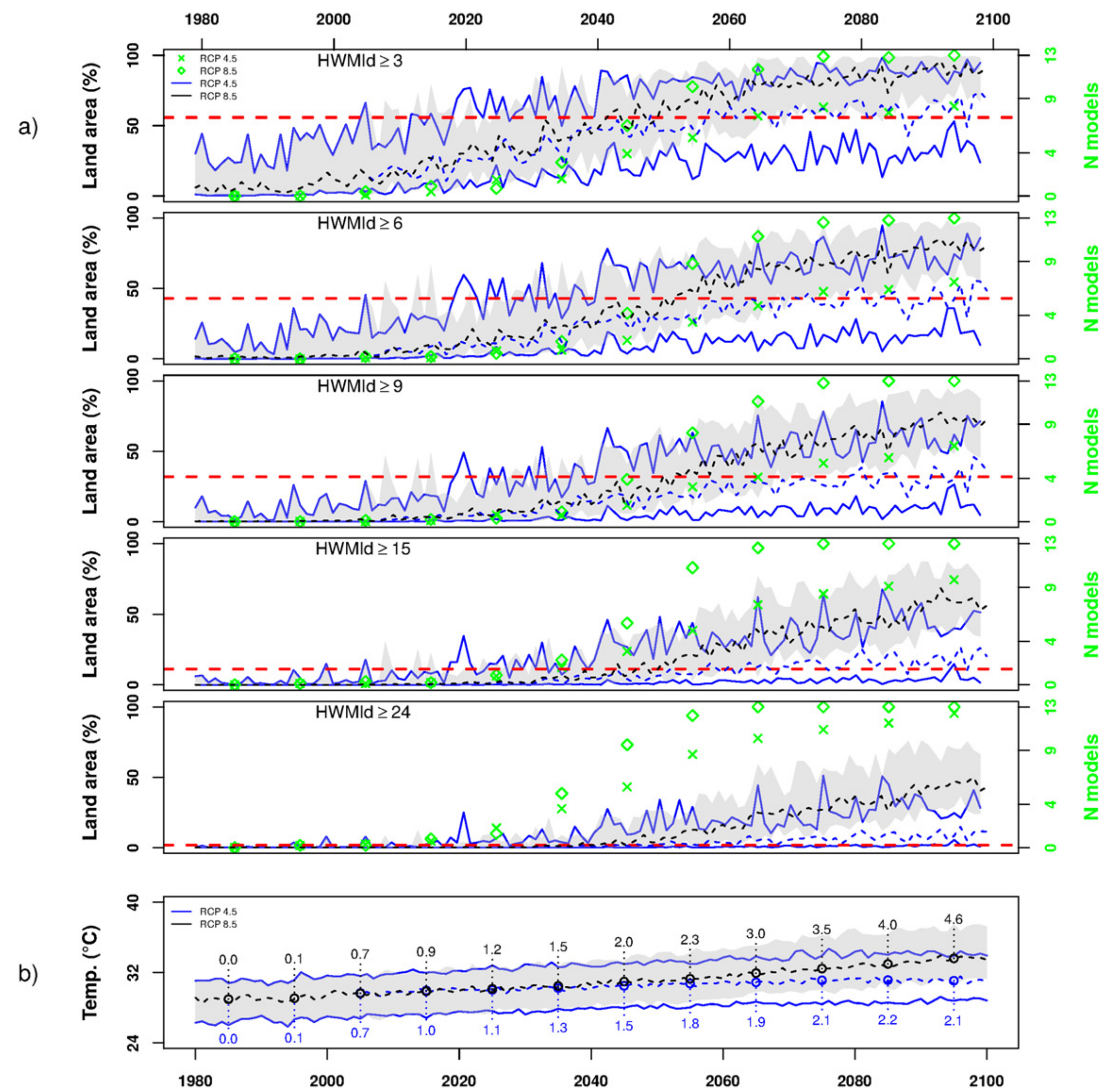

Figure 4. (a) As figure 3 but only for CORDEX-AFRICA ensemble model values for historical, RCP4.5 and RCP8.5 scenarios. The dashed blue and black lines denote the annual median of percentage of area with HWMId values greater than a given magnitude for all 13 simulations for historical-RCP4.5 and RCP8.5 scenarios, respectively. The blue lines and the shaded gray areas in each panels denote the range of seasonal percentage of area with HWMId ⩾ 3, 6, 9, 15, 24 from the range (maximum–minimum) calculated for all 13 simulations for RCP4.5 and RCP8.5 scenarios, respectively. The red dashed horizontal line at each HWMId level represents the percentage of area covered by an unusual heat wave as defined in section 3.1. The green crosses and open rhombus are the decadal medians of the number of models simulating in DJF an unusual heat wave under the moderate and high scenario, respectively. (b) As figure 4(a) but for annual mean temperature averaged across Africa region. Open black and blue circles represent the decadal mean temperatures for RCP8.5 and RCP4.5 scenarios, respectively. The black and blue values associated to the open circles are the decadal mean temperature changes over Africa with respect to the decade 1980–1989.

obtained across all the other seasons (see figures S2–S4). However, it is important to note that the most extreme heat wave that occurred in Africa in DJF 2009–2010 (see table 2 and figure 2) was simulated only by one out of 13 models.

5. Heatwaves in the future

Temperatures over almost all land areas, including Africa, are projected to rise faster than the globalmean temperature during the 21st century (Christensen *et al* 2007, Joshi *et al* 2011, Sanderson *et al* 2011, James and Washington 2013, IPCC 2014, Seneviratne *et al* 2016). Thus, it is expected that along with warming temperatures, a significant percentage of African land fraction will see more intense heat waves in a shorter time horizon than that estimated for Europe and other continents (Clark *et al* 2006, Fischer *et al* 2013, Russo *et al* 2015). Inrecent years (2004–2015) Africa has experienced heat waves at least every two years.

Temperatures over subtropical Africa have risen more than twice the global rate over the last five decades (IPCC 2014). In the two warmest years on record, 2010 and 2015, Africa was hit by very intense heat waves during different seasons. Both reanalysis and ensemble model simulations show that a larger percentage of the African continent is already

Table 2. List of record-breaking seasonal heatwaves in the period 1979–2015 with ERA-INTERIM data interpolated toCORDEX AFR-44 for the most severe heatwaves since 1979. For each specific event the spatial extent is estimated as the land area fraction exceeding a fixed HWMId value. The area fraction is expressed in percentage. The HWMId peak is the highest spatial HWMId value recorded during each specific event. The values in bold are those of an unusual heat wave calculated as the maximum of each column as defined in section 3.1.

Date	HWMId **Peak**	Area (%) **⩾3**	Area (%) **⩾6**	Area (%) **⩾9**	Area (%) **⩾15**	Area (%) **⩾24**
1983 (MAM)	53.3	26.29	9.58	3.35	1.06	0.24
1987 (AMJ)	27.8	24.75	12.83	7.99	4.03	0.10
1988 (JJA)	19.0	19.39	4.99	1.52	0.24	0.00
1990 (OND)	38.8	12.07	5.19	3.02	1.29	0.55
1997–98 (DJF)	29.4	33.81	18.37	9.69	2.96	0.09
1998 (MAM)	28.7	32.96	11.41	4.82	0.46	0.05
2004–05 (DJF)	37.6	33.16	21.91	14.71	6.02	1.12
2008 (SON)	32.0	22.74	8.72	4.25	1.55	0.44
2009–10 (DJF)	41.5	55.84	42.83	31.73	11.04	1.71
2010 (AMJ)	30.0	35.90	14.96	5.50	0.43	0.05
2010 (ASO)	20.9	27.85	11.94	4.10	0.56	0.00
2011 (OND)	38.2	17.71	7.47	4.18	1.00	0.31
2012–13 (NDJ)	27.6	40.19	22.74	11.34	2.15	0.08
2012 (MJJ)	34.8	20.03	7.66	3.92	1.11	0.08
2015 (MAM)	27.6	26.36	13.62	7.61	2.51	0.16
2015 (JAS)	53.0	33.67	13.73	7.25	2.62	0.18
2015–16 (NDJ)	55.7	26.47	16.45	9.50	2.38	0.83
2010 Russia (ASO)	69.8	32.65	24.28	20.48	16.59	10.31
UHW	**57.0**	**55.84**	**42.83**	**31.73**	**11.04**	**1.71**

experiencinghotter and longer heat waves than those of the past decades.

Warming projections under a high emissions scenario (RCP8.5) indicate that extensive areas of Africa could exceed 2 °C of warming relative to the late 20th century annual mean temperature by the mid-21st century (figure 4(b)).

By 2025 (±5 years), when regional annual mean temperatures are expected to be 1 °C greater than that in the last two decades of the 20th century, the occurrence of heat waves with magnitude between 3 and 9 is expected to be more likely than in the period 1979–2015 (figures 4(a), S5–S7). The choice of scenario, i.e. RCP4.5 or RCP8.5, does not affect this result.

In the coming decade two out of 13 models simulated a percentage of area greater than that of a UHW for different level of magnitudes and across each season (figures 4(a), S5–S7). By 2045 (±5 years) the ensemble model median of the annual mean temperature shows a difference around 0.5 °C between the high (RCP8.5) and moderate (RCP4.5) scenarios (figure 4(b)). Under the high scenario 50% of the models project a percentage of area at each HWMId level greater than that of the UHW as defined in section 3.1 on regular basis, occurring across all seasons every year. By 2065 the same frequency of occurrence of UHWs is projected by 50% of the models under the moderate scenario (i.e. RCP4.5). Finally at the end of the century (by 2075 ± 5 years), if mitigation policy has not been adopted, we can expect a very dramatic scenario with 50% of African land fraction experiencing heat waves with magnitude greater than 15 on a regular basis (figures 4(a), S5–S7).

According to all models, by 2075 (±5 years) UHWs will become normal occurring 4 times in a year, at least once per season under the RCP8.5 scenario.

6. Conclusions

In this work we have investigated seasonal African heat waves that occurred since 1979 by using the seasonal HWMId. By applying the HWMId to reanalysis and IPCC AR5 Africa-CORDEX model output, we have shown a reasonable modelperformance in simulating present-day extreme heat waves. Further we show that anthropogenic increase in greenhouse gas concentrations have led to an increased probability of extreme heat waves in Africa already in the present.

Unusual heat waves could occur every year across allseasons already by the year 2045 under the most severe scenario. By the year 2045 the median of the model ensemble has reached a globally averaged near-surface temperature of 1.5 °C (see figure 4(b)) with respect to the reference period 1980–1989 (see figure 4(b)), which is the internationally negotiated climate target under the COP21 agreement, although relative to pre-industrial climate (https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf). Events of great severity, such as the 2009–2010 African heat waves, will become more likely already in the next decade. Note that only 1 out of 13 models was able to simulate this heat wave, which could be due to some model deficiency in simulating really extreme heat waves or due to the length of the analyzed time period in the model simulations. Thus, the projections of the occurrence of extreme heat waves in the coming decade should be considered as conservative estimates.

By the end of the century, heat waves that are unusual under current climate will become very common along with rising global mean temperatures and could occur with a frequency of every season in any country in Africa. Given that adaptation and resilience measures presently undertaken in most African countries are already reaching their limits under current climate (IPCC 2014), the projected increase in extreme heat waves in the coming decades can result in humanitarian crises of unknown dimensions. Combined with prolonged drought conditions as currently experienced in Ethiopia (Climate Home 2016) that often co-occur with heat waves under *El Niño* conditions, will put further stress on humans and ecosystems in the affected regions, making some of them uninhabitable and forcing people to migrate. This calls for ambitious global mitigation action and sustainable solutions for local adaptation.

Acknowledgments

We would like to thank ECMWF for providing ERA-Interim data. We acknowledge the Task Force for Regional Climate Downscaling (TFRCD) of the World Climate Research Programme (WCRP), who created the CORDEX initiative to generate regional climate change projections for Africa within the timeline of the Fifth Assessment Report (AR5). JS is supported by ClimateXL (project no.243953) funded through the Norwegian Research Council.

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