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ORIGINAL ARTICLE

Climate change impacts in the Middle East and Northern Africa (MENA) region and their implications for vulnerable population groups

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Abstract The Middle East and North Africa (MENA) region emerges as one of the hot spots for worsening extreme heat, drought and aridity conditions under climate change. A synthesis of peer-reviewed literature from 2010 to date and own modeling work on biophysical impacts of climate change on selected sectors shows that the region is highly affected by present and future climate change. These biophysical impacts paired with other pressures and a lack of resilience in some countries cause high vulnerabilities within these sectors and for social dimensions in the MENA region. The agricultural sector, of which 70 percent is rain-fed, is highly exposed to changing climatic conditions. This is of critical importance as the agriculture sector is the largest employer in many Arab countries and contributes significantly to national economies. Impacts will be high in a 2 °C world, as, e.g., annual water discharge, already critically low, is projected to drop by another 15–45% (75% in a 4 °C world) and unusual heat extremes projected to affect about one-third of the land area with likely consequences for local food production. As a consequence, deteriorating rural livelihoods associated with declining agricultural productivity will continue to contribute to migration flows, often to urban areas as already observed. The region could be heavily challenged by both rising food and water demand given its

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projected increase in population that may double by 2070. As a result, the regions already substantial import dependency could increase and thus its vulnerability to agricultural impacts well beyond its country borders. A severe and sustained pressure on resources could contribute to further social unrest in the already unstable political environment that currently characterizes parts of the region. While the particular societal responses to such changes are hard to foresee, it is clear that extreme impacts would constitute unprecedented challenges to the social systems affected.

Keywords Regional climate change · Rain-fed agriculture · Water scarcity · Migration · Heat extremes · Aridity · Health

Introduction

The MENA region is one of the most diverse regions in the world in economic terms, with per capita annual gross domestic products (GDP) ranging from only US$ 1400 in Yemen to more than US$ 20,000 in the Arab Gulf States in 2013 (World Bank 2016). The oil-rich Arab countries Qatar, Kuwait and United Arab Emirates ranked 3, 19 and 24 in GDP per capita on a list of 195 countries in 2013, while Morocco, Egypt and Yemen rank 129, 132 and 155 on the same list (World Bank 2016). In consequence, adaptive capacity and vulnerability to climate risks varies enormously within the region, especially between the Arab Gulf States and the other MENA countries. The region's population is projected to increase from 341 million in 2015 to 571 million in 2050, 685 million in 2070 and 845 million in 2100 in the United Nation's medium-fertility scenario (United Nations 2013). In the high-fertility scenario, MENA's population is expected to double by 2080 which, together with projected climate impacts, puts the resources of the region, especially water and land, under enormous pressure. However, despite its extreme water scarcity, the Arab Gulf States consume more water per capita than the global average, with Arab residential water and energy markets among the most heavily subsidized in the world. Electricity consumption per capita is twice as high as or higher than the world average in Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates (World Bank 2013a, b) pointing to underdeveloped climate change mitigation options.

Countries in the MENA region heavily rely on agriculture as a source of food and income, not only in the historically important "fertile crescent" of the Euphrates and Tigris region, but also in the Mediterranean region and the Nile, while being largely covered by drylands and deserts. Seventy percent of the region's agriculture production is on rain-fed land (Selvaraju 2013). Taking into account that most of the land area in MENA receives less than 300 mm of annual rainfall and that the lower limit for rain-fed agriculture is between 200 and 300 mm annual rainfall, MENA is highly vulnerable to temperature and precipitation changes, with associated consequences for food security and rural livelihoods. Less than half of the water required for producing a daily diet of 3000 kcal is available in the countries on the Arabian Peninsula (Gerten et al. 2011). The region has coped with its water scarcity through a variety of means: abstraction of groundwater, water harvesting and storage, wastewater reuse, desalinization plants and food imports. The region is at present already highly dependent on food imports. Approximately 50 percent of the domestic wheat and barley supply, 70 percent of rice consumption and 60 percent of corn consumption are met through imports (Verner 2012). This is not only a matter of economic choices but rather linked to water and land constrains that avoid self-sufficiency already today, and may even intensify with population growth (Fader et al. 2013). This makes the region also vulnerable to price shocks on the global markets and harvest failures in other world regions.

The aim of this paper is to provide an overview of possible global biophysical climate impacts on selected sectors in the MENA region in a 2 and 4 °C world[1] as represented by the low and high greenhouse gas

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[1] Impacts in a "2°C World" or "with 2°C global warming" refer to the impacts assigned to a 2°C warming category which spans from 1.75°C to 2.25°C warming relative to pre-industrial temperatures in 1850-1900. Median warming for the full CMIP5 model ensemble under the RCP2.6 is about 1.6°C with 22 percent of the models projecting a warming above 2°C. Therefore we refer to the RCP2.6 as a "2°C World" or "2°C global warming". For the estimation of heat extremes, precipitation, and aridity, this study uses a subset of the CMIP5 models (gfdl-esm2m, hadgem2-es, ipsl-cm5a-lr, miroc-esm-chem, noresm1- m) showing a median warming of 1.8°C above preindustrial levels by 2081–2100 for the RCP 2.6 scenario. Similarly, impacts in a "4°C world" refer to the impacts assigned to a 4°C warming category which relates to warming above 3.5°C relative to pre-industrial temperatures. The median warming of the RCP8.5 CMIP5 ensemble for the period 2081–2100 is 4.3°C, whereas the projected warming for the subset ensemble used for heat extremes, precipitation and aridity is 4.6°C above pre-industrial levels.

concentration scenarios RCP2.6 and RCP8.5, respectively (Moss et al. 2010). We combine a literature review using mostly peer-reviewed journal articles published in 2010 or later and own work about impacts on regional climate and sea-level rise and selected sectors: the agricultural sector and water resources in the region, health and migration patterns and the occurrence of conflicts.

These aspects are subsequently highlighted in terms of their interaction with existing vulnerabilities among several population groups. It is especially the synthesis of literature review and our own contribution on climate impacts rather than presenting climate change adaptation and mitigation options what distinguishes our work from earlier publications on climate change in the MENA region.

Regional climate change

Temperatures and heat extremes

Warming of about 0.2° per decade has been observed in the MENA region from 1961 to 1990, and at even faster rate since then (Fig. ESM1 in "supplementary material"). A regional summer warming well above global mean temperature increase is projected for most of the region except southern parts (Oman, Yemen and Djibouti). The strongest warming is projected to take place close to the Mediterranean coast (Fig. 1). Here, but also in inland Algeria, Libya and large parts of Egypt, regional warming by 3 °C with 2 °C global warming is projected by the end of the century. With 4 °C global warming, mean summer temperatures are expected to be up to 8 °C warmer in parts of Algeria, Saudi Arabia and Iraq by the end of the century due to a simultaneously drying trend in the region (Fig. 1, right panel).

The observational record reveals a robust increase in the number of extremely high temperatures (Seneviratne et al. 2012) and in the warm spell duration index since the 1960s. This index represents the longest annual spell of at least six consecutive days with maximum temperatures exceeding the local 90th percentile of a reference period (Donat et al. 2014). An increase in the heat wave intensity index (+1.33 ± 0.06 °C/decade) has also been observed since the 1960s and is particularly pronounced over North Africa, the Eastern Mediterranean and the Middle East (Kuglitsch et al. 2010).

We define heat extremes as temperatures exceeding three times and five times the standard deviations of the historic monthly temperatures in 1951–1980, and we will refer to these as 3- and 5-sigma events, respectively (see "Appendix A.1" in World Bank 2014, Coumou and Robinson 2013). Using five global climate models, we find that by the end of the century, in a 2 °C world, 3-sigma or *unusual* heat extremes will occur in about 30 percent of summer months almost everywhere in the MENA region (Fig. 2, top). This implies that on average one of the summer months June, July and August each year will be an unusual hot month. The 2012 US heat wave and the 2010 Russian heat wave are classified as 3-sigma heat events. 5-sigma or u*nprecedented* heat extremes (Fig. 2, bottom) occur much less frequently with a return period of several million years. Please note that monthly mean temperatures are not necessarily normally distributed and hence the return period might vary considerably (see also World Bank 2014, "Appendix A.1"). 5-sigma heat extremes, however, will remain largely absent in a 2 °C world, except for in some isolated coastal regions including the Mediterranean coasts of Egypt, and in Yemen, Djibouti and Oman (Fig. 2, lower right panel). In a 4 °C world, about 65 percent of summer months in the MENA region are projected to be classified as 5-sigma heat extremes by 2071–2099. Whereas the increase in frequency of heat extremes is expected to level off by mid-century with 2 °C global warming, with 4 °C global warming it will continue increasing until the end of the century (Figure ESM2 in "supplementary online material").

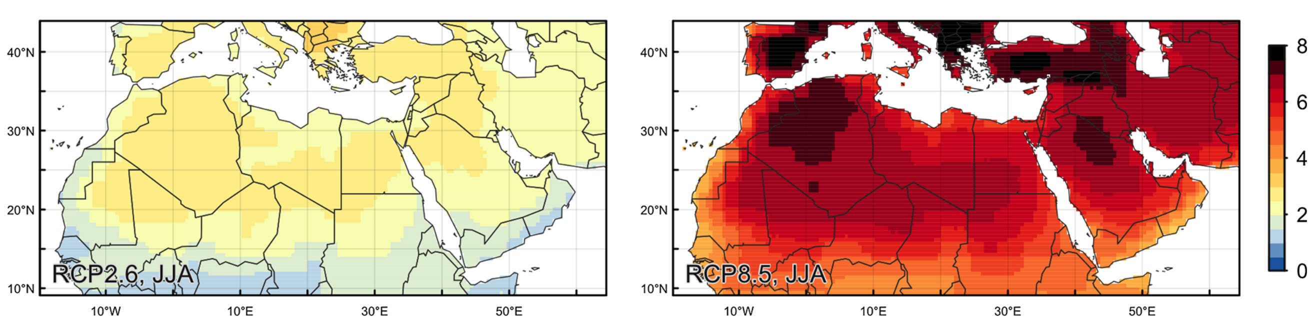


Fig. 1 Temperature projections (in degrees Celsius) for the scenarios RCP2.6 and RCP 8.5 and the summer months of June–July–August (JJA) in 2071–2099 per grid cell **a**. Please see Appendix A.1 in World Bank 2014 for further details on methods and models used

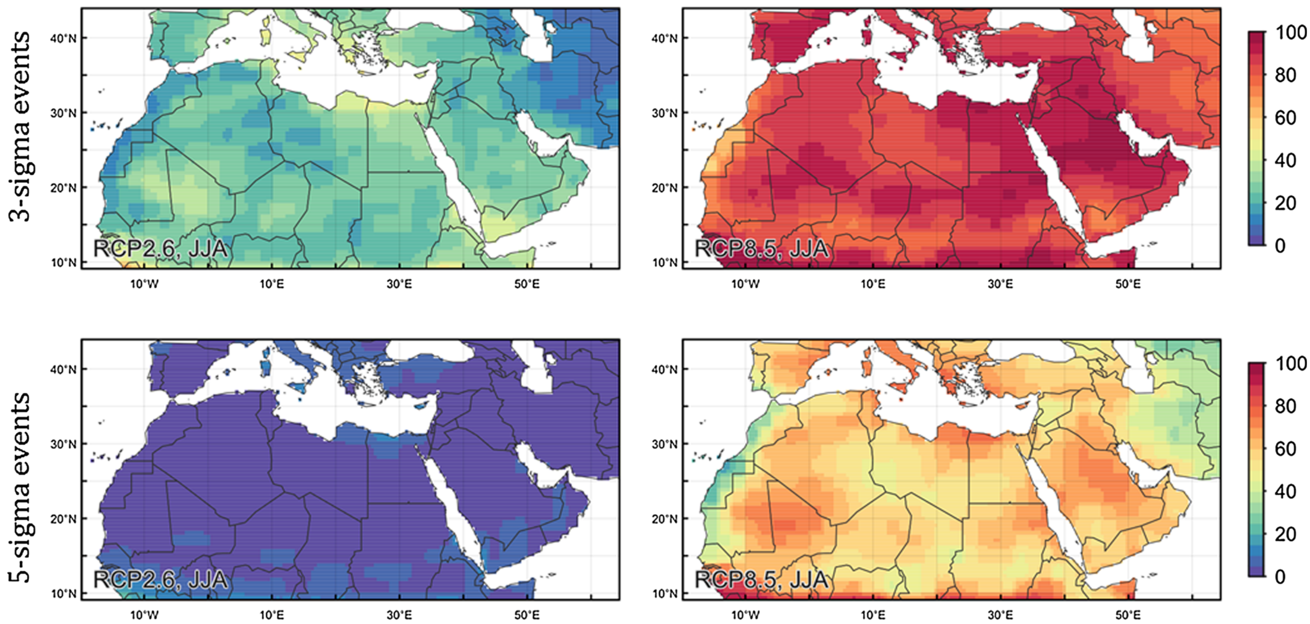


Fig. 2 The percentage of summer months June–July–August (JJA) in 2071–2099 with temperatures greater than three times the standard deviation of the historic local climate in 1951–1980 (top row) and greater than five times the standard deviation of the historic local climate in 1951–1980 (*bottom row*) for scenarios RCP2.6 (*left*) and RCP8.5 (*right*). Please see Appendix A.1 in World Bank 2014 for further details on methods and models used

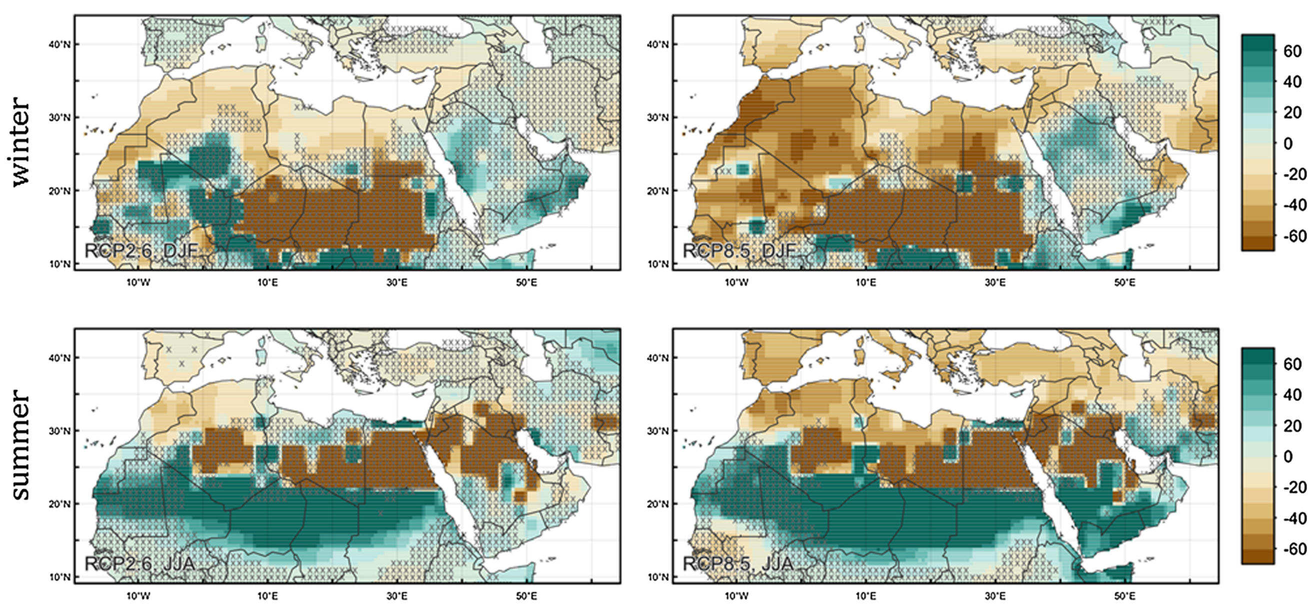


Fig. 3 The percentage change in winter (December–January–February, top) and summer (June–July–August, bottom) precipitation for scenarios RCP2.6 (left) and RCP8.5 (right) by 2071–2099 relative to 1951–1980. Hatched areas indicate uncertain results, with models disagreeing on the direction of change. Note that projections are given as relative changes; thus, over dry regions like the Sahel/Sahara, large relative changes reflect only small absolute changes. Please see Appendix A.1 in World Bank 2014 for further details on methods and models used

Precipitation, aridity and drought

Future northward shifts of air moisture associated with a stronger North Atlantic Oscillation (NAO) anomaly are projected to reduce rainfall in North Africa and West Asia (Maghreb and Mashrek, see "supplementary online material 2" for a definition of subregions). In a 2 °C world, countries along the Mediterranean shore, notably Morocco, Algeria and Egypt, are projected to receive substantially less rain (Fig. 3). However, a projected northward shift of the inter-tropical convergence zone (ITCZ) is expected to increase moisture delivery to the southern parts of the MENA region (which are already under the influence of monsoon systems), in particular to the southern Arabian Peninsula (Yemen, Oman). Consequently, projected annual mean precipitation changes show a clear north–south dipole pattern, with regions north of 25°N becoming relatively drier and regions to the south becoming wetter. The absolute increase in precipitation in the southern regions, however, will be very small, given this regions hyper-arid present-day climate conditions (with the exception of Yemen).

An increase in precipitation in the southern part of the MENA region may be associated with more intense and extreme precipitation events. The observational record for North Africa, the Middle East and the Arabian Peninsula indicates an overall reduction in extreme precipitation events since the 1960s, despite a local positive trend over the Atlas mountains since the 1980s (Donat et al. 2014). At the same time, an increase in meteorological drought has been reported since the 1960s, consistent with an overall regional drying trend (Donat et al. 2014; Sousa et al. 2011). Despite a global trend toward more extreme precipitation events over the twenty-first century, Kharin et al. (2013) find no significant change in heavy precipitation across most of North Africa and the Middle East from an analysis using CMIP5 global climate models for the RCP8.5 scenario. It is not clear, however, to what extent these models are able to reproduce rare climatological phenomena like the Active Red Sea Trough (ARST) that is associated with extreme heavy precipitation events in the Middle East in the observational record (de Vries et al. 2013). While the projected changes in extreme precipitation events are below the global average for Saudi Arabia and the Islamic Republic of Iran, the southern tip of the Arabian Peninsula (notably Oman and the Republic of Yemen) is projected to experience a substantial intensification of extreme precipitation events over the twenty-first century under the RCP8.5 scenario (Kharin et al. 2013; Sillmann et al. 2013).This is consistent with the robust projection for increasing annual precipitation over the Horn of Africa.

There is a close match between the pattern of change in the annual mean aridity index (AI) and projected precipitation changes. Changes in the aridity are primarily driven by changes in precipitation, with wetter conditions south of 25°N and in most southern parts of the Arabian Peninsula causing a drop in aridity, and drier conditions north of 25°N causing aridity there to increase (Fig. 4). In the Mediterranean coastal region, the relative increase in aridity is more pronounced than what would be expected from the drop in precipitation alone, due to a substantial increase in evapotranspiration here due to enhanced warming.

The North African countries (and notably Morocco, Algeria and Tunisia), as well as the countries of the Middle East, are consistently projected to become global hot spots for drought by the end of the twenty-first century under all but the most stringent mitigation scenario investigated (RCP 2.6, Dai 2012; Orlowsky and Seneviratne 2013; Prudhomme et al. 2013; Sillmann et al. 2013). Prudhomme et al. (2013) report an increase of more than 50 percent in the number of drought days around the Mediterranean by the end of the twenty-first century (2070–2099 relative to 1976–2005) for scenario RCP8.5. For the same region, Orlowsky and Seneviratne (2013) project the occurrence of more than six months per year with at least moderate drought conditions on average in 2080–2100 under the RCP8.5 scenario, compared to less than 30 days per year under RCP2.6. Although projections of future droughts vary between models and also largely depend on the methodology and baseline periods chosen (Trenberth and Dai 2014), an increase in extreme drought conditions around the Mediterranean, Northern Africa and the Middle East is consistently projected across a variety of studies (IPCC 2012).

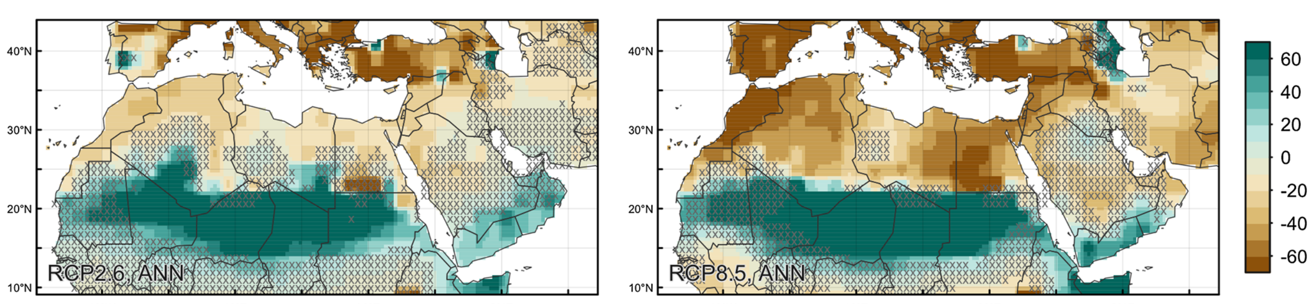


Fig. 4 The percentage change in the aridity index for scenarios RCP2.6 (*left*) and RCP8.5 (*right*) by 2071–2099 relative to 1951–1980. Hashed areas indicate uncertain results, with models disagreeing on the direction of change. Note that a *negative* change corresponds to a shift to *more arid* conditions. Please see Appendix A.1 in World Bank 2014 for further details on methods and models used

Regional sea-level rise

Sea-level rise (SLR) projections for the MENA region constitute a particular challenge due to the semi-enclosed nature of both Mediterranean and Red Sea basins. Both are connected with the broader Atlantic and Indian Oceans, respectively, through relatively narrow straits which are not well represented in global, coarse-resolution general circulation models (GCM) (Marcos and Tsimplis 2008). For that reason, please note that the ocean's dynamical response to changing density and atmospheric conditions from GCMs analyzed here is explorative.

In the Mediterranean area, tide gauges recorded below-average sea-level rise during the twentieth century, with an average rise of 1.1–1.3 mm per year (Tsimplis and Baker 2000) which is lower than the global average of 1.8 mm per year (Meehl et al. 2007). There has been significant inter-decadal variability, with reduced rise between 1960 and 1990 and rapid (above average) rise after 1990. In the 2009/2010 and 2010/2011 winters, sea levels rose 10 cm above the seasonal average. Atmospheric influence is thought to be the primary driver, where pressure and wind variations associated with the North Atlantic Oscillation control water flow through the Gibraltar Strait (Landerer and Volkov, 2013; Tsimplis et al., 2013). Compared to the well-studied Mediterranean basin, tide gauge records in the Red Sea and Arabian Sea are much sparser—limited to a few, non-continuous records. Available evidence from the neighboring Northern Indian Ocean, also including satellite altimetry and modeling, suggests past rates of rise consistent with the global mean sea-level rise (Han et al. 2010; Unnikrishnan and Shankar 2007).

In comparison with previous work on SLR in the MENA region, this work benefits from recent advances with respect to sea-level modeling, in particular thanks to the IPCC AR5. Future projections for the MENA region[2] indicate median sea-level rise of about 0.35 m under scenario RCP2.6 and 0.6 m under scenario RCP8.5, between 1986–2005 and 2080–2099. The projected upper bound is about 0.6 m under RCP2.6 and 1 m under RCP8.5.[3] These regional estimates are slightly lower than the global average, mostly as a result of the gravitational influence of the Greenland ice sheet. Also for that reason, while projections for all locations in the region are within 0.05 m of the values reported above, projections for locations in the east (e.g., Muscat, on the Arabian Sea coast) are up to about 0.1 m higher than for locations in the west (Tunis, Western Mediterranean; Tangier, Atlantic coast) (Fig. 5). Note that these projections focus on long-term, climate-related trends in the average sea level. It is unclear whether and how variability on sub-annual, inter-annual and inter-decadal time scales may change, compared to, say, the kind of observations reported above for the recent past. Additionally, land subsidence due to human activity (e.g., groundwater mining) should also be accounted for.

Human population in the MENA region as well as agricultural, industrial and other economic activities tend to be concentrated in coastal zones. The population of MENA's coastal cities was approximately 60 million people in 2010, but the number is expected to reach 100 million by 2030 (World Bank 2011). Key impacts of climate change in coastal zones are expected to be inundation resulting from slow-onset sea-level rise, floods and damages caused by extreme events including storms and storm surges, saltwater intrusion into coastal aquifers and increased erosion (Brecht et al. 2012; Hunt and Watkiss 2011).

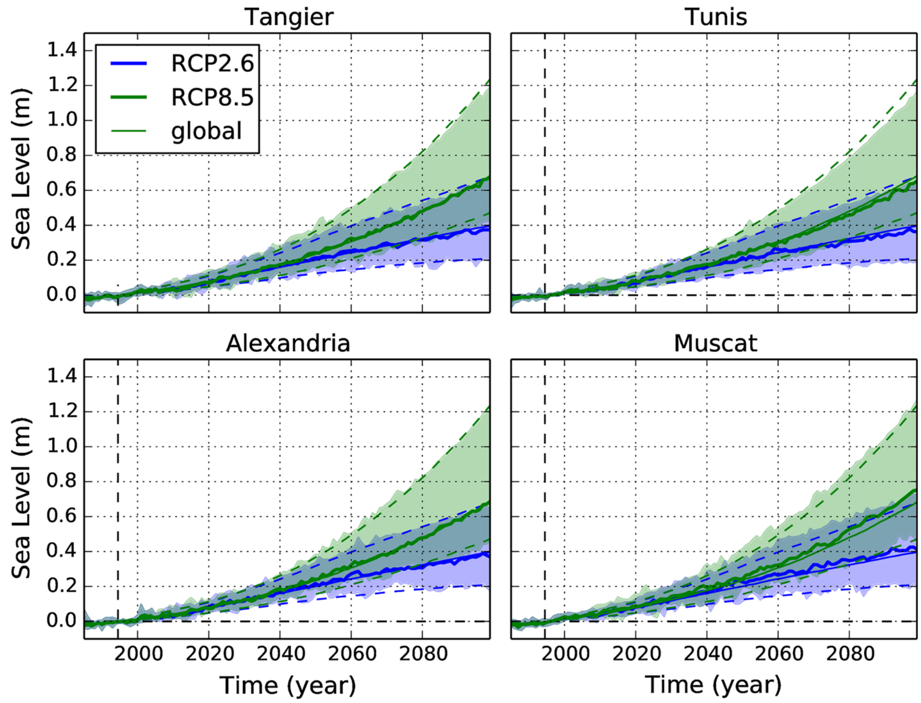
Dasgupta et al. (2009) found that about 0.25 percent of MENA's land area would be impacted by a 1-m SLR. This is a small number compared to other world regions. However, the impact is much more severe in terms of urban and agricultural areas affected, population affected and GDP loss with Egypt, Tunisia, Libya and the United Arab Emirates being among the countries with largest impacts also compared to countries in other world regions. With a 1-m SLR, 3.2% of MENA's population would be affected (compared to 1.3% worldwide), 1.49% of its GDP (compared to 1.30% worldwide), 1.94% of its urban area (compared to 1.02% worldwide) and 1.15% of its agricultural area. Egypt would be the most severely affected country in the study with about 13% of its agricultural area lost (Dasgupta et al. 2009). The total number of people actually flooded, in the absence of adaptation, is estimated to be 0.03, 0.26, 1.82 and 1.97 million people per year in Libya, Tunisia, Morocco and Egypt in a 2° world and 0.13, 0.80, 2.07 and 3.60 million people per year, respectively, in a 4° world (Brown et al. 2009).

Sea-level rise impacts in Egypt's Nile Delta will be exacerbated by land subsidence, especially in the eastern part of the delta, and extensive landscape modification resulting from both coastal modification and changes in the Nile's hydrogeology (Frihy and El-Sayed 2013; Wöppelmann et al. 2013). Aside from direct inundation, SLR is expected to have serious impacts in terms of saltwater intrusion, the salinization of groundwater, rising water tables and impeded soil drainage (Hunt and Watkiss, 2011; Werner and Simmons, 2009). Saltwater intrusion into coastal aquifers has been documented across MENA, e.g.,

[2] A subset of global climate models from the IPCC AR5 report was used in this study, with an IPCC AR5-like methodology to project sea level rise, expect for Antarctica, which was updated with more recent research, leading to more differentiated sea level projections between RCP2.6 and RCP8.5 scenarios. See Appendix A.2 in World Bank 2014a for further details on methods and models used.

[3] Note that while we report model-based upper bounds in this report, other assessments, such as expert polling, lead to higher estimates. We thus suggest the reported uncertainties for sea-level be interpreted as the "likely" range (67%).

Fig. 5 Sea-level projections for Tangier, Tunis, Alexandria and Muscat for the scenarios RCP2.6 (*blue*) and RCP8.5 (*green*). Median estimates are given as *full thick lines* and the lower and upper bound given as shading. *Full thin lines* are global median sea-level rise with *dashed lines* as lower and upper bounds. *Vertical* and *horizontal black lines* indicate the reference period and reference (zero) level. Please see "Appendix A.2" in World Bank 2014 for further details on methods and models used



in Tunisia, Egypt and Israel (Kerrou et al. 2010; Kouzana et al. 2009; Yechieli et al. 2010). The principal causes of observed saltwater intrusion have been over-extraction of waters for supplementary irrigation, and reductions in the recharge of aquifers. These factors are likely to remain immediate challenges, although they will be aggravated by the effects of sea-level rise (Kouzana et al. 2009).

Another expected consequence of climate change is a greater intensity of storms (e.g., Knutson et al. 2010). Coupled with higher sea levels, more intense storms are likely to result in more powerful storm surges. Dasgupta et al. (2009) state that under a 1-m SLR and 10% increase in storm intensity, 50% or more of the coastal population in Kuwait, Djibouti, UAE and Yemen would be at great risk from storm surges. The effects of climate change would leave 2.7 million more people in Alexandria and 1.2 million more people in Aden exposed to storm surges (Dasgupta et al. 2011). The same study calculated that storm intensification would cause additional annual losses to GDP in MENA of US$ 12.7 billion by 2100, with exposure particularly high in Kuwait, UAE, Morocco and Yemen (Dasgupta et al. 2011). For a detailed discussion about adaptation options in North African coastal cities up to 2030, refer to Bigio (2011).

Impacts on agriculture and water

The MENA region is water scarce with most of the land area receiving less than 300 mm of annual rainfall (200–300 mm roughly represents the lower limit of rain-fed agriculture). Semiarid belts along the coasts and mountains are the only water source areas and provide productive land for rain-fed agriculture (Immerzeel et al. 2011). The availability of renewable water resources in most countries is below 1000 m^3 per capita and year (except for Iraq, Oman, Syria and Lebanon) and as low as 50 m^3 per capita and year in Kuwait (Selvaraju 2013; Sowers et al. 2011). Accordingly, withdrawal-to-availability ratios exceed a critical threshold of 40 percent in all MENA countries except Lebanon; they exceed 100 percent in Jordan, the Republic of Yemen, Libya and most of the Arab peninsula countries (FAO 2013a), leading to groundwater resource depletion. This water scarcity prevents MENA countries from producing all required food domestically and makes the region dependent on food imports. From the current situation of critical water and arable land scarcity, global warming is likely to result in further increased pressures on water resources and agriculture such as:

- Cropland: Warmer and drier climate is projected to shift vegetation and agricultural zones northwards, e.g., by 75 km for 2090–2099 relative to 2000–2009 in a 4 °C world (Evans 2009). Ferrise et al. (2013) also projected a shift northward for olive plantations.
- Length of growing period: Lower rainfalls and higher temperatures will shorten growing periods for wheat in the MENA region by about two weeks by mid-century (2031–2050) (Ferrise et al. 2013). The wheat growing period in Tunisia is expected to be shortened by 10 days for 1.3 °C, by 16 days for 2 °C, by 20 days for

2.5 °C and by 30 days for 4 °C warming (Mougou et al. 2010).

- Crop yields: Most agricultural activities in the MENA region take place in the semiarid climate zone, either close to the coast or in the highlands. Crop yields are expected to decline by 30 percent with 1.5–2 °C warming (Al-Bakri, Suleiman, Abdulla, and Ayad 2011; Drine 2011) and up to 60 percent with 3–4 °C warming (Schilling et al. 2012), with regional variation and without considering adaptation. Reductions in crop productivity of 1.5–24 percent are expected for the western Maghreb and 4–30 percent in parts of the Mashrek, by mid-century. Legumes and maize crops are expected to be worst affected in both regions as they are grown during the summer period (Giannakopoulos et al. 2009). Figure 6 shows results of a meta-analysis of the impact of temperature increase on crop yields from 16 different studies in the MENA region (see "Supplementary Online Material 3" for references and details on methods), indicating that there exists a significant correlation between crop yield decrease and temperature increase regardless of whether the effects of CO_2 fertilization or adaptation measures are taken into account. However, exclusively looking at the few studies considering the CO_2 fertilization effect or adaptation measures, yields statistically insignificant relationships (Fig. 6, right panel, dotted lines). Some adaptation measures have the potential to compensate of even offset negative climate change impacts.
- Livestock: Climate change will impact livestock production through various pathways, such as changes in the quantity and quality of available feeds, changes in the length of the grazing season, additional heat stress, reduced drinking water and changes in livestock diseases and disease vectors (Thornton et al. 2009). The vulnerability of livestock production systems to droughts was recently demonstrated in northeastern Syria, where herders lost almost 85 percent of their livestock as a result of the recurring droughts between 2005 and 2010 (Selvaraju 2013).

Uncertainty in projections on crop yield arises from differences in methodologies, climate models and whether or not the CO_2 fertilization effect is assumed to be effective, since increasing atmospheric CO_2 concentration can potentially increase plant water-use efficiency through structural or physiological effects and thus improve crop productivity.

An increase in temperature and evapotranspiration rate shifts in the precipitation regime, and the intensification or change in frequencies of extreme events may trigger or enhance the desertification processes. The role of climate change in the desertification spiral varies depending on local conditions and interactions between drivers and can be multifaceted. Increase in temperatures and evapotranspiration, change in precipitation regime, intensification or change in frequencies of extreme events can directly trigger or enhance the desertification processes. No study could attribute recent climate change as the single driver of desertification. In general, desertification and also the closely related salinization and dust storms are well understood and described in the literature. However, there are still large gaps when it comes to the multifaceted role of climate change and especially to the role of CO_2 fertilization. However, the manifold studies about the observed

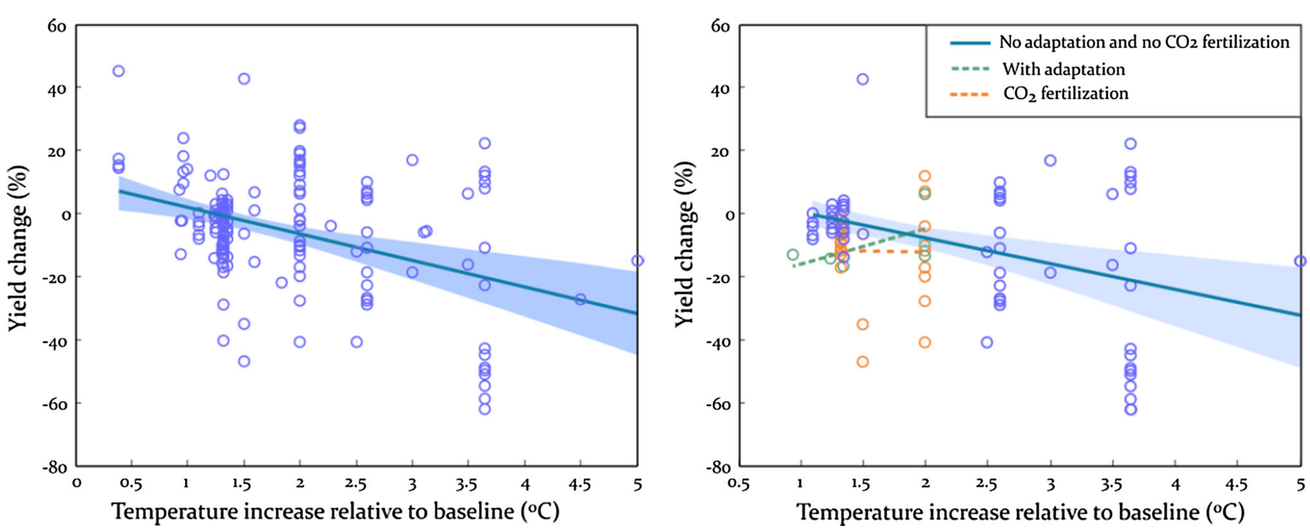


Fig. 6 Crop yield changes with temperature increase in the MENA region over all studies (left) and for studies that take the effects of adaptation measures (*green line*) and CO2 fertilization (*orange line*) into account. The *blue line* in both panels indicates the best-fit line, and the *blue shade* shows the 95% confidence interval of regressions consistent with the data based on 500 bootstrap samples. The solid line depicts a significant relationship and dotted lines nonsignificant relationships. See "Appendix 1" for methods and studies included

impacts of desertification in the MENA region show that there is a strong need for integrated model approaches in order to assess desertification under global change (Aguirre-Salado et al. 2012; Belaroui et al. 2013; Scheiter and Higgins, 2009; Schilling et al. 2012; Verstraete et al. 2009).

Being covered mostly by drylands, the MENA region is frequently threatened by dust storms, causing massive damages to people, agriculture and economy (Akbari 2011; Kumar 2013). As for desertification, there are no direct projection studies on dust storms in the MENA region (Goudie 2009). However, wind as a driving factor can be projected from climate models. Yet, there are no regional studies on wind under climate change in the MENA region and future trends have to be derived from global studies.

As a result of regional warming and changes in precipitation patterns, water availability is projected to decrease in most parts of the MENA region throughout the twenty-first century (García-Ruiz et al. 2011), with the exception of the southernmost areas. For example, the eastern Anatolian mountains (headwaters of Euphrates and Tigris rivers) a runoff decrease of 25 percent to 55 percent is projected with 4 °C warming (Bozkurt and Sen 2013). Mountain areas in Morocco, Algeria, Lebanon, Syria, Iraq, Iran and Turkey play an important role in the water supply of the MENA region, as they catch atmospheric moisture, generate large amounts of runoff and store a fraction of precipitation as snow. With projected reduction in snowfall and snow water storage, peak flows of melt water will shift toward earlier months, with negative impacts for downstream river systems and water availability in distant regions.

Impacts on health

Human societies in the MENA region face a variety of health risks, many of which are exacerbated by the hot and arid conditions and relative water scarcity that generally characterize the region. Water-related diseases such as cholera, which is associated with high temperatures and water contamination, and trachoma, which is associated with dry conditions and poor sanitation, already affect the region (WHO and EMRO, 2009, International Trachoma Initiative, 2016). The prevalence of these and other illnesses may increase as water supply, water quality and access to sanitation are affected by climate change.

Several studies exist that indicate that various climatic changes may favorably affect the transmission of vector-borne diseases such as malaria (Salehi et al. 2008; van Lieshout et al. 2004), lymphatic filariasis, also known as elephantiasis, a disease of the lymphatic system caused by parasitic worms transmitted by mosquitoes (Slater and Michael, 2012) and leishmaniasis, a skin disease carried by sandflies endemic to the MENA region (Ben-Ahmed et al. 2009; Toumi et al. 2012). Seasonal occurrence of malaria, for example, is linked to temperature, elevation, humidity and rainfall (Salehi et al. 2008). Dengue fever also poses a growing risk in the region, with outbreaks reported more frequently since 1998, particularly in Saudi Arabia and Yemen (WHO and EMRO, 2009). Modeling exists suggesting that some areas that are currently climatically unfavorable to the dengue vector *Aedes aegypti*, including the Arabian Peninsula and southern Iran, may become more favorable with climate change (Khormi and Kumar 2014). Extreme weather events such as heat waves, flooding, droughts and landslides can more directly result in morbidity and mortality. MENA at present already experiences already very high summer temperatures, making the populations of the region highly susceptible to further temperature increases (Habib et al. 2010; Lelieveld et al. 2012). High temperatures can cause several medical conditions including heat stress, heat exhaustion and heat stroke, with the elderly, the young and people with existing medical conditions most vulnerable. The number of emergency hospital admissions has been observed to increase during heat waves—by 1.47 percent per 1 °C increase in ambient temperature in Tel Aviv, for example (Novikov et al. 2012). In a 2 °C world, the number of consecutive hot days is projected to increase in several capital cities in the MENA region: from four days to about two months in Amman, from eight days to about three months in Baghdad and from one day to two months in Damascus, for example. The number of hot days in Riyadh is expected to increase even more—from about three days to over four months. Overall the number of hot days in a 4 °C warmer world is projected to exceed the equivalent of four months in most capital cities (Lelieveld et al. 2013b).

In addition, the MENA region already bears a significant health burden associated with air pollution (Lelieveld et al. 2013a), and while emissions of future anthropogenic air pollutants are uncertain, photochemical air pollution is projected to increase substantially due to heat extremes leading to strongly increased ozone formation (Lelieveld et al. 2013b). Air pollution can cause or exacerbate respiratory illnesses such as asthma (Portier et al. 2010).

Impacts on migration and human security

Migration, in the form of pastoral nomadism in search of forage and water for livestock, has long been a part of traditional lifestyles in MENA and the Sahelian adjacent territories in the south (Brücker et al. 2012). As the economies of MENA countries have changed, migration, both within MENA countries and to richer countries, has become a common route by which people attempt to increase their livelihood security. Indeed, migration has always been a human response to climatic and other hazards. Migration, in the context of climate change, happens as soon as the physical, economic, social or political security of a population decreases, and no other resources can be mobilized to adapt to the new conditions. Some studies therefore consider migration as a last resort (Laczko and Piguet 2014; Warner et al. 2010), while others debate whether migration should be considered a successful adaptation strategy or a failure to adapt (Bardsley and Hugo 2010; Gemenne 2013; Luecke 2011; Tacoli 2009). However, instead of improving living conditions, migration may bear new insecurities and vulnerabilities (Warner et al. 2010).

The literature review revealed a linkage between climate change and migration for the MENA region that is majorly due to water scarcity (Wodon et al. 2014) and sea-level rise (Kumetat 2012). It is expected that migration options will be limited in a warmer world (Gemenne 2011a). Among MENA inhabitants, internal migration will continue to be important, but traditional patterns of mobility might be disrupted (Gemenne 2011b). Many people will be forced to move, while others trapped in poverty will be forced to stay (Black et al. 2011b). This indicates that climate-induced migration should be addressed not only within the framework of climate change, but also by means of policies that address other economic, cultural, technological or political conditions that might foster or limit migration.

Climate change might act as a threat multiplier (Center for Naval Analysis 2007) in the MENA region by placing additional pressure on already scarce resources and by reinforcing preexisting threats such as political instability, poverty and unemployment. Jointly with lacking additional elements of human security, e.g., water, food, energy and health (Scheffran et al. 2012), this can create the potential for social uprising and violent conflict. However, establishing a direct link between climate change and conflicts in MENA is challenging due to contradictory conclusions and methods (see, e.g., Buhaug 2010; Burke et al. 2009; Hsiang and Meng 2014; Hsiang et al. 2013 for a detailed discussion). Some findings are based on single extreme events, and others use rainfall or temperature variability as proxies for long-term changes and some examine short-term warming. Considering that many countries are currently experiencing climate change without insecurity, conflict or crisis leads to the conclusion that well-established and effective institutions are crucial for building higher levels of resilience, and for reacting and adapting to climatic changes, or shocks such as climate variability-related increases in food prices. Institutions already weakened by conflicts or crisis have less capacity to build resilience to climatic changes and extreme events. Further research is required to further investigate and establish the link between climate change and conflicts and to relate long-term climate change, instead of single climatologic hazards, to migration and conflicts.

Syntheses and discussion of implications of climate change impacts for vulnerable population groups

Climate change interacts with existing inequalities to affect particular population groups more than others and may also undermine poverty alleviation efforts (Leichenko and Silva 2014, Al-Riffai and Breisinger 2012). The following implications of climate change are discussed in this section in order to relate climate change impacts to vulnerable population groups in the MENA region: (1) the implications for poor farmers and the rural population and (2) the implications for the urban population and migrants. We adopt the most recent definition of vulnerability from Burkett et al. (2014) that defines vulnerability as the propensity or predisposition to be adversely affected. Vulnerability is understood as a multidimensional concept that is influenced not only by biophysical but also by social stressors, the latter meaning structural conditions of poverty and inequality. This allows us to identify vulnerable population groups through these societal risks.

Table ESM2 in “supplementary material 4” summarizes the key climate change impacts under different warming levels in the Middle East and North Africa region and Fig. 7 summarizes the key subregional impacts.

Rural population and poor farmers

Farmers in the MENA region have traditionally coped with harsh climatic conditions, and climate change adds to the existing challenges. Most agricultural activities in MENA take place in the semiarid climate zones close to the coast or in the highlands, where rainfall and thus water availability are predicted to decline most strongly. As agriculture supports about one-third of the region’s population (Dixon et al. 2001) and contributes 13 percent to the region’s GDP (the global average is 3.2 percent) (Verner 2012), climate change impacts have important implications for farmers’ livelihoods, national economies, food security and poverty (Al-Riffai and Breisinger 2012) and represent a key challenge for sustainable development in the region.

The prevalence of poverty is extensive among highland farmers because of poor infrastructure and the degradation of natural resources; among small farmers in dryland farming systems because of low rainfall and weak market linkages; and among small herders in pastoral farming systems for the same reasons (Dixon et al. 2001). Yet

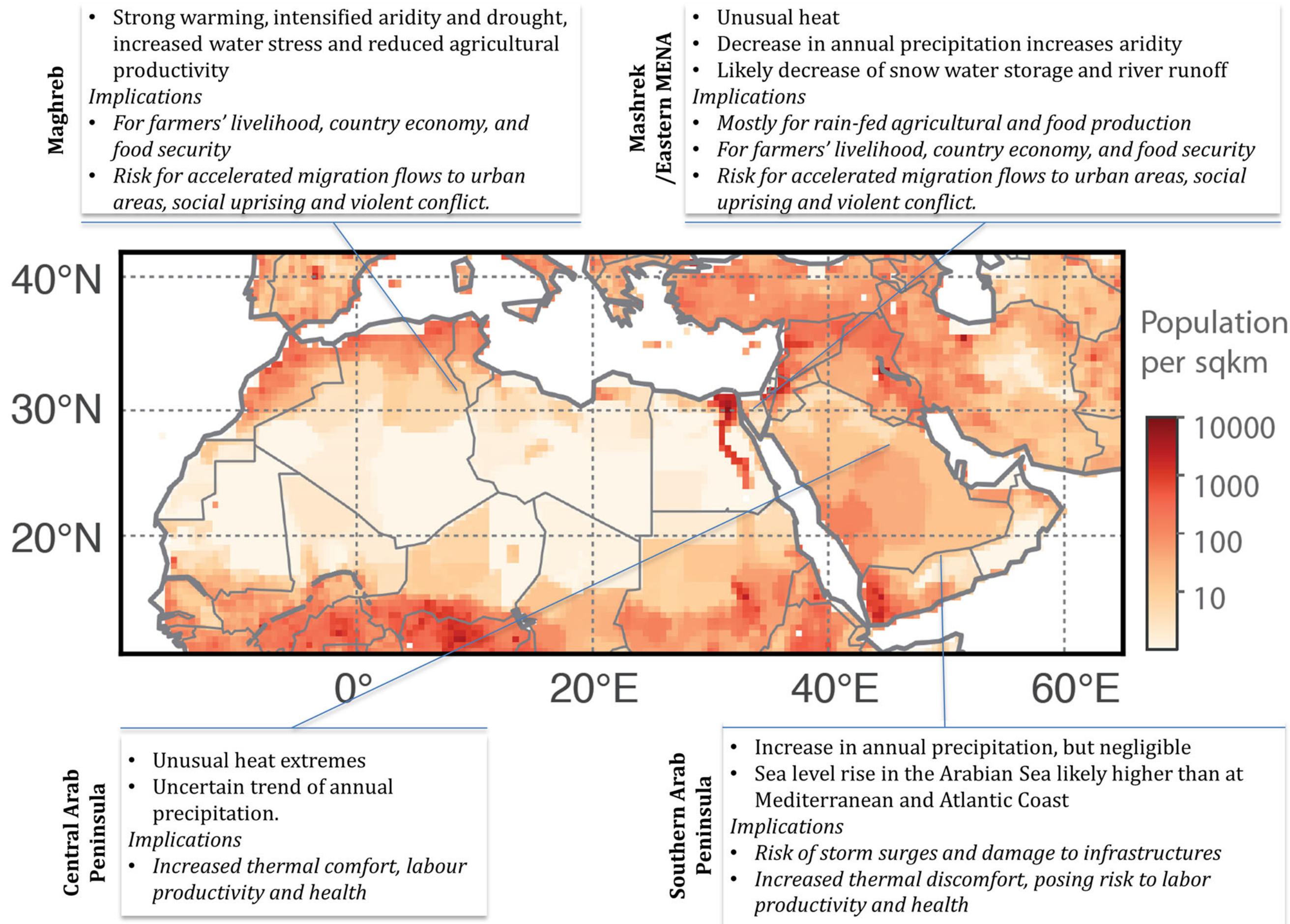


Fig. 7 MENA population experiencing unusual monthly boreal summer temperatures and expected subregional impacts under 4 °C warming by the end of the twenty-first century (RCP 8.5, 2071–2090) compared to preindustrial temperatures. Population estimates are based on the Shared Socio Economic Pathway 2 (SSP2) and shown in terms of population density. The basis for the gridded population estimates is the National Aeronautics and Space Administration GPWv3 y-2010 gridded population dataset, which is linearly scaled up on country basis to match the SSP projections, thus neglecting population redistribution within countries. The SSP2 population estimates on country basis with 5-year time steps were obtained from the SSP database as in Schewe et al. (2014). Compare with projections for RCP2.6 and different time periods shown in Figure ESM4 in ESM1. See "supplementary online material 2" for a definition of the subregions

poverty in the first place results from lack of access to resources, including inequitable sharing of water, food and energy resources. Land management practices are often inefficient and many policies favor urban populations and the supply of cheap food instead of supporting rural development (Dixon et al. 2001). Addressing these factors could considerably reduce the risk of climate change contributing to increased poverty.

In addition, as MENA countries are heavy food importers, the region also indirectly suffers from climate change impacts in distant food-producing regions. A shortfall in wheat yield due to drought conditions in China and Russia and extreme precipitation in Canada, major wheat exporters to the MENA region where the staple food is majorly, have contributed to shortages in food in 2010/2011 (Sternberg 2012). However, it is unclear whether these extremes are attributable to climate change or are variabilities in weather patterns.

Urban population and migrants

Within the MENA region, most migration is internal as urbanization is the predominant migration pattern. As rural livelihoods are directly affected by climate change, especially where a high proportion of the population is employed in agriculture, the urbanization trend will likely continue. In Algeria, for example, migrants move rural areas to mid-sized towns (Gubert and Nordman 2010). This movement is partly due to slow-onset environmental degradation, including water scarcity, soil erosion and desertification, which threatens agricultural livelihoods in rural Algeria (Wodon et al. 2014). However, while many people will be forced to move, others will be forced to stay because they lack the financial resources or social networks that facilitate mobility. This indicates that climate-induced migration should be addressed not only within the framework of climate change, but also within other economic, cultural, technological or political conditions that might foster or limit migration (Gemenne 2011a).

Several studies bring attention to the quality of housing in urban centers and the capacity of urban infrastructure to accommodate an increasing population. Migrants to urban areas often live in marginal land with poor infrastructure, liable to flooding or on unstable slopes, and this at great risk from extreme events. The migrants are likely to be poor, face health risks related to low-income urban environments (e.g., overcrowding, poor water quality, poor sanitation). Such areas are also typically at higher risk of crime (Black et al. 2011a; Hugo 2011) In some areas, migrants also face discrimination based on their ethnicity, making it harder for them to access services and find employment, with the risk that poor migrant children may have more limited access to education than other local children (Marcus et al. 2011).

Social ties play an important in role in finding employment and housing in migration destinations. Migrants, especially those coming from rural areas, are often at disadvantaged since they usually have less education and lower language capabilities (e.g., not speaking both French and Arabic in Morocco). Furthermore, many migrants live in overcrowded apartments and in slums. Lack of permanent access to electricity for cooling in the night can lead to loss of sleep and lower productivity during the day (Kjellstrom et al. 2009).

If current migration patterns continue, the majority of migrants are likely to be men migrating without their families, at least initially. Women left behind in rural areas may thus face more intensive workloads in agriculture, domestic work and the management of scarce water supplies (Verner 2012). If rural women taking on new roles do not have the skills to generate productive livelihoods, as a result of discriminatory social norms and limited education opportunities, then they are at risk of falling into poverty. Promoting gender equity, by tackling both discriminatory norms and inequalities in access to resources, is thus a vital component of effective climate change adaptation strategies (Verner 2012).

The number of days with exceptional high temperatures is expected to increase in several capital cities in the MENA region, e.g., Amman, Baghdad, Damascus and Riyadh which can cause heat-related illnesses, including heat stress, heat exhaustion and heat stroke. While there is robust evidence from global studies for increased mortality rates during extreme heat events, particularly for people with chronic diseases, those who are overweight, pregnant women, children, the elderly and people engaged in outdoor manual labor (Kjellstrom and McMichael 2013; Smith et al. 2014), further research on future patterns of heat-related illness in MENA, as well as on the indirect effects of extreme heat, is needed. Conditions for workers in the construction industry in the region are already very tough today, with workers reported to suffer from heat exhaustion and dehydration. Measures to limit working hours during peak heat periods, such as those implemented by Qatar (Verner 2012), may become increasingly necessary, with implications for productivity. Thermal discomfort is expected to increase, in particular in southern parts of the Arabian Peninsula and will challenge people's health, especially in densely populated large cities that already today experience high maximum temperatures. Heat stress is likely to be worse for the urban poor households who cannot afford cooling and may also lack access to electricity (Satterthwaite et al. 2007) as in the Republic of Yemen, for example, where only about 40 percent of the population has access to electricity (World Bank 2013a).

Conclusions

The MENA region is one of the world's most exposed region to negative climate change impacts. The region is already affected by heat extremes and water shortages. With 4 °C global warming, the mean summer temperatures can increase by up to 8 °C, water runoff could decrease by 75%, and land aridity could increase in many parts of the region by more than 60%. In particular vulnerable to negative climate change impacts is the rain-fed agricultural production and livelihoods of poor farmers. Yield reductions and increased food import dependency may affect everyone, but urban populations are particularly vulnerable to rising food prices, while poor farmers in rural areas are particularly vulnerable to hunger and malnutrition as a direct consequence of yield losses. The region is characterized by pronounced inequalities and the poor will suffer most from climate change impacts on water and land resources, health and the energy systems. About 25 million people in the MENA region are currently undernourished—four million in Northern Africa (2.7 percent of the total population) and 21 million in Western Asia (10 percent of the total population), higher than in 2008–2010 (FAO 2013b). Although the region has been historically experiencing large migration flows, the recent migration patterns differ from the historic ones. Many people are already forced to leave while the poorest often cannot afford the costs for the journey or migrate through lifethreatening channels. The newcomers are often stigmatized and have worse access to local networks and education.

While food supply, the transmission of certain diseases, migration patterns and the occurrence of conflicts can be affected by climatic factors, there is no a mono-causal relationship with global warming: But other political and socioeconomic factors must be taken into account. One example is the 2011 food supply crisis in Egypt and subsequent protests and political instability. There is a relation to extreme events causing poor harvest in major producing countries, but also Egypt's high import dependency, inefficient bread subsidy system and high unemployment rate were major contributing factors. Other MENA countries, where the population spends a lower percentage of income on food and early adjustment of food prizes were made, were spared from protests and social conflicts.

Suitable measures for each separate sector examined here to absorb any kind of shock from a biophysical climate impact might help to buffer sudden impacts in the short and in the long term. Our findings may serve as a base to explore suitable adaptation measures in the MENA region.

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