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Climate Change and Weather Extremes in the Eastern Mediterranean and Middle East

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Key Points:

- The Eastern Mediterranean and Middle East is warming almost two times faster than the global average and other inhabited parts of the world
- Climate projections indicate a future warming, strongest in summers. Precipitation will likely decrease, particularly in the Mediterranean
- Virtually all socio-economic sectors will be critically affected by the projected changes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Observation-based and modeling studies have identified the Eastern Mediterranean and Middle East (EMME) region as a prominent climate change hotspot. While several initiatives have addressed the impacts of climate change in parts of the EMME, here we present an updated assessment, covering a wide range of timescales, phenomena and future pathways. Our assessment is based on a revised analysis of recent observations and projections and an extensive overview of the recent scientific literature on the causes and effects of regional climate change. Greenhouse gas emissions in the EMME are growing rapidly, surpassing those of the European Union, hence contributing significantly to climate change. Over the past half-century and especially during recent decades, the EMME has warmed significantly faster than other inhabited regions. At the same time, changes in the hydrological cycle have become evident. The observed recent temperature increase of about 0.45°C per decade is projected to continue, although strong global greenhouse gas emission reductions could moderate this trend. In addition to projected changes in mean climate conditions, we call attention to extreme weather events with potentially disruptive societal impacts. These include the strongly increasing severity and duration of heatwaves, droughts and dust storms, as well as torrential rain events that can trigger flash floods. Our review is complemented by a discussion of atmospheric pollution and land-use change in the region, including urbanization, desertification and forest fires. Finally, we identify sectors that may be critically affected and formulate adaptation and research recommendations toward greater resilience of the EMME region to climate change.

1. Introduction

The human influence on the Earth's climate, including atmospheric, ocean and land components, is unequivocal (IPCC, 2021). Since the industrial revolution, a continuous increase in the volume of greenhouse gases (GHGs) being emitted into the atmosphere, in addition to land-use changes (e.g., extensive deforestation and urbanization), have caused a significant increase in the global surface temperature, as well as changes in other meteorological parameters such as rainfall. The regional responses to climate forcing due to anthropogenic GHG emissions are not linear or uniformly distributed. Due to geographically specific climate feedback mechanisms, some regions warm more rapidly than the global mean. One such climate change hotspot is the Eastern Mediterranean and Middle East (EMME) region (Figure 1) (Cramer et al., 2018; Giorgi, 2006; Lelieveld et al., 2012; Zittis & Hadjinicolaou, 2017; Zittis et al., 2019).

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The observed warming trends are projected to continue and intensify throughout the twenty-first century, depending on future tendencies of GHG concentrations which, in turn, are subject to societal and technological developments (IPCC, 2021; Zittis et al., 2019). Besides the mean climate conditions, changes are expected in the temporal variability of meteorological features, adding support to the characterization of the region as a global climate change hotspot (Diffenbaugh & Giorgi, 2012; Giorgi, 2006; Lionello & Scarascia, 2018; Zittis et al., 2019). The inter-annual temperature variability is projected to mostly increase in summer (Fonseca et al., 2021), which, along with the mean warming, could lead to an enhancement of extreme weather events (Cherif et al., 2020; Giorgi & Lionello, 2008). Parts of the region have already been affected by some of the most severe record-breaking weather events (Coumou & Rahmstorf, 2012). Examples include the exceptional summer of 2007, which was, at the time, the hottest on record in Greece since 1891, and was associated with devastating wildfires throughout the country (Founda & Giannakopoulos, 2009; Tolika et al., 2009). In the same year (2007), cyclone Gonu, the strongest tropical cyclone over the Arabian Sea since 1970, was observed. In terms of economic damage and fatalities, this storm was the biggest natural disaster in the history of Oman (Fritz et al., 2010). Future high-impact events may include unprecedented extreme heatwaves (Lelieveld et al., 2016; Zittis, Hadjinicolaou, et al., 2021), more prolonged and severe droughts (Spinoni et al., 2020, 2021), as well as compound extreme events of great societal impact (Hochman et al., 2022).

Such considerable changes in environmental and climate conditions could imply severe impacts on a variety of sectors and socio-economic activities including the management of water resources and agriculture, human health, energy demand and production, transportation, ecosystems, biodiversity, forest fires and many more (Cramer et al., 2018; Lelieveld et al., 2012; Waha et al., 2017). These impacts will likely exacerbate by additional factors, such as rapid regional population growth and urbanization, which will inevitably increase the demand and competition for natural resources. The EMME region is also prone to pronounced social inequalities, and the poor are expected to suffer the most from climate change impacts, for example, from heat extremes and shortage of water resources (Waha et al., 2017).

The region includes a variety of climatic zones ranging from deserts and semi-arid to sub-tropical and temperate climes (Belda et al., 2014; Lelieveld et al., 2012, 2016). With warm to hot, dry summers, occasional droughts and mild, relatively wet winters, the climate of the northern EMME is mostly temperate (Lionello et al., 2006). The southern EMME encompasses large, arid and hot desert regions with sparse vegetation (Fonseca et al., 2021; Francis, Chaboureau, et al., 2021; Hamidi et al., 2013; Issar & Zohar, 2007). Precipitation is among the highest in Europe in some regions, for example, up to 2,000 mm/year or more over the Dinaric Alps, Pindus, Taurus, Caucasus and Alborz mountains, while several degrees latitude further south this can be orders of magnitude less or near zero (Francis et al., 2020). The region is located at an atmospheric crossroads, directly influenced by a variety of atmospheric circulation patterns and meteorological processes on different continents (Carmona & Alpert, 2009; Lelieveld et al., 2002). For example, winter precipitation, critical for replenishing water resources, is largely related to the southward movement of the polar front jet, that drives cyclonic disturbances across the region (Francis, Alshamsi, et al., 2019; Francis, Eayrs, et al., 2019; Krichak et al., 2000). The steep orography, the complex coastlines and the effects of large water bodies (e.g., the Mediterranean, Red, Arabian, and Black Seas) add important feedbacks that influence the regional peculiarities of global warming. To adequately assess the regional and local-scale impacts, climate information of high spatial resolution and quality is required.

The present study complements and updates previous regional and national assessments by using extended palaeoclimate proxies and observational records, improved information from climate models with greater geographical coverage, spatial resolution, and variety of future scenarios. Our main objectives are to (a) assess the regional manifestations of global warming in the EMME region by using state-of-the-art climate information from up-to-date observational records and regional climate models, (b) provide an extensive literature review of the causes and regional effects of climate change, and (c) identify knowledge gaps and scientific challenges and formulate recommendations for regional co-operation toward improved understanding and resilience to climate change. The 17 countries included in our analysis are Bahrain, Cyprus, Egypt, Greece, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Turkey, and the United Arab Emirates.

This review is organized as follows. In Section 2, we discuss recent observations and trends of regional GHG emissions, air pollution and dust. These are identified as key drivers of both global and regional climate change. In Section 3, we present information on the regional climate, from paleoclimatic evidence to very recent observations. In Section 4, we present future projections of key meteorological parameters. In Section 5, we discuss

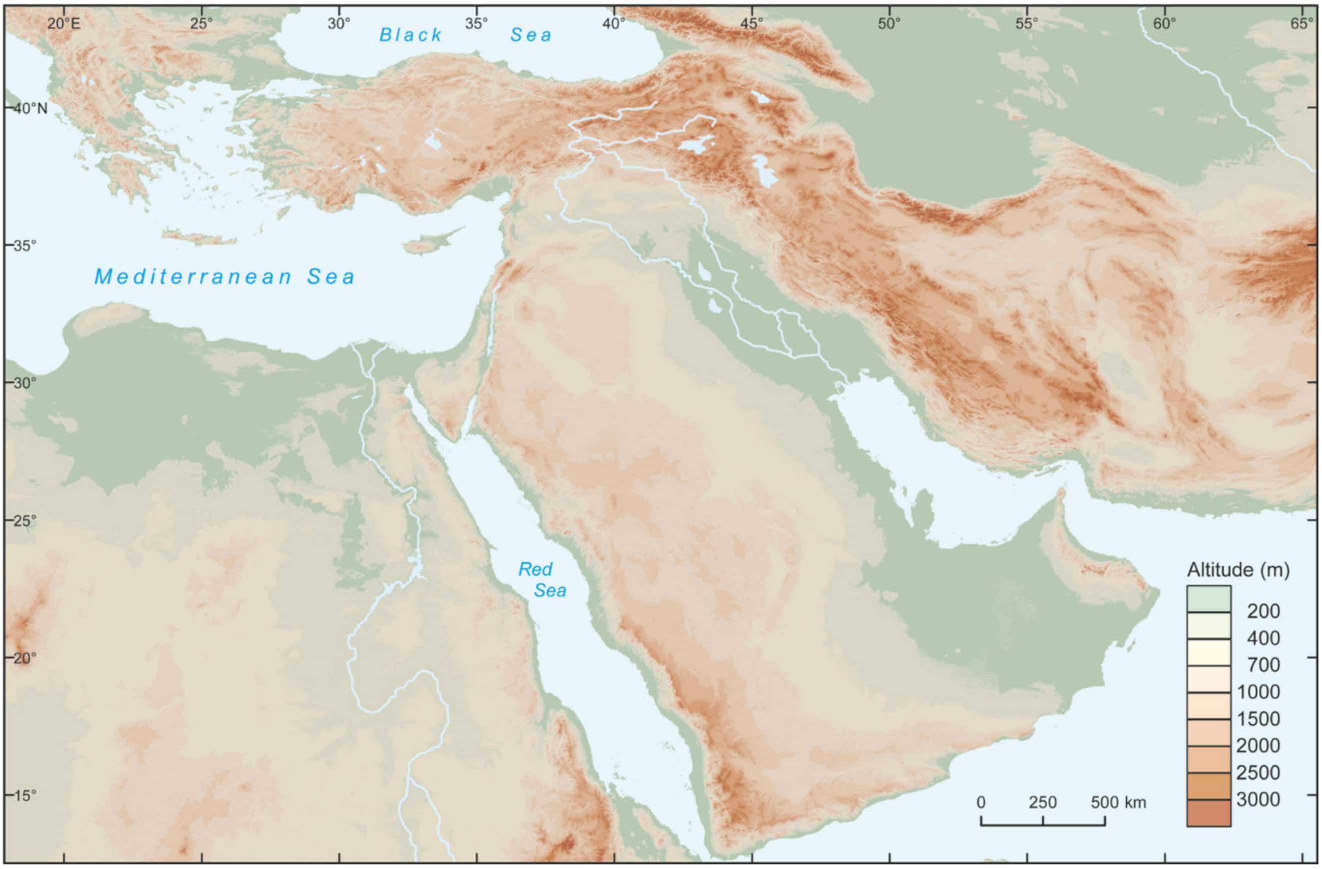

Figure 1. Topographic map of the Eastern Mediterranean and the Middle East region.

additional important drivers of regional environmental change. In Sections 6 and 7, we identify critical sectors and impacts and propose adaptation solutions, and, finally, in Section 8, we conclude with research recommendations.

2. Historical Greenhouse Gas Emissions and Pollution

2.1. Global and Regional Greenhouse Gas Emissions

Anthropogenic greenhouse gas emissions in the EMME region have increased dramatically since the 1950s (Figure S1 in Supporting Information S1). Based on the country-reported (HISTCR) emissions from the PRIMAP-hist data set, version 2.3.1 (Gütschow et al., 2016, 2021), the emission rates rose sixfold, from 0.6 ± 0.1 gigatonnes of carbon dioxide equivalent per year ($GtCO_2eq/yr$) during the 1960s to 3.6 ± 0.3 $GtCO_2eq/yr$ during the 2010s. These estimates include emissions from all EMME countries except Palestine due to the lack of data. Given the disproportionate rate with respect to global GHG emissions (which increased 2.5-fold), the share contributed by the EMME region more than doubled from 3 ± 0.2% in the 1960s to 7.7 ± 0.3% in the 2010s (Figure 2). In the 2010s, emission rates in the region (3.6 ± 0.3 $GtCO_2eq/yr$) were larger than those of India (2.8 ± 0.3 $GtCO_2eq/yr$) and close to the EU27 (Figure 2), and were characterized by a steeper long-term increase than that in India (0.067 vs. 0.045 $GtCO_2eq/yr$, respectively, between the 1960s and the 2010s). While annual total regional emissions are now similar to those of the EU27, considering the European decarbonization tendency and ambitious targets, EMME emissions will likely exceed those of the European Union in the coming years. The regional emission trends have not been constant over the past 50 years. The emission growth of 0.04 $GtCO_2eq/yr$ between the early 1960s and the late 1970s was followed by a decline of about 10% during the years 1980–1983, associated with the oil crisis. Subsequently, emissions surged again at a rate of 0.076 $GtCO_2eq/yr$, except for an anomalous spike of +34% during the Gulf War. Regional emissions increased from 1.5 $GtCO_2eq/yr$ in 1990 to 2.0 $GtCO_2eq/yr$ in 1991 and declined to 1.6 $GtCO_2eq/yr$ in 1992.

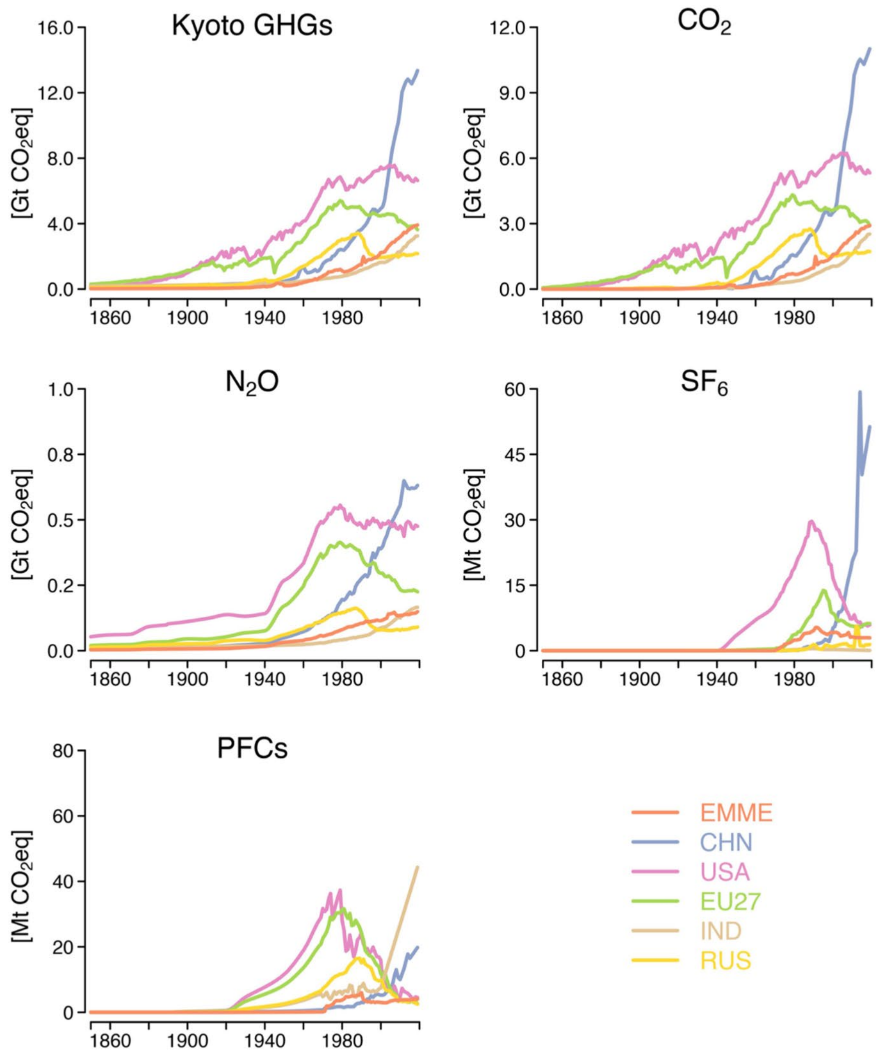

Figure 2. Historical emissions of greenhouse gases across selected countries and regions (EMME = Eastern Mediterranean and Middle East; CHN = China; USA = United States of America; EU27 = European Union; IND = India; RUS = Russia; OTHERS = other countries). Data sources: country reported (HISTCR) emissions from the PRIMAP-hist data set version 2.3.1 (Gütschow et al., 2016, 2021).

Breaking down the emissions by different gases and sectors shows that, historically, emissions of methane (CH_4), followed by nitrous oxide (N_2O), dominated total GHG emissions in the EMME region (Figure S2 in Supporting Information S1), with major contributions from the agricultural sector (including industrial livestock activities) until the late 1910s and early 1920s (Figure S3 in Supporting Information S1). Socio-economic growth and increasing global energy demand, notably after World War II, have promoted fossil fuel exploitation and use in many EMME countries, where energy production has gradually become the sector with the greatest emissions. Accordingly, increasing emissions of CO_2 and CH_4 from the energy sector have driven the evolution of GHG emissions. Based on the PRIMAP-hist data set, CO_2 and CH_4 together account for 91%–96% of the total anthropogenic emissions over the past five decades, of which the vast majority (82%–88%), is emitted by the energy sector. The two gases contributed 96% of the emission increases between the 1960s and the 2010s. The relative share of CO_2 and CH_4 in total GHG emissions has shifted over time (Dimitriou et al., 2021). The contribution of CO_2 has generally increased to become dominant since the 1980s (Figure S2 in Supporting Information S1). This was accompanied by an overall decrease in the contribution of CH_4 emissions (mainly fugitive) that peaked between the 1950s and the 1970s. The historical spike in emissions during the Gulf War is due to an unusually large share of CO_2 release, whereas increased gas extraction explains the rapid growth of CH_4 emissions since the 1960s, followed by the implementation of advanced technologies to reduce leaks after the first oil crisis of 1976–1984 (Figures S1 and S2 in Supporting Information S1). This peak and decline of CH_4 in EMME countries

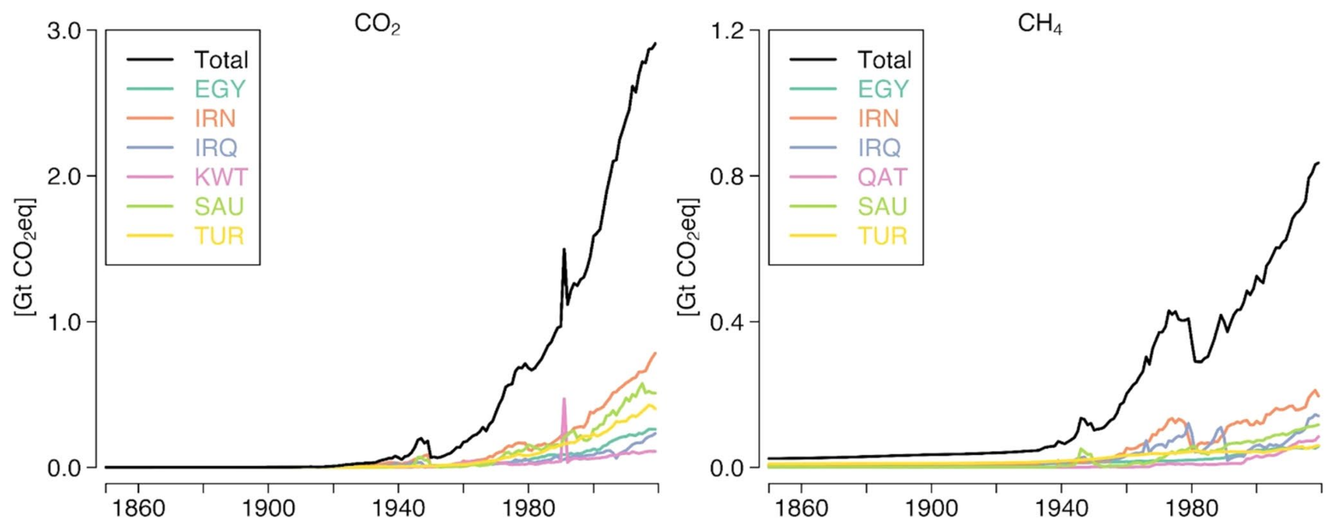

Figure 3. Historical emissions of CO_2 and CH_4 by country (EGY = Egypt; IRN = Iran; IRQ = Iraq; QAT = Qatar; KWT = Kuwait; SAU = Saudi Arabia; TUR = Turkey). Data sources: country reported (HISTCR) emissions from the PRIMAP-hist data set version 2.3.1 (Gütschow et al., 2016, 2021).

is reconstructed from inventories and was not verified by atmospheric observations, although independent global methane measurements from ice cores suggest that fossil sources of methane peaked during the 1960s–1970s and decreased sharply afterward (Aydin et al., 2011).

The major CO_2 emitting countries in the region are Iran, Saudi Arabia, Turkey, Egypt, and Iraq (Figure 3). These five countries alone account for 73% of the total CO_2 emissions during the 2010s, and 74% of the increase in emissions over the past five decades. Kuwait, ranked as the eighth-largest CO_2 emitting country in the EMME region, was also the driver of the anomalous emissions spike in 1991, related to the ignition of oil wells which were difficult to extinguish. Iran, Iraq, and Saudi Arabia are the three largest emitters of CH_4 in the EMME region, contributing 53% of the regional total during the 2010s. These countries were also responsible for the exceptionally high CH_4 emissions in the early 1970s and the drastic decline afterward.

2.2. Regional Aerosol Pollution and Dust

The Middle East is a major contributor to global dust emissions (15%–20% of the total), affecting the regional climate, human health, terrestrial and marine ecosystems (Huneeus et al., 2011; Kok et al., 2021; Zender et al., 2003). Several active deserts are located in the region such as the Egyptian and Nubian deserts in the north-eastern Sahara; the Rub-Al Khali, An Nafud and Al Dahna deserts in the Arabian Peninsula; the Negev desert in Israel; the Syrian-Iraqi desert; the alluvial flood plains in Mesopotamia; the Dasht-e Kavir and Dasht-e Lut deserts in Iran as well as the desiccated, ephemeral or dried-up lakes like Urmia, Jazmurian and Hamouns in Iran (Cao et al., 2015; Francis, Alshamsi, et al., 2019; Francis, Chaboureau, et al., 2021; Francis, Eayrs, et al., 2019; Ginoux et al., 2012; Kaskaoutis et al., 2016). The regional dust activity is highly sensitive to weather conditions (Bodenheimer et al., 2018; Hermida et al., 2018; Nabavi et al., 2016; Shaheen et al., 2021) and climate perturbations (Hemming et al., 2010; Hoerling et al., 2012). Dust storms originating in the Middle East strongly affect the regional atmospheric radiation budget, cyclogenesis, monsoon circulation and air quality (Francis et al., 2020; Q. Jin et al., 2016; Soleimani et al., 2020; Solmon et al., 2015). Desert dust dominates, while other aerosol types include sea salt, black carbon from fossil fuel combustion and biomass burning, and mixed particulates (Ali et al., 2020; Basart et al., 2009; Hamill et al., 2016; Kaskaoutis et al., 2007; Sabetghadam et al., 2021; Ukhov et al., 2020; Xu et al., 2020). Dust activity exhibits a distinct seasonality with a spring/summer maximum and a winter minimum, driven by synoptic circulation and persistent or seasonal winds like the Shamal and Levar (Bou Karam Francis et al., 2017; Hamidi et al., 2013; Nelli, Fissehaye, et al., 2021; Rashki et al., 2019; Yu et al., 2016). Furthermore, the interrelation of large-scale atmospheric dynamics and teleconnection patterns, changes in sea surface temperature over the Indian Ocean and the Eastern Mediterranean, and displacements of the Inter-Tropical Convergence Zone (ITCZ) affect the intra-seasonal and inter-annual variations of dust activity (Huang et al., 2021; Labban et al., 2021; Yu et al., 2015). Dust also affects the regional seas, for example, the

Red Sea and the Arabian Gulf (Osipov & Stenchikov, 2018). The mean dust shortwave radiative forcing over the southern Red Sea is among the largest in the world, reaching 60 W/m^2 (Jish Prakash et al., 2015).

Several studies have shown a general increase in dust aerosols, and the frequency and intensity of dust storms over the Iraqi Plains and the Arabian Peninsula during the past two decades (De Meij & Lelieveld, 2011; De Meij et al., 2012; Ganor et al., 2010; Hsu et al., 2012; Klingmüller et al., 2016; Pozzer et al., 2015). Over eastern Iran a decrease in dust aerosol optical depth (AOD) was observed after 2003 (Miri et al., 2021; Rashki et al., 2014). More specifically, AOD trends (1980–2018) over the region revealed a declining trend over southeastern Europe and an increase in AOD over the desert areas in the Middle East (Shaheen et al., 2020). Reversed decadal tendencies are also observed in specific periods (e.g., after 2010), while satellite data confirm an increasing AOD over desert areas in the past two decades (Shaheen et al., 2020). Regional dust emissions increased by 15% per year from 2001 to 2012 (Yu et al., 2018). A shift in 2006–2007 from an inactive to an active dust period in the Fertile Crescent is attributed to synergistic interrelations between the El Niño Southern Oscillation and the Pacific Decadal Oscillation (Notaro et al., 2015). The combined effect of these large-scale teleconnection patterns enhanced prolonged dryness over the region that increased dust activity. Stronger Shamal winds in recent years, with a higher probability of dust activity, were observed in central Iraq and the eastern and southern parts of the Arabian Peninsula (Yu et al., 2016). Moreover, the AOD variability over the desert areas in the Middle East was related to soil moisture, precipitation and surface winds (Klingmüller et al., 2016). The increasing AOD was associated with declining precipitation, soil moisture and relative humidity, and an increase in temperature during the past decade, indicating the sensitivity of dust emissions to climate change.

On the other hand, several studies note a decreasing AOD trend over the Eastern Mediterranean in the past two to three decades, attributed to decreasing anthropogenic aerosol emissions and sulfate levels, following fuel desulfurization policies (Nabat et al., 2013, 2014). Decreasing AOD trends were also identified over the southern Arabian Peninsula, but these were attributed to precipitation increases (Nelli, Fissehaye, et al., 2021; Nelli, Francis, et al., 2021). Particulate matter with a diameter of 10 μm or less (PM_{10}) decreased over the past decade in Cyprus (Pikridas et al., 2018), while a positive PM_{10} trend was observed over the Gaza Strip during 2001–2014 (Shaheen et al., 2017). Statistically significant decreasing trends in AOD were found over Egypt and the Eastern Mediterranean, and increasing trends over the Middle East (Georgoulias et al., 2016). Likewise, the long-term dust variability over the past 10–15 years across the Eastern Mediterranean indicated a decrease (−4% per year) in dust AOD (Marinou et al., 2017). These results are in accord with those of other studies (De Meij et al., 2012; Hsu et al., 2012; Pozzer et al., 2015; Shaheen et al., 2021; Yoon et al., 2014) based on data from satellite sensors. Other regional studies reported increasing trends in dust frequency over Israel in 1958–2006 (Ganor et al., 2010) and 2001–2015 (Krasnov et al., 2016), while in Cyprus, a statistically significant decreasing tendency in the frequency of dust events (−7 events per year) was detected during 2006–2017 (Achilleos et al., 2020). A negative NO_2 trend was recorded over major cities in the region during 2010–2015 due to declining anthropogenic emissions from fossil fuel combustion, related to regional conflict and migration (Lelieveld et al., 2015). Apart from the declining trend in anthropogenic AOD over the Eastern Mediterranean due to environmental policies in Europe (Floutsi et al., 2016; Nabat et al., 2013), the significant decrease was also attributed to a weakened dust contribution, consistent with a decrease of dust activity over the Sahara Desert (Hsu et al., 2012). The debate about which factors (anthropogenic or natural) drive AOD changes over the Mediterranean continues, with most studies agreeing that dust variations have been mostly responsible for the trends in the southern parts of the area (Floutsi et al., 2016; Gkikas et al., 2013; Marinou et al., 2017; Nelli, Fissehaye, et al., 2021), while a decrease in anthropogenic emissions triggered the AOD decline over the European part of the Mediterranean and around major urban centers. In accord with the observed increasing AOD, model projections suggest an increase in the intensity of dust events over the region in the twenty-first century, likely related to climate change (Tsikerdekis et al., 2019).

3. Past and Present State of the Climate

3.1. Variability Over the Past 2,000 Years

Palaeoclimate proxy information provides the basis for reconstructing climates before the instrumental period (Bradley, 2015; Li et al., 2021). Past climate information for the Mediterranean is preserved in natural archives, such as marine and lacustrine sediments, corals, tree rings, loess, and cave deposits (speleothems). While calibration against instrumental data is a necessary step to determine how well proxies reflect the climate, proxy records

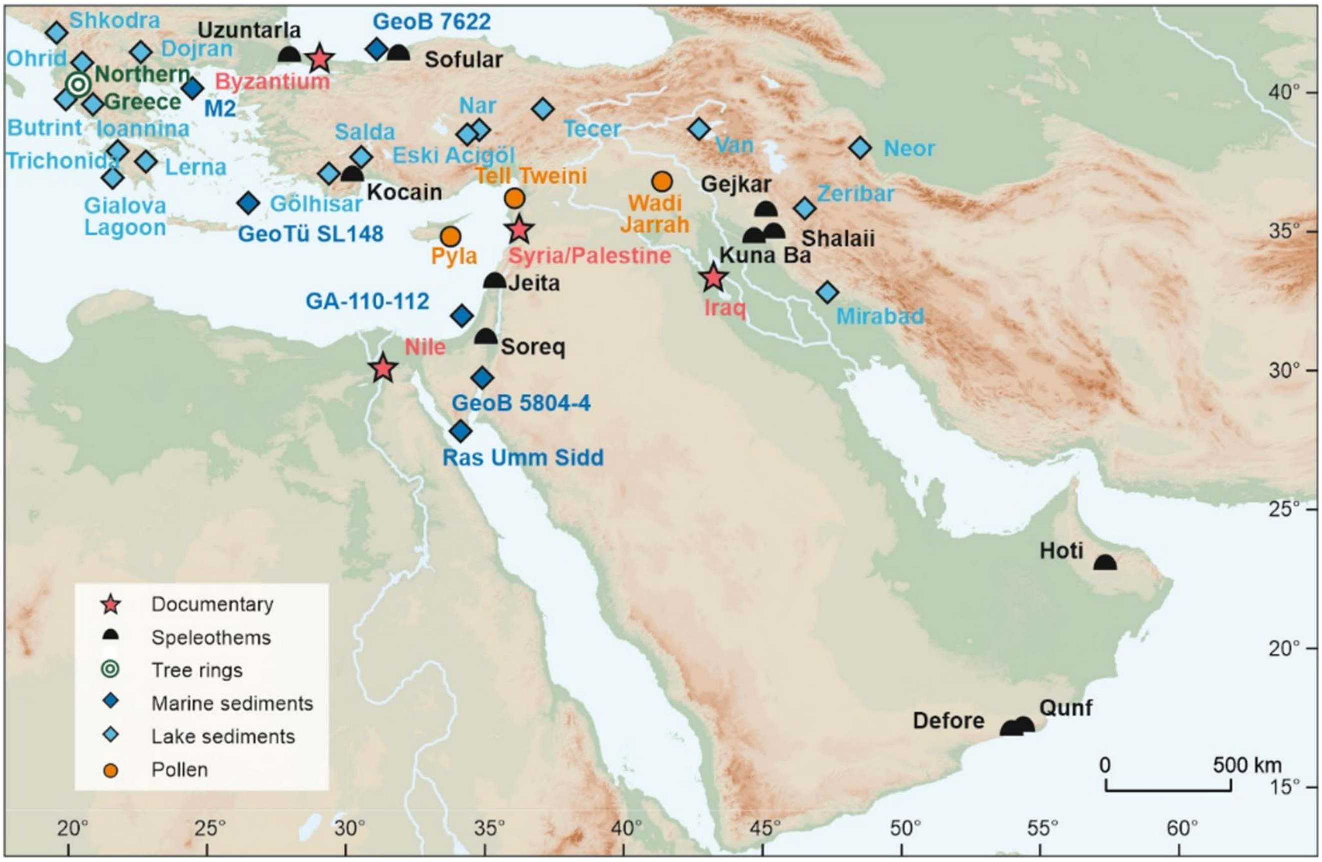

Figure 4. Natural and documentary proxy locations covering the past 1,000–2,000 years in the Eastern Mediterranean and Middle East region.

are not to be compared with rain gauges or thermometers, yet they provide a measure of prevailing climatic conditions at a particular point in time. The temporal resolution of records ranges from annual (e.g., corals, tree rings, some speleothems) to decadal (sediments), the latter characterized by dating uncertainties and changing sampling resolution over time. Natural proxies are also sensitive to multiple and interacting parameters (e.g., precipitation, soil moisture, air or sea surface temperature, sea-level changes, water circulation, and pH), and the length of their records vary. Apart from natural proxies, there is a wealth of textual evidence from the Mediterranean covering the past centuries (Haldon et al., 2014; Izdebski, Holmgren, et al., 2016; Izdebski, Pickett 2016; Labuhn et al., 2019; Luterbacher et al., 2012, 2022; Newfield et al., 2022; Xoplaki et al., 2016, 2018, 2021) which supports the reconstruction of historical weather and climate conditions, including extreme events and their potential societal impacts. The EMME region offers a relatively dense network of natural archives and documentary evidence covering the past 1,000–2,000 years with a strong bias toward hydrological changes. There is hardly any paleoclimatic evidence available that resolve temperature conditions.

Luterbacher et al. (2006, 2012, 2021), Lelieveld et al. (2012), Xoplaki et al. (2018), Labuhn et al. (2019), Finné et al. (2019), Luterbacher and Xoplaki (2019), Sinha et al. (2019), and Jones et al. (2019) provide recent reviews of proxy availability, distribution, potential, opportunities and limitations of paleoclimatic data across the EMME region. Figure 4 presents the most updated distribution of natural proxy records, including speleothems, lake and marine sediments, tree rings and documentary evidence that resolve annual to multidecadal hydroclimate variability covering the past two millenia. Amid the multitude of records, only a portion provides complete information, much of it focused on the southern and southeastern areas of the EMME. Detailed palaeoclimate information on Northern Africa, the Nile basin and the Arabian Peninsula that covers the past 2,000 years is currently limited, largely due to the prevalence of semi- to hyper-arid environments in parts of these areas over the time period. Dry climates generally preclude the long-term existence of lakes and wetlands that typically preserve long records of environmental change. Existing reconstructions are primarily based on lake sediments, which have a multidecadal resolution and suffer from considerable chronological uncertainties and changing sampling resolution. Speleothemes deliver annually resolved records of hydroclimate in some areas of the EMME (Baker et al., 2010; Fleitmann et al., 2004, 2007; Flohr et al., 2017).

A variety of proxies can be used for reconstructing hydroclimate, such as oxygen isotopes, pollen, and the concentration of certain trace elements, for example, titanium (Ti) in lake sediments as an indicator for aridity (Luterbacher et al., 2022). Oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes are the most frequent palaeoclimate proxies obtained from stalagmites. $\delta^{18}O$ is often used as an indicator for the amount of precipitation above the cave (more negative $\delta^{18}O$ values indicate wetter climatic conditions) and changes in the seasonality of rainfall. $\delta^{13}C$ values are mainly influenced by vegetation and soil microbial activity above the cave, they are both strongly governed by moisture and temperature. Mediterranean lakes record changes in past climate and water balance through a range of proxy indicators that are preserved in their sediments. Lakes lose water mainly through evaporation and may become hydrologically closed, and thus their waters can turn saline. During periods of negative water balance, the region of a closed lake shrinks, water levels decline and salinity increases, while the opposite occurs at times of positive water balance. Lake records from across the Mediterranean are of great value for reconstructing climate fluctuations over multi-decadal or longer timescales. A few hydroclimatic reconstructions from marine and lake sediment with various temporal resolutions are available for the Balkans, central and eastern Mediterranean (Figures 4 and 5). Oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope records, as well as titanium (Ti) from lake sediments and stalagmites, show multidecadal fluctuations (Figure 5). For example, for the Gialova Lagoon, a shallow coastal ecosystem in southwest Peloponnese (Katrantsiotis et al., 2018), the first principal component (PC1) of the X-ray fluorescence data reflects hydroclimatic variations. The Nar Lake $\delta^{18}O$ record (Jones et al., 2006), through its precipitation-evaporation balance signal, presents information on the amount and variability of precipitation. The aeolian input to the peripheral peat of the Neor Lake (Sharifi et al., 2015) increased during dry periods as defined by the Ti records. The $\delta^{13}C$ stalagmite records of the Uzuntarla and Kocain caves (Göktürk, 2011), and the $\delta^{18}O$ record of the Soreq (Bar-Matthews et al., 2003) and the Kuna Ba (Sinha et al., 2019) caves present effective moisture variations, indicative of precipitation. The caves are located in different climatic zones, and therefore some inconsistencies exist between their effective humidity records. These inconsistencies may be exacerbated by chronological uncertainties of up to several decades.

The first two centuries of the first millennium were characterized by less variable, relatively warm and humid climatic conditions that coincided with the Roman Empire. While the Kuna Ba cave records suggest more humid conditions for almost the entire first millennium, most proxy records indicate a continuous path to drier conditions over the first six centuries. The Nar Lake indicates a rapid and extreme shift to a humid fourth century followed by a drier period until almost the end of the seventh century. A century earlier, all other records show increased humidity that lasted during most of the Medieval Climate Anomaly period (MCA, ∼950 to ∼1250; Masson-Delmotte et al., 2013). At the beginning of the MCA, abundant rainfall and a mild climate characterized the northern EMME and Byzantium. Favourable climatic conditions for the local societies prevailed up to the early to mid-twelfth century, when in some cases abrupt drying occurred (Xoplaki et al., 2015, 2016). Highly variable hydro-climatological conditions prevailed during the transition period between the MCA and the Little Ice Age (∼1400 to ∼1850; Mann et al., 2009). During this period, strong hydroclimate variability occurred across almost the entire region. Multiple natural and documentary records substantiate cooler and rainier conditions over the Eastern Mediterranean during the past nearly two centuries (Xoplaki et al., 2001). All proxies and their adjacent areas, except the lakes Neor and Nar, experienced strong variability and a clear drying trend. It is worth noting that the Neor Lake record presents the last major atmospheric dust event as late as the 1930s, while the Nar Lake's humid twentieth century corresponds to a combination of the influence of the Indian monsoon and the North Atlantic Oscillation over the area.

3.2. Recent Changes

3.2.1. Temperature

Following the global trend, observed regional changes over the past 120 years are characterized by pronounced warming (Figure 6, left panel). There is unequivocal evidence that this is related to anthropogenic activities and is mostly driven by elevated global concentrations of GHG gases in the atmosphere (Eyring et al., 2021). This regional warming is accelerated over the past four decades to reach about 1.4°C–1.5°C compared to the beginning of the twentieth century. For example, due to the so-called desert amplification phenomenon, the surface temperature of the Sahara Desert increased at a rate two to four times greater than that of the tropical-mean

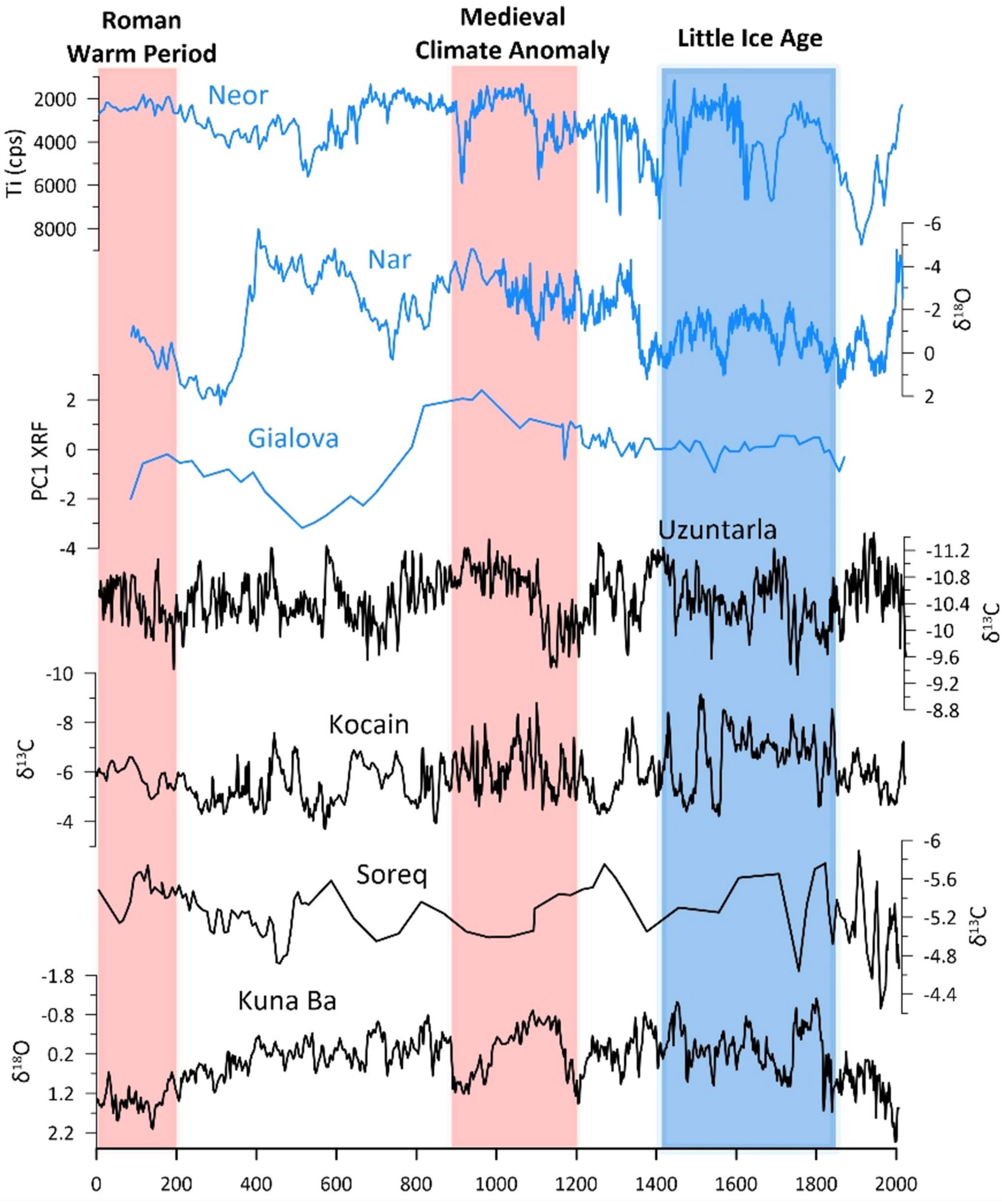

Figure 5. Regional hydroclimate proxy records of the past 2,000 years (source: Luterbacher & Xoplaki, 2019; Xoplaki et al., 2021, updated).

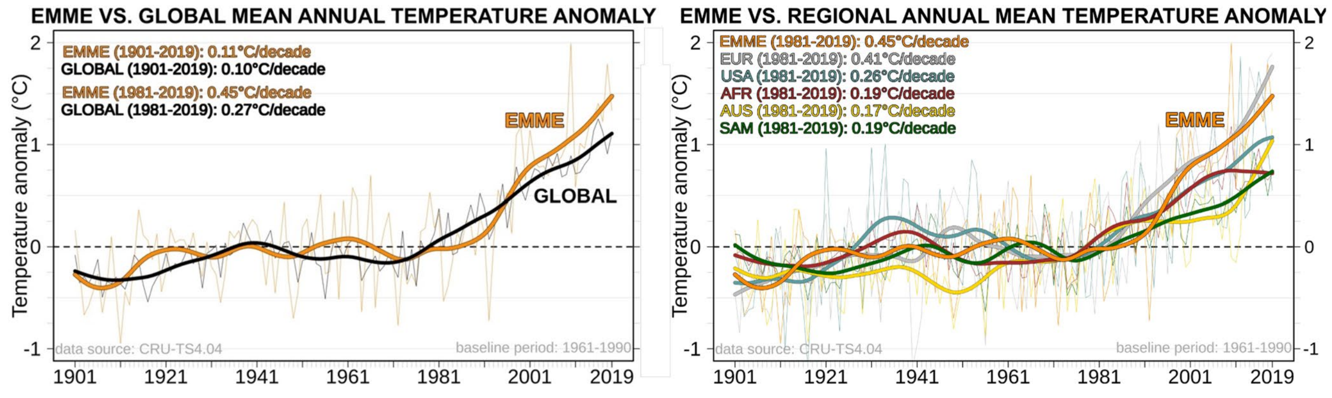

Figure 6. Eastern Mediterranean and Middle East versus global (left panel) and regional (right panel) temperature anomalies since 1901(w.r.t. the 1961–1990 reference period) as annual values (thin curves) and cubic smoothing splines (thick curves). Linear trends are also presented for Europe (EUR), the United States of America (USA), Africa (AFR), Australia (AUS), and South America (SAM). Data source: Climate Research Unit gridded observations over land (Harris et al., 2020).

temperature during the past three decades (Cook & Vizy, 2015). This recent acceleration in regional warming is indicated by numerous studies (Christensen et al., 2013; Cramer et al., 2018; Lionello & Scarascia, 2018; Zittis & Hadjinicolaou, 2017). Because of a range of global, regional and local meteorological processes and feedbacks (e.g., modes of internal climate variability, land-atmosphere and land-sea interactions, urbanization and other types of land use change), the sign, magnitude and significance level of observed temperature trends vary. These can depend on (a) the location and geographical characteristics, (b) the type of data set investigated, (c) the season under consideration, and (d) the period of analysis. Nevertheless, significant positive trends of the order of 0.1°C–0.6°C/decade have been identified for most EMME territories, including Egypt, Turkey, Greece, Israel, Jordan, Lebanon, the Arabian Peninsula and more (Almazroui, 2020a; Almazroui et al., 2014; Donat et al., 2014; El Kenawy et al., 2019; Feidas et al., 2007; Fonseca et al., 2021; Freiwan & Kadioğlu, 2008; Mariotti et al., 2015; Mohammed & Fallah, 2019; Mostafa et al., 2019; Ramadan et al., 2013; Shohami et al., 2011; Tanarhte et al., 2012; Xoplaki et al., 2016).

Our updated analysis reveals an EMME region-average trend of 0.45°C/decade for 1981–2019, which is nearly twice the global trend for the same period (0.27°C/decade) (Figure 6). These values are based on the latest version of the Climate Research Unit data set (CRU-TS4.04) of the University of East Anglia (Harris et al., 2020). Considering the entire time coverage of the data set (1901–2019), the global and regional temperature trends are similar (0.11°C/decade). When regional warming is compared with other inhabited parts of the world, including Europe, the United States, Africa, South America, and Australia (Figure 6, right panel), warming trends of the past four decades are found to be strongest in the EMME (0.45°C/decade) and Europe (0.41°C/decade). Regions in the southern hemisphere (e.g., South America and Australia) are found to warm at a relatively slower pace.

Besides changes in the mean temperature conditions, the frequency and intensity of high-impact extreme events (e.g., severe heatwaves) have also increased (Cherif et al., 2020). For example, summer temperatures have warmed at a faster pace than the mean annual warming (Cos et al., 2022). With respect to other types of extremes (e.g., extreme precipitation), there is high confidence in the human contribution to the observed increases of heat extremes in the broader region (IPCC, 2021). In the past decades, extreme weather events' characteristics, including the frequency, duration, and intensity of heatwaves, have amplified across the EMME (Abbasnia & Toros, 2019; Ceccherini et al., 2017; Donat et al., 2014; Hochman et al., 2022; Kostopoulou & Jones, 2005; Kuglitsch et al., 2010; Lelieveld et al., 2016; Nashwan et al., 2018; Tolika, 2019). Particularly in the Middle East, the observed trend of cumulative heat (i.e., the product of all seasonal heatwave days, including heatwave frequency and average heatwave intensity) is +50% per decade, being among the highest in the world (Perkins-Kirkpatrick & Lewis, 2020). Parts of the region were affected by some of the most severe, record-breaking hot weather events of the past decade (Coumou & Rahmstorf, 2012; Founda & Giannakopoulos, 2009). On 4 September 2020, the surface temperature record in Athalassa, Cyprus, hit a record of 46.2°C, which is the highest temperature officially recorded on the island. Similarly, temperature records were broken for other locations in the Middle East (e.g., Syria, Jordan, Lebanon, and Israel) during this exceptional autumn heatwave (Blunden & Boyer, 2021). A little west of the EMME, the Sicilian Meteorological Information Service for Agriculture reported a record of 48.8°C on 11 August 2021 (WMO, World Meteorological Organization, 2021), being the highest temperature ever recorded in Europe, while earlier in the same month, a temperature record of 47.1°C was recorded in northern Greece. In the same summer, the Kuwaiti city of Nawasib recorded 53.2°C, the highest temperature in the inhabited world in 2021. On 21 July 2016, in the hottest year on record so far, the temperature in Mitribah, Kuwait, reached a record 54°C (Merlone et al., 2019). In the following summer, on 29 June 2017, a temperature of 53.7°C was recorded at Ahwaz, southwest Iran. In the arid regions of the Arabian Peninsula and east Iran, summer land surface temperature, usually derived by satellite sensors, routinely soared above 60°C (Mildrexler et al., 2011). In 2018, the world highest land surface temperature of 80.8°C was observed in the Lut Desert in Iran (Y. Zhao, Norouzi, et al., 2021). The Arabian or Persian Gulf recently also recently experienced record-breaking sea surface temperatures. On 30 July 2020, sea surface temperatures in Kuwait Bay reached 37.6°C (Alosairi et al., 2020). Cold-weather extremes in the region (e.g., cold spell duration, number of ice, and frost days) were also subject to warming trends; however, these have not been as significant as the trends for hot-weather extremes (Abbasnia & Toros, 2020; Donat et al., 2014; Ntoumos et al., 2020; Yosef et al., 2019).

3.2.2. Precipitation

In addition to the dominant warming trends, changes in the hydrological cycle have occurred in the past century. However, the alterations between relatively drier and wetter periods were mainly driven by natural climate variability, while the role of anthropogenic climate change and external forcing has only recently become more evident (Hoerling et al., 2012; Mariotti & Dell'Aquila, 2012; Mariotti et al., 2002, 2015; Seager et al., 2014; Xoplaki et al., 2000, 2004). Several observation-based studies have investigated precipitation trends in the EMME. The sign, magnitude and significance of trends vary strongly and depend on the location and period under consideration. For example, precipitation in Greece declined during the period from 1950 to 2018, yet in the last 30 years of this period, the trend is mostly positive (Cherif et al., 2020). Nonetheless, the majority of analyses suggests a reduction of mean precipitation across the EMME region, most importantly during the wet part of the year (Almazroui et al., 2012; Güner Bacanli, 2017; Maheras et al., 2004; Partal & Kahya, 2006; Philandras et al., 2011; Shaban, 2009; Sousa et al., 2011; Tanarhte et al., 2012; Xoplaki et al., 2004; Yosef et al., 2019; Zittis, 2018; Ziv et al., 2014). However, over the southern Arabian Peninsula, increasing trends have been observed both in the cold (Nelli, Francis, et al., 2021) and warm seasons (Al Hosari et al., 2021). In most climate analyses, in contrast with temperature, regional precipitation trends are less statistically significant (Donat et al., 2014; Gado et al., 2019; Khadr, 2017; Ouarda et al., 2014; Partal & Kahya, 2006; Shohami et al., 2011; Yosef et al., 2019; Zittis, 2018). Similar declining trends in precipitation were identified in other sub-tropical, Mediterranean-type climate regimes around the globe (Deitch et al., 2017).

There is strong evidence that the frequency and intensity of droughts have increased in many countries of the region (Caloiero et al., 2018; Donat et al., 2014; Güner Bacanli, 2017; Hoerling et al., 2012; Nastos et al., 2013; Pashiardis & Michaelides, 2008; Seager et al., 2019; Spinoni et al., 2019). Recent mega-droughts in the Eastern Mediterranean and the Levant have received great attention, and their magnitude cannot be explained by natural climate variability alone (Cook et al., 2016; Kelley et al., 2015; Mathbout, Lopez-Bustins, Martin-Vide, et al., 2018). In the Mediterranean particularly, and to a lesser extent in West Asia, there is confidence in the human contribution to the observed increase in agricultural and ecological droughts (IPCC, 2021). Between 1951 and 2016, about 10% of the most extreme macro-regional drought events globally occurred in the broader EMME region (Spinoni et al., 2019). This list includes high-impact events, such as the 1989–1991 drought in the southern Balkans, the 2000–2002 drought in Cyprus and Greece, the 2007–2008 drought in Turkey and Cyprus, and the more recent multiyear drought events in the Middle East that affected many countries in the region including Syria, Iraq, and Iran (Spinoni et al., 2019). Other examples include the drought in the Fertile Crescent, Iraq, during 2007–2008 (Notaro et al., 2015) and the prolonged drought in southeast Iran from 1999 to 2002 (Rashki, Kaskaoutis, et al., 2013).

Despite the observed decrease in precipitation totals, for some Mediterranean regions, a paradoxical increase of extreme rainfall magnitude or in the number of heavy precipitation days is evident (Alpert et al., 2002; Founda et al., 2013). Particularly for the Middle East, extreme precipitation events can be the result of tropical-extratropical interactions, for example, Active Red Sea Troughs (De Vries et al., 2013) and cut-off lows and highs from mid-latitudes (Francis, Alshamsi, et al., 2019) associated with changes in the polar jet circulation (Francis, Eayrs, et al., 2019; Francis & Vavrus, 2012; Francis et al., 2018; J. Liu et al., 2021). Stratospheric potential vorticity streamers, as indicators of Rossby wave breaking, combined with intense moisture transport, can contribute

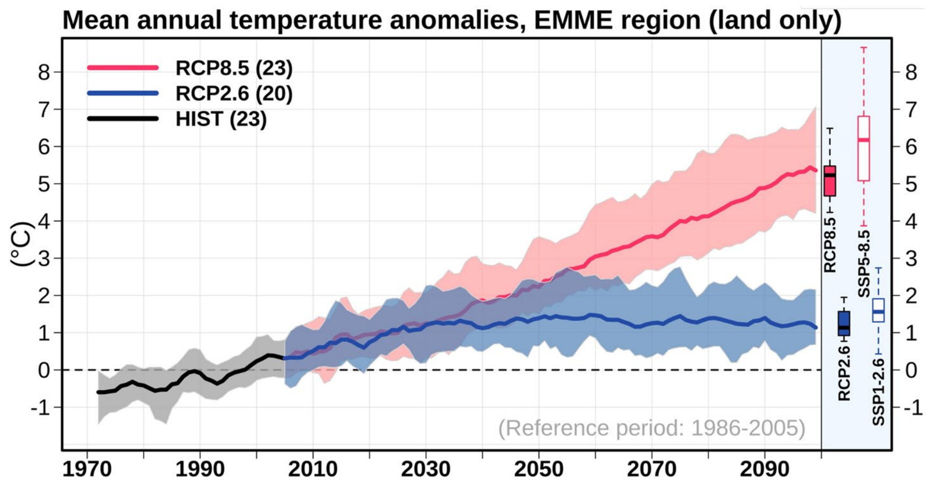

Figure 7. Projections of mean annual temperature anomalies in Eastern Mediterranean and Middle East (EMME) (with respect to the 1986–2005 reference period), based on CORDEX-CORE projections and two Representative Concentration Pathways (RCP2.6 and RCP8.5). Boxplots represent the range of projected anomalies for the end of the twenty-first century (2091–2100) based on CORDEX-CORE (RCPs) and CMIP6 data (Shared Socio-economic Pathways [SSPs]).

substantially to this type of extreme event in the region (De Vries, 2021; De Vries et al., 2018). Dust radiative forcing may shift the ITCZ northwards, thus affecting extreme precipitation events over the southwest Arabian Peninsula (Bangalath & Stenchikov, 2015; Nelli, Francis, et al., 2021), while it may modulate the rainfall over southwest and south Asia (Q. Jin et al., 2021). Such mesoscale convective systems are commonplace during the spring months (Nelli, Francis, et al., 2021). The torrential rains can trigger flash floods with dramatic societal impacts, including major economic damage and loss of life (De Vries et al., 2013, 2018; Spyrou et al., 2020). At the same time, such episodes can replenish freshwater resources that are of crucial importance for agriculture and ecosystems (De Vries et al., 2018). Due to the rare and local nature of such events, trends are not always statistically significant (Abbasnia & Toros, 2020; Mathbout, Lopez-Bustins, Royé, et al., 2018; Nashwan et al., 2018; Yosef et al., 2019; Zittis, 2018). It is likely that mean and extreme precipitation trends are masked due to strong temporal variability (low signal-to-noise ratio) along with the selection of the study period length and the trend magnitude (Yosef et al., 2019).

4. Future Climate

4.1. Temperature—Averages and Extremes

According to the CORDEX-CORE regional climate projections (Coppola, Nogherotto, et al., 2021) (see Methods and Data Sets in Supporting Information S1), the region will continue to warm during the twenty-first century (Figure 7). Global and regional models corroborate that this rise will continue to be faster than the global rates (Lionello & Scarascia, 2018; Zittis et al., 2019). For example, for every degree of global warming, parts of the region will experience a robust regional warming of 1.4°C–1.8°C (Doblas-Reyes et al., 2021). Under a business-as-usual Representative Concentration Pathway (RCP8.5), the increase is expected to be linear and exceed 5°C (with respect to the 1986–2005 reference) by year 2100. For the more optimistic RCP2.6 (close to meeting the main Paris Agreement target), the annual temperature anomaly will peak by the mid-twenty-first century and then stabilize or slightly decrease to 1°C–1.5°C. Projections for both pathways are very similar up until the 2030s and only then start to diverge significantly. The end-of-century spread of models is more evident for the RCP8.5, indicating that the climate sensitivity to GHG forcing varies among the different models. To approximate the warming levels since pre-industrial times (e.g., from 1880 to 1899 onwards), about 0.8°C, estimated from observations, should be added to these values (Cramer et al., 2018; Zittis et al., 2019).

Maps of projected changes of near-surface annual temperature are presented in Figure 8. The simulated temperature climatology of the historical period is presented in Figure S5 in Supporting Information S1 for reference. The changes are significant for both pathways and time horizons under investigation (middle and end of the twenty-first century). In other words, the signal of change is larger than the inter-annual variability of the

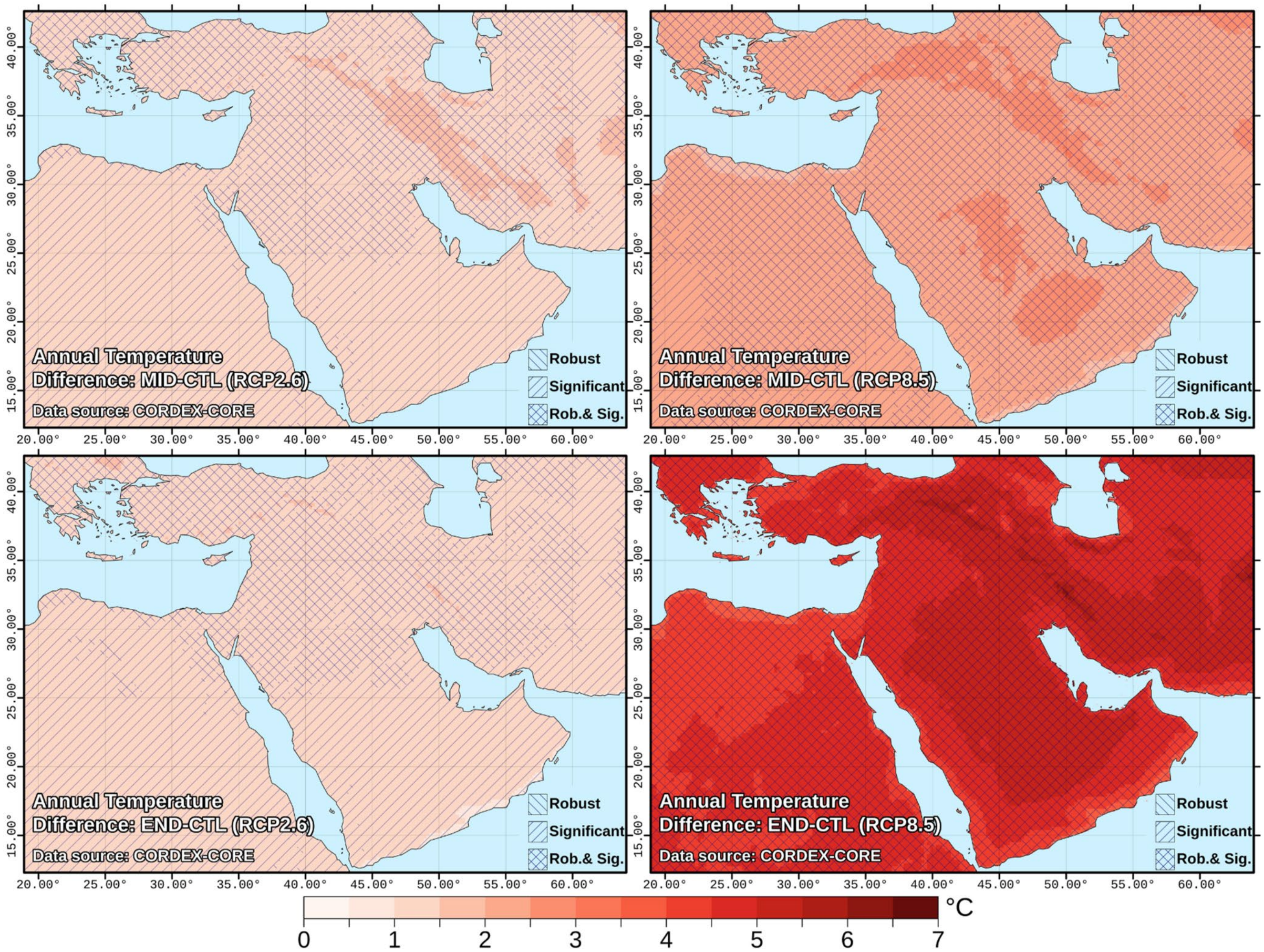

Figure 8. Projected changes of mean annual temperature (with respect to the 1986–2005 reference period). Source: CORDEX-CORE climate projections, for RCP2.6 (left panels) and RCP8.5 (right panels) and for mid-twenty-first (2041–2060, top panels) and end-of-century projections (2081–2100, bottom panels).

reference period, while, particularly for RCP8.5, the models tend to agree more on the magnitude of changes (i.e., high robustness). RCP2.6 implies a more uniform regional warming, which will likely not exceed 1.5°C (with respect to the 1986–2005 reference) for most of the region. This would be about 2°C–2.5°C since pre-industrial times. Exceptions are some mountainous regions (e.g., the Zagros Mountains), where the projected warming can exceed these values by mid-century. Instead, RCP8.5 suggests a strong annual temperature warming by 2°C–3°C for the 2050s. This is expected to reach 5°C–6°C by the end of the century relative to 1986–2005 (>6°C since the pre-industrial period). Temperature increases are overall projected to be strongest in mountainous areas due to reduced snow cover and alterations in the snow-albedo positive climate feedback. This is supported by the fact that this regional response is most evident in projections for the winter and spring seasons when snow cover is more widespread (Figures S6 and S7 in Supporting Information S1). The continental part of the Arabian Peninsula is also projected to warm more strongly, particularly toward the end-of-century and under RCP8.5.

For most of the region temperature increases will likely be most pronounced (up to 6°C–8°C) during summers and to a lesser extent in autumns (Figures S8 and S9 in Supporting Information S1). This seasonal warming response is more evident in the relatively wetter parts of the EMME, which is also expected to become drier (see the following section). This is partially explained by land-atmosphere interactions and amplification feedbacks related to the hydrologic cycle (Zittis et al., 2014). For example, when precipitation, soil water content, and thus evaporative cooling decrease, near-surface air temperature increases. The exceptional summertime warming is also associated with a thermal low (expansion of the Indo/Pakistan monsoon thermal low over the region), which

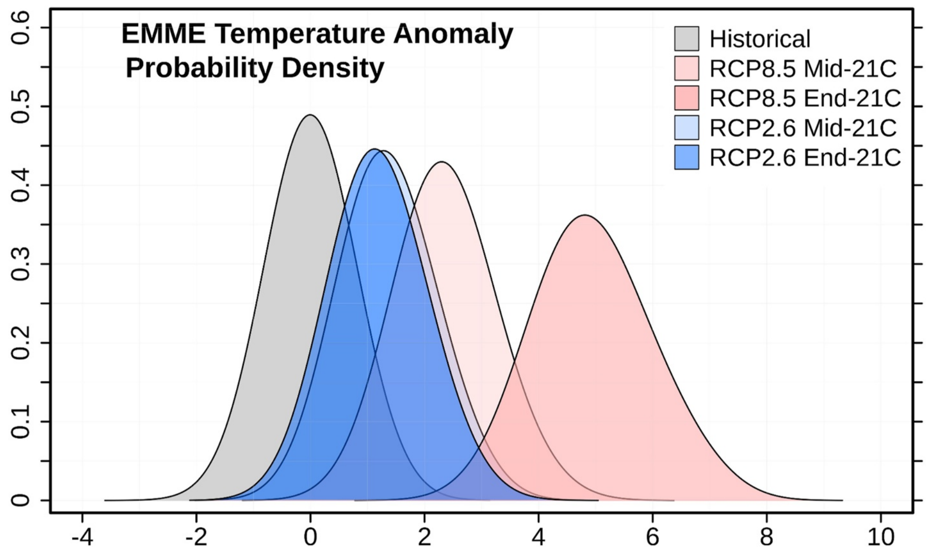

Figure 9. Probability density curves of annual temperature anomalies (with respect to the 1986–2005 mean conditions), averaged across the Eastern Mediterranean and Middle East (EMME) region.

is conceived as a widening of the Persian trough that extends from South Asia to the Eastern Mediterranean and is projected to further expand westwards and combine with the intensifying thermal low over the Sahara (Lelieveld et al., 2016). For the broader Mediterranean region, the summer warming amplification is similar in the CMIP5 and CMIP6 model ensembles (Cos et al., 2022).

Region-average temperature anomalies for the various periods and pathways are presented as probability density plots (Figure 9). For RCP8.5, the comparison with the historical simulations indicates a median shift to warmer conditions (+5°C) by the end of the century. Under a business-as-usual scenario (RCP8.5) and by 2100, the coolest future years will be comparable to the very warmest years of the reference period. This is in agreement with a recent analysis of CMIP6 models for the region (Almazroui et al., 2021). At the same time, the width of the distribution is projected to change to a more platykurtic shape, implying increased year-to-year variability and thus more pronounced extreme years or seasons. This is an indication that the region could be subjected to unprecedented heat conditions. Median changes under the optimistic RCP2.6 are projected to be milder throughout the current century (1°C–1.5°C). Nevertheless, temperatures in the warmest years will still be well in excess of the range of historical values. The mid-century projections for RCP8.5 are in between (2°C–2.5°C).

Previous national or regional assessments have been developed for the region or parts of it (Almazroui et al., 2020; Bucchignani et al., 2018; Coppola, Raffaele, et al., 2021; Driouech et al., 2020; Drobinski et al., 2020; Georgoulias et al., 2022; Giannakis et al., 2020; Hadjinicolaou et al., 2011; Hochman, Mercogliano, 2018; Jacob et al., 2014; Lelieveld et al., 2012, 2016; Mostafa et al., 2019; Önol & Unal, 2014; Ozturk et al., 2018; Varotsos et al., 2021; Zanis et al., 2009; Zittis et al., 2019, 2020). Although different models, pathways and/or scenarios might have been used, the ranges of projected temperature trends, warming patterns and significance levels are in close agreement with the present, updated analysis. A comparison between RCP-driven projections and the Shared Socio-economic Pathways (SSPs) that are discussed in the latest IPCC Assessment Report (IPCC, 2021) reveals a slightly warmer temperature response in the more advanced SSP-driven experiments (CMIP6) (Cos et al., 2022; Iturbide et al., 2021; Tebaldi et al., 2021). This is more pronounced for the end of the century and particularly for high-emission pathways (box-whisker plots of Figure 7) and is also evident for extreme heat indicators such as the number of heatwaves and tropical nights (Coppola, Nogherotto, et al., 2021; Coppola, Raffaele, et al., 2021). Pathways RCP2.6 and RCP8.5, discussed in the present assessment, correspond to SSP1-2.6 and SSP5-8.5 of the latest IPCC Assessment Report (AR6), respectively. Critical global warming levels (GWLs), since pre-industrial times, are exceeded earlier in the results of the CMIP6 models (SSPs) (Tebaldi et al., 2021). On average, the 1.5°C GWL is expected in 2025 in the SSP1-2.6 projections and about a decade later (2034) under RCP2.6. In terms of regional warming levels for the EMME, the difference between the two generations of global projections is up to 0.2°C per 1.0°C of global warming (Tebaldi et al., 2021).

A peculiarity of the EMME region is that days are expected to warm more strongly than nights. Minimum and maximum daily temperatures in the global 30–46°N latitudinal zone increase similarly, or the minimum temperature increases more strongly (Lionello & Scarascia, 2018). In the broader Mediterranean area, maximum temperature increases are expected to be stronger than of minimum temperature. Particularly under high-emission pathways, there is consensus that the enhanced warming during the warm season will further augment the extreme heat conditions and cause increases in the frequency, magnitude, and duration of heatwaves. The projected heat stress intensification and related impacts have received great attention. There is a large number of available regional studies based on various extreme temperature indicators, heatwave definitions, and sources of climate information (Almazroui, 2020b; Diffenbaugh & Giorgi, 2012; Diffenbaugh et al., 2007; Fischer & Schär, 2010; Goubanova & Li, 2007; Jacob et al., 2014, 2018; Lelieveld et al., 2014; Molina et al., 2020; Ntoumos et al., 2020; Pal & Eltahir, 2016; Russo et al., 2014; Zittis et al., 2016).

Extremely hot summers that occurred only rarely in the recent past are projected to become commonplace by the middle of the century (Lelieveld et al., 2014). Indicatively for the city of Athens in Greece, historical 1-in-20-year heatwaves will likely become 1-in-5-year events under GWLs of 1.5°C (Jacob et al., 2018). In a 3°C warmer world, such events are projected to occur annually. Particularly in the Middle East and North Africa, exceptional heatwaves have been observed in this century, and these thus far unprecedented events could become the norm by the end of the century (Molina et al., 2020; Zittis, Hadjinicolaou, et al., 2021). Compared to present-day standards, extreme heatwave characteristics in the region are projected to increase tremendously (Zittis et al., 2016). The annual number of heatwave events is projected to increase by 3–6 times, their amplitude to increase by 6°C–7°C, while the duration of the longest-lasting events will likely be several weeks to months. In high-emission pathways, by the end of the century, 80% of the densely populated cities of the EMME are expected to suffer from heatwaves for at least 50% of the warm season (Varela et al., 2020). Besides daytime conditions, parts of the region will likely face an increase of more than 60% in the number of tropical nights, augmenting potential adverse effects on societies and ecosystems (Dosio & Fischer, 2018; Lelieveld et al., 2016; Sillmann et al., 2013; Zittis et al., 2016). In some locations in the Middle East and the Gulf region, peak temperatures during extreme future heatwaves could exceed 56°C (Ntoumos et al., 2022; Zittis, Hadjinicolaou, et al., 2021).

These model estimates are conservative since they do not consider the urban heat island (UHI) phenomenon. Typical present-day UHI magnitudes for the region (Santamouris, 2015) could add another 3°C–4°C. If such high temperatures become a reality during the warm season, parts of the region may become uninhabitable for some species. These will likely include humans and even animals tolerant of high temperatures, such as camels. Dangerous heat-stress conditions in parts of the region, mainly in the Arabian Peninsula (days with wet-bulb temperature ≥27°C), have already increased in frequency by 10%–20% due to irrigation and the associated increase of humidity in the atmosphere (Krakauer et al., 2020). Widespread adverse impacts on public health, the water-energy-food nexus and other socio-economic sectors are expected (Abel et al., 2019; Ahmadalipour & Moradkhani, 2018; Constantinidou et al., 2016; Drobinski et al., 2020; Dunne et al., 2013; Habib et al., 2010; Lange, 2019; McGeehin & Mirabelli, 2001; Waha et al., 2017; Zachariadis & Hadjinicolaou, 2014). Calculations of the heat index (combined effect of high temperature and humidity) corroborate that several areas across the region may reach temperature levels critical for human survivability (Ntoumos et al., 2022). Mass gathering events in the region, such as the Muslim Pilgrimage or Hajj, may be particularly affected by extreme heat conditions (Kang et al., 2019; Saeed et al., 2021). For example, Kang et al. (2019) cautioned that there might be future increases in the frequency and intensity of heat stress in Mecca during the Hajj, with pronounced health consequences under both business-as-usual and mitigation scenarios.

Extreme ocean-warming events, known as marine heatwaves (MHWs), can be critical since they severely affect marine ecosystems and fisheries, while they can also induce amplifying feedbacks on atmospheric heatwaves by limiting the moderating effect of the surrounding seas and suppressing cooling mechanisms such as land-sea breezes (Darmaraki, Somot, Sevault, & Nabat, 2019; Zittis et al., 2016). The projections for MHWs suggest longer and more intense events for the Mediterranean, including the eastern parts. By the end of the century and under business-as-usual pathways, at least one long-lasting MHW every year, up to several weeks longer and about four times more intense than present-day events is expected (Darmaraki, Somot, Sevault, Nabat, et al., 2019). An increase in sea surface temperature over the Arabian Sea may strongly modulate the sea-atmosphere interactions, cyclonic activity and general atmospheric circulation, and in turn, the climatology of wind regimes and dust activity over the region (Yu et al., 2015).

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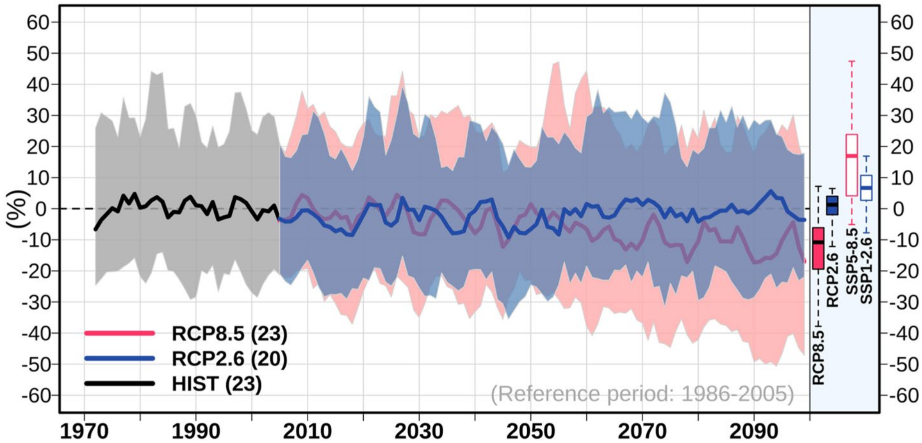

Figure 10. Same as Figure 7 for annual precipitation changes (in %).

Cold-weather extremes are expected to decline throughout the region. These decreases will likely be most profound in the mountainous areas of Greece, Turkey, and Iran (Kostopoulou et al., 2014). For example, under an intermediate warming scenario, the number of frost nights per year will be likely reduced by 50–60 days. Moreover, glaciers in the mountainous parts of the region (e.g., Anatolia, Caucasus, Alborz, and Zagros mountains) are projected to rapidly lose mass in the twenty-first century (even under RCP2.6) and will likely completely disappear by 2100 under RCP8.5 warming conditions (Hock et al., 2019).

4.2. Precipitation—Averages and Extremes

Global warming is associated with a Hadley Cell circulation expansion and the poleward shift of the westerlies and associated storm tracks (see Section 4.3.1). About 85% of the reduction in precipitation during the wet season, averaged across the Mediterranean, is attributed to such atmospheric circulation responses (Zappa et al., 2015). In addition, the drying of the Eastern Mediterranean is largely caused by enhanced warming over land (Drobinski et al., 2020). Annual precipitation anomalies, averaged for the EMME region, are presented in Figure 10. The inter-annual variability and model spread are more pronounced than for temperature, highlighting the greater uncertainty of precipitation projections. For RCP2.6, no significant change in precipitation is projected. The business-as-usual RCP8.5 is projected to lead to a 10%–20% precipitation decrease by the end of the century. For the Eastern Mediterranean, this range is in very good agreement with other assessments, suggesting that the mean rate of the decrease in land precipitation across the Mediterranean is 4% per degree of global warming (Cherif et al., 2020). In addition to the overall drying trend, individual years, at least according to some models, could be drier or wetter than the present-day mean conditions as a result of the increased variability, combined with alterations in atmospheric thermodynamics and circulation drivers.

A comparison between CMIP5 and CMIP6 projections (box-whisker plots of Figure 10) highlights similar conclusions for the more sustainable pathways (RCP2.6 vs. SSP1-2.6). Interestingly, this is not the case for high-emission scenarios. On the one hand, RCP8.5-driven projections indicate a precipitation decrease on average, while, on the other hand, the CMIP6 ensemble suggests a precipitation increase (10%–20%) for the end of the twenty-first century. This is mostly driven by a relatively strong precipitation increase over the Arabian Peninsula and most of the southern EMME (Almazroui et al., 2020; Iturbide et al., 2021), and not in the Eastern Mediterranean. This is illustrated in Figure 11, which depicts the regional precipitation changes for different GWLs based on the two CMIP ensembles. Although for relatively low GWLs (e.g., 1.5°C and 2°C), the two ensembles are in agreement overall, this is not the case for higher warming levels (e.g., 4°C). In such scenarios, the CMIP5 ensemble suggests an EMME-average precipitation decrease of about −7% (Figure 11a), while CMIP6 models project an increase of about the same order of magnitude. Such differences are mainly the result of more profound precipitation increases in the southern EMME areas (Figure 11c). This needs to be investigated further in view of significance for the regional water resources and rainfall characteristics such as seasonality and intensity. In particular, future changes and regional responses to the synoptic and thermodynamic drivers of precipitation need to be addressed.

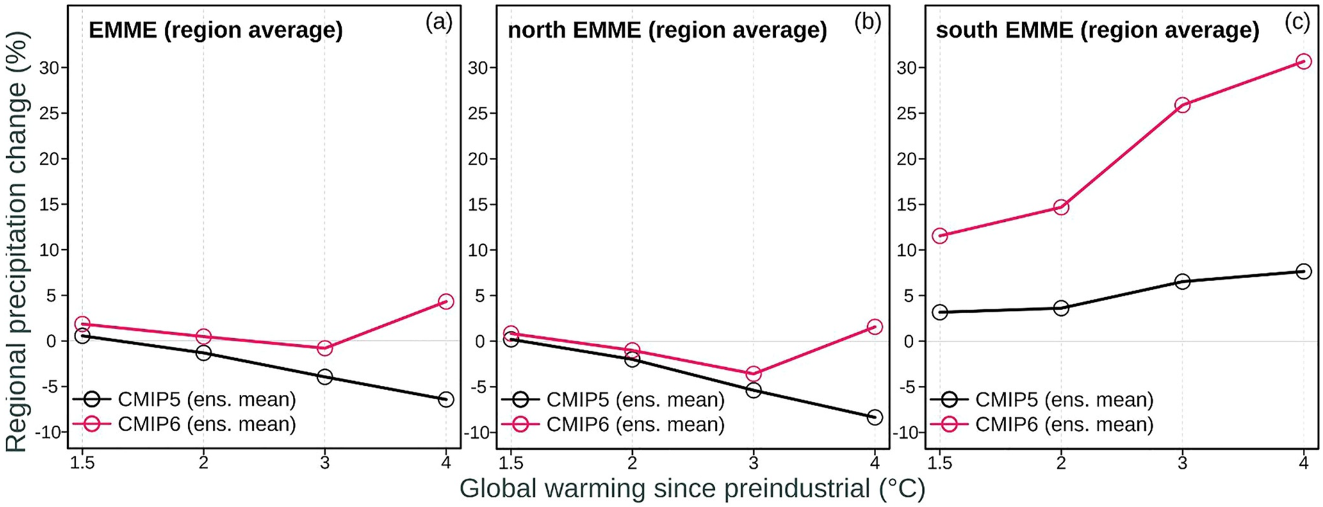

Figure 11. Relationship between global warming levels (since preindustrial) and precipitation change in the Eastern Mediterranean and Middle East (EMME) region (with respect to the 1986–2005 reference period), based on the CMIP5 and CMIP6 ensembles of global climate projections (a). The north (b) and south EMME (c) are defined as land grid-cells at latitudes higher and lower than 27.5°N, respectively. Data source: Iturbide et al. (2021).

The spatial pattern of annual precipitation changes is shown in Figure 12, whereas changes on a seasonal basis are presented in Figures S11–S14 in Supporting Information S1. The reference climatology of the historical period is presented in Figure S10 in Supporting Information S1. For RCP2.6 and both time horizons, annual precipitation changes are limited to about ±10%, with increases projected mainly for the southern and southeastern territories of the EMME. The robustness and significance levels are low, indicating that projected changes are within the present-day variability, and the model spread is comparable or higher than the climate change signal. Under RCP8.5, the mid-century conditions are similar to RCP2.6 and associated with low levels of significance and inter-model agreement. However, the end-of-century signal is stronger. For regions adjacent to the Mediterranean Sea (for instance, Greece, Turkey, Cyprus, Lebanon, Israel, Palestine, and north Egypt), the ensemble suggests a significant and occasionally robust precipitation decrease (20%–40%). Conversely, in the southern regions (e.g., parts of the Arabian Peninsula and south Egypt), precipitation is expected to increase (up to 50%). Although the percentage increase seems large, it is not always significant in terms of rainfall amounts. Under the business-as-usual pathway, the rainfall increase in the southern parts of the domain is mainly projected for the transition seasons of spring and autumn (Figures S12 and S14 in Supporting Information S1), coinciding with the seasonal displacement of the ITCZ. The contribution of the rainiest days of the year to the annual precipitation total is projected to increase (Zittis, Bruggeman, & Lelieveld, 2021).

Several studies, based on a variety of indicators, suggest a future increase in the severity, duration, and impact of drought events across the broader Mediterranean and Middle East region (Danandeh Mehr et al., 2020; Driouech et al., 2020; Dubrovský et al., 2014; Naumann et al., 2018; Prudhomme et al., 2014; Sen et al., 2012; Spinoni et al., 2018, 2020; Tabari & Willems, 2018; Touma et al., 2015; Waha et al., 2017; W. Liu et al., 2018). For example, the Aridity Index, which considers both precipitation and potential evapotranspiration, is projected to increase by up to 50% for most of the Eastern Mediterranean (Waha et al., 2017). Dry periods are projected to last longer (up to 90%) in about 80% of the Middle East area (Tabari & Willems, 2018). High-resolution projections for Israel and Cyprus also highlight that the number of consecutive dry days is expected to increase by up to 20–40 additional days per year (Hochman, Mercogliano, 2018; Zittis et al., 2020). In Cyprus, for example, the dry period of the year is projected to expand by one to 2 months by 2100. This can be partly attributed to a shorter wet season and a longer dry season due to the projected decrease in the occurrence of Cyprus Lows and the increase in the frequency of Persian Troughs (Hochman et al., 2018a, 2018b). Toward the end of the century, droughts are anticipated to increase more strongly under high-forcing pathways, while the projected changes in the severity of such events are more pronounced when the synergetic impact of temperature is also considered (Driouech et al., 2020; Spinoni et al., 2020). For example, changes corresponding to an overall increase of 20%–40% in the percentage of dry years with the highest values exceeding 40% lead to a doubling of the present-day ratio (Driouech et al., 2020).

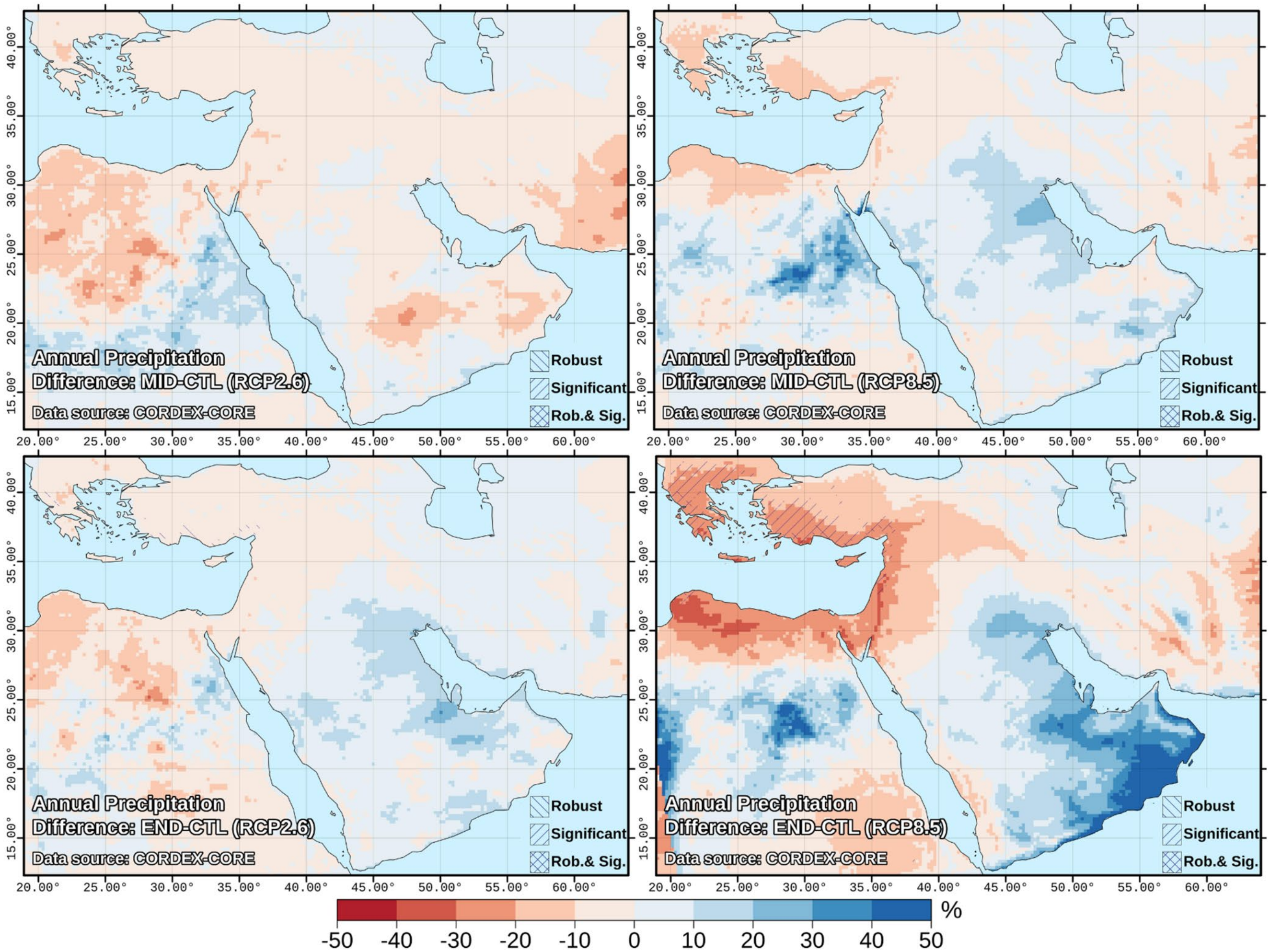

Figure 12. Projected changes (%) in annual precipitation (with respect to the 1986–2005 reference period), based on CORDEX-CORE climate projections for RCP2.6 (left panels) and RCP8.5 (right panels) and for mid-twenty-first-century (2041–2060, top panels) and end-of-century projections (2081–2100, bottom panels).

Extreme precipitation is expected to intensify with global warming as the concentration of atmospheric water vapor, which supplies the moisture for precipitation, increases at about 6%–7% per degree temperature rise (Allen & Ingram, 2002). Parts of EMME lie in the transitional zone, where, on the one hand, decreases of weak to moderate precipitation are expected, while on the other hand, climate models suggest an increase in extremes. Besides the uncertainties involved in the precipitation projections and the contribution of internal climate variability, which cannot be neglected, several studies have highlighted that climate change is likely to affect the severity and frequency of high-impact extreme precipitation events in the region (Chen et al., 2014; Donat et al., 2016; Drobinski et al., 2018; Giorgi et al., 2019; Paxian et al., 2015; Rajczak & Schär, 2017). In the Fertile Crescent (except for the southeastern coasts of the Mediterranean Sea), the number of extremely wet days is expected to increase by approximately 25%, particularly for RCP8.5, by the end of the twenty-first century (Samuels et al., 2018). Mesoscale convective systems over the southern Arabian Peninsula, often accompanied by extreme precipitation, are expected to be even more impactful in a warming world (Nelli, Francis, et al., 2021). For the semi-arid and arid parts of the EMME, global climate models suggest an increase of up to 5%–10% in 1-in-30-year extreme precipitation intensity per degree of global warming in 2070–2099 under RCP8.5 (Tabari, 2020). Such projections challenge the assumption of climate stationarity, a standard hypothesis in estimating extreme precipitation quantiles, often used as design criteria for infrastructure (Martel et al., 2020). Moreover, the contribution of the wettest day of the year to the annual precipitation total is projected to increase in the future throughout the Mediterranean region (Zittis, Bruggeman, & Lelieveld, 2021). Global and regional climate projections indicate a strong north/south gradient with a projected increase of extreme precipitation indicators in the northern Mediterranean and a decrease in the south (Lionello & Scarascia, 2020; Tramblay & Somot, 2018; Zittis, Bruggeman, & Lelieveld, 2021). It should be noted, however, that most studies focus on Mediterranean countries, and more research is needed to assess the future of extreme precipitation in the Middle East.

Apart from the effects of water management, nearly all rivers flowing into the Mediterranean are expected to see significant reductions in their natural discharges through the twenty-first century due to the projected rainfall reduction (Alpert et al., 2013; F. Jin et al., 2010; Mariotti et al., 2008). The Nile may be an exception since its water resources are in the tropical regions where some rainfall increases are projected. The Fertile Crescent is expected to dry, and its fertility will be challenged by the end of the century (Kitoh et al., 2008), with significant drying of the Euphrates and Jordan rivers (streamflow decreases of 29%–73% and 82%–98%, respectively). The Euphrates discharge regime has changed substantially since the construction of the first dams in the 1970s, while the natural flow may be expected to drop by ∼70% in high-warming scenarios (Alpert et al., 2014; Kitoh et al., 2008).

4.3. Other Meteorological Parameters

4.3.1. Atmospheric Circulation

Global warming is accompanied by an expansion of the Hadley Cell circulation and a poleward shift of the westerlies and associated storm tracks (Evans, 2010). This creates easterly wind anomalies at mid-latitudes (Lu et al., 2007). Normally, westerlies lead to moisture convergence at Mediterranean latitudes; however, the easterly shift weakens this phenomenon and contributes to drying (Seager et al., 2019). Trends in recent cyclone numbers affecting the Mediterranean are largely absent; however, when detected, these are mostly negative (Cherif et al., 2020). A reduction in the total number of cyclones crossing the Mediterranean region is expected under future climate change conditions (Nissen et al., 2014). Exceptions are parts of the Levant and the Arabian Peninsula, where climate models predict a statistically significant increase in the number of cyclones. A large fraction of the reduction in Mediterranean wet-season precipitation is attributed to such atmospheric circulation responses (Zappa et al., 2015). Furthermore, a drying trend in the Eastern Mediterranean is enhanced by warming over land (Drobinski et al., 2020). Local circulation patterns are also likely to be affected, particularly under high radiative forcing pathways. For example, Cyprus Lows (mid-latitude disturbances that tend to develop in the Levantine Basin during the wet season) are expected to weaken toward the end of the twenty-first century (Hochman et al., 2018a). These changes may be partially compensated by increases in Persian Troughs and Red Sea Troughs, especially during the winter season, however, these weather systems may be less active in terms of precipitation. For Mediterranean tropical-like cyclones or Medicanes that might develop or generate impacts in parts of the Eastern Mediterranean (e.g., Greece), climate projections indicate decreasing frequency but increasing intensity (González-Alemán et al., 2019; Romero & Emanuel, 2013). In addition to the atmospheric circulation changes, alterations in the lengths of seasons may occur through the twenty-first century. Of particular relevance is the duration of synoptic seasons (Alpert et al., 2004), especially the rainy winter relative to the warm and dry summer. The winter synoptic season may dwindle by 2 months, while the summer could lengthen by up to 5 months (Hochman et al., 2018a, 2018b).

4.3.2. Near-Surface Winds

Wind speed changes over the continental parts of the EMME may vary in sign and magnitude and have a different seasonal response. Under an intermediate scenario, the northern parts of the EMME (southern Balkans and Anatolia) will experience decreased wind speeds during the winter (∼10%) and increases of similar magnitude during summer (Mcinnes et al., 2011). The southern regions will be affected differently, as they are projected to experience increased wind speeds in winter and relatively small changes in summer. One exception is the southern part of the Arabian Peninsula (including Yemen and Oman), where wind speeds are projected to increase (∼10%), mostly during the summer season (Feron et al., 2020). This is significant increase, also found in the output of CMIP6 models (Iturbide et al., 2021), which is especially relevant for future changes in dust outbreaks from the southern Arabian deserts (e.g., Rub-Al Khali, Oman desert) toward the Arabian Sea (Francis, Chaboureau, et al., 2021). On average, off-shore wind speeds over the Eastern Mediterranean Sea are projected to decrease by up to 10% (Cherif et al., 2020; Dobrynin et al., 2012). Wind speed changes will impose a general decrease in the mean wave height, as well as in the number and intensity of extreme waves, over a large part of the region, especially in winter (Cherif et al., 2020). The Etesian winds over the Aegean Sea, mainly active during summer,

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are an exception since increases in their magnitude are expected for the future (Anagnostopoulou et al., 2014; Dafka et al., 2019; Ezber, 2019). The wind speed along the western coast of the Arabian Sea is also expected to increase by the end of the century by about 5%–10% (Dobrynin et al., 2012; Mcinnes et al., 2011). These changes are expected to have implications in several respects, including renewable energy resources (Davy et al., 2018) and aeolian dust activity. For example, in Crete, a future aeolian energy rise is expected in summer and fall, while in the island of Cyprus, wind energy production is projected to decrease in all seasons (de la Vara et al., 2020). Decreases in windstorm days are expected over most of the EMME region (Nissen et al., 2014). This overall reduction is due to a decrease in the number of events associated with local cyclones.

4.3.3. Total Cloud Cover

The projected poleward expansion of the Hadley Cell will likely induce a reduction (of up to 5%–10%) in total cloud cover across the broader Mediterranean region (Bartók et al., 2017; Enriquez-Alonso et al., 2016; Hentgen et al., 2019). Nevertheless, this signal is not always significant and is more evident in the results of global than in regional models (Cherif et al., 2020). It is also projected to be stronger under high climate forcing pathways and toward the end of the century. This reduction is mostly expected for the northern countries of the EMME and is projected to be statistically significant under intermediate and high-emission pathways (IPCC, 2013). For the Arabian Peninsula, minor and insignificant changes in the mean cloudiness are projected, associated with an increase of about 5% in the cloudiness variability by mid-century (Feron et al., 2020; IPCC, 2013). This enhanced cloudiness variability will likely influence photovoltaic energy production (Fountoulakis et al., 2021; Kosmopoulos et al., 2020). For example, summer days with very low photovoltaic power outputs will likely double in the Arabian Peninsula. For the Eastern Mediterranean (e.g., in Cyprus), a slight decrease in photovoltaic productivity is projected during spring, summer and fall, especially by the end of the century (de la Vara et al., 2020). During the winter months, significant changes in future photovoltaic productivity are not expected.

4.3.4. Relative Humidity

The atmospheric relative humidity is a critical weather parameter for ecosystems and human comfort in many parts of the EMME. Particularly in the Gulf region, the shallow and warm waters are an abundant humidity source. As a result of atmospheric warming and circulation changes, relative humidity changes in the region are subject to strong seasonal responses. Under a business-as-usual pathway, global climate models suggest a mild decrease (up to 5%) throughout the region during the winter season (Collins et al., 2013). In summer, a stronger and statistically significant decrease in relative humidity is expected (by up to 10%) for the northern parts of the EMME (e.g., the Balkans and Anatolia). For the southern (incl. the Arabian Peninsula and the Gulf region), relative humidity is projected to increase by up to 5%. This increase will further augment heat discomfort and thermal stress in these areas, while it could potentially affect other human activities, for example, transportation, through decreased visibility. The projected relative humidity changes are expected to be more pronounced toward the end of the current century.

4.4. Changes in Climate Regimes

Climate classifications offer a systematic way of describing the main climatic features of a region. The Köppen-Geiger classification system, applied in the present assessment, is one of the most widely used. It is based on the concept that climate zone boundaries also describe the vegetation and ecosystem distribution. A detailed description of the classification, including the climate constraints for its application, is presented in Section S.1.4 and Table S2 in Supporting Information S1. The synergistic effects of temperature and precipitation changes, and alterations in their monthly and seasonal distribution, are expected to cause changes in the main climate characteristics of the region. Such changes will likely introduce adverse impacts on both human and natural systems. The classification results for the 1986–2005 reference period are presented in Figure 13 (top left). Most of the EMME (about 75%) is a hot desert (BWh) or steppe (BSh) (see Table S2 in Supporting Information S1). Such regions involve large parts of the Arabian Peninsula and North Africa. The Balkan and Anatolia peninsulas, and parts of the Fertile Crescent, are identified as warm temperate climates across several subcategories (e.g., Cfa, Cfb, Csa, and Csb), with the colder classes found in the northern parts of the region. These areas represent about 18% of the surface area. In the remaining 7%, snow climates prevail (i.e., the temperature of the warmest month is greater than 10°C, and the temperature of the coldest month is −3°C or lower). These constraints are met at the highest elevations, for example, the Taurus, Caucasus, Alborz, and Zagros mountains. Because of the projected

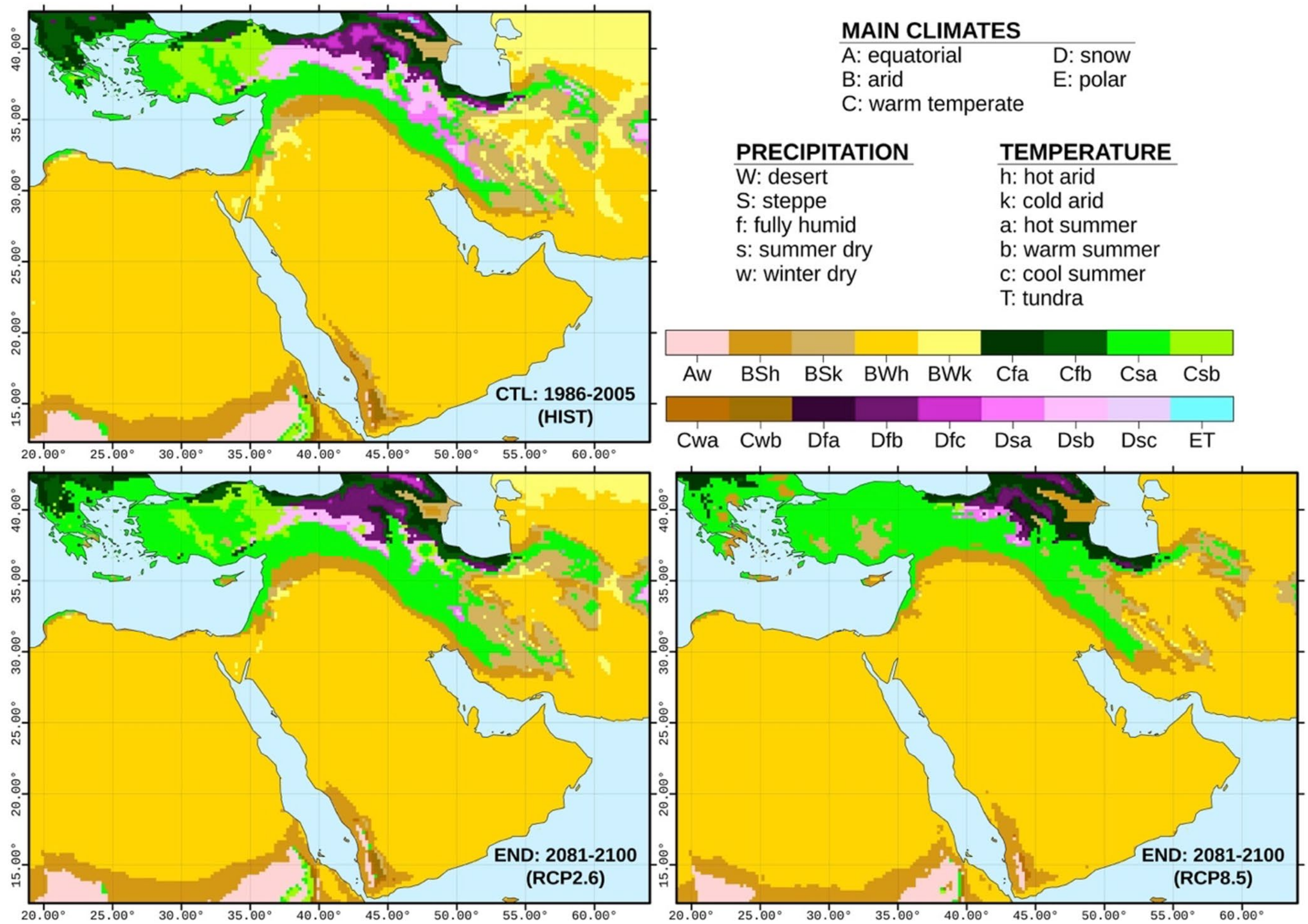

Figure 13. Application of the Köppen-Geiger climate classification system, based on the CORDEX-CORE data set for the 1986–2005 historical reference period (top left panel) and the end of the twenty-first century (2081–2100) under RCP2.6 (bottom left panel) and RCP8.5 (bottom right panel).

warming and alterations in the hydrological cycle, by the end of the century and under the high-emission pathway (RCP8.5), the climate characteristics of the region are expected to change (Figure 13, bottom right panel). The most profound alterations include a northward expansion (by 5%) of the dry zones (BWh and BSh) against the more temperate climates (Cf and Cs; see Table S2 in Supporting Information S1). Such arid zones will likely expand to parts of Cyprus, eastern Greece and Turkey, currently characterized as temperate zones. Because of the strong winter warming in high-elevation regions, snow climates (Df and Ds) are projected to mostly diminish to less than 2% of the EMME region. This will have a large impact on water resources, especially in places that rely on winter and spring snow cover upstream. On the other hand, under RCP2.6, the milder warming and less pronounced changes of precipitation seasonality and total amounts imply less significant changes in the climatic characteristics of the region (Figure 13, bottom left panel).

4.5. Regional Sea-Level Rise

Over the past decades, the sea level has risen globally, primarily due to global warming, which has led to an increase in ocean warming and thermal expansion, as well as significant land-ice mass loss. The altimetry-based global mean sea level average trend was 3.1 ± 0.3 mm yr^{-1} for the period 1993–2018, with ocean thermal expansion, glaciers, Greenland and Antarctica contributing 42%, 21%, 15%, and 8% to the global mean sea level rise, respectively (Cazenave et al., 2018). Amid the ongoing energy uptake of the global ocean, this trend has high inertia and will continue in the future. Indications of Antarctic land ice destabilization are steadily gaining support (e.g., Francis, Mattingly, et al., 2021), strengthening the likelihood of the significant acceleration of sea-level rise (SLR) during the present and following centuries. This will potentially affect coastal settlements,

Table 1
Mean Sea-Level Rise Projections (in m) for the Mediterranean and the Seas Surrounding the Arabian Peninsula, Relative to the 1995–2014 Reference Period Based on the Ensemble Median of 35 CMIP6 Global Climate Projections

	Mediterranean Sea		Arabian Penisula (Red Sea and Gulf)	
Period	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
Near term (2021–2040)	0.1 (0.0, 0.2)	0.1 (0.0, 0.2)	0.1 (0.0, 0.2)	0.1 (0.1, 0.2)
Medium term (2041–2060)	0.2 (0.1, 0.4)	0.3 (0.1, 0.4)	0.2 (0.1, 0.3)	0.2 (0.1, 0.4)
Long term (2081–2100)	0.4 (0.2, 0.7)	0.7 (0.4, 1.0)	0.4 (0.2, 0.6)	0.6 (0.4, 1.0)

Note. Values in brackets represent the likely range (5th and 95th percentiles). Data source: IPCC Working Group I Interactive Atlas (Gutiérrez et al., 2021; Iturbide et al., 2021).

infrastructure, agriculture and cultural heritage sites. The anthropogenic signal in regional sea-level change will emerge in most regions, including the Mediterranean, by 2100 (Fox-Kemper et al., 2021). Thermal expansion, ocean dynamics, land-ice loss contributions, vertical land movements and the Earth's gravity field will shape regional SLR differences of the order of 0.1 m (Asariotis & Benamara, 2012; Oppenheimer et al., 2019). This section focuses on observed and future changes in sea levels in three important basins of interest: the Arabian or Persian Gulf, the eastern part of the Mediterranean Sea and the Red Sea. Such changes may imply severe impacts on coastal infrastructure and the quality of the intensively exploited Mediterranean aquifers (Izaguirre et al., 2020; Kron, 2013; Mazi et al., 2014).

4.5.1. Arabian (Persian) Gulf

The Arabian Gulf is located in the sub-tropics between 24°N and 30°N latitude and 48°E and 57°E longitude. It is considered a biogeographic sub-province of the northwestern Indian Ocean. The mean depth of this shallow water body is about 50 m. The Gulf region, particularly the shallow southern basin, is the warmest sea on the planet during summer, with sea surface temperatures regularly exceeding 35°C in August (Vaughan et al., 2018). An increase in sea surface temperatures by 0.7°C/decade along the western side of the Arabian Gulf is observed, a rate that substantially exceeds the annual global warming since pre-industrial times (Hereher, 2020). For a period of more than 28 years (1979–2007), a relative SLR of 2.2 ± 0.5 mm yr^{-1} was also estimated for the northwestern part of the Arabian Gulf, a relative SLR of 2.2 ± 0.5 mm yr^{-1} was estimated (Alothman et al., 2014). After considering the vertical land motion, the absolute rise for the same period is estimated at 1.5 ± 0.8 mm yr^{-1}, which is consistent with the global estimate of 1.9 ± 0.1 mm yr^{-1} (Church & White, 2011). An analysis of tidal data from seven stations along the west coast of the Arabian Gulf in Saudi Arabia revealed an increase in sea levels, reaching a maximum of 3.4 ± 0.98 mm yr^{-1} from 1979 to 2008 (Siddig et al., 2019). Recent observations (1993–2019) report an average SLR rate of 2.85 mm per year (Naderi Beni et al., 2021). SLR projections are also available for the Arabian Gulf and Oman Sea. The SimCLIM model, driven by data from CMIP5 coupled climate models, projects a significant increase in regional mean sea levels by the end of the century, with most models projecting a future SLR between 100 and 130 cm (Irani et al., 2017). Updated estimations, based on CMIP6 models, and a more recent reference period (Table 1), indicate more conservative increases in mean sea level rise. In the most extreme scenarios, this will likely not exceed 1 m.

4.5.2. Mediterranean Sea

The Mediterranean Sea is a semi-enclosed overturning water body situated between Southern Europe, the Middle East, and Northern Africa, connected to the global ocean by the narrow Strait of Gibraltar. The average depth is about 1.5 km, but in some areas, it exceeds 5 km. The inflow of Atlantic water through the strait compensates for the water deficit generated by the excess of evaporation over precipitation (Soto-Navarro et al., 2020). For the period 1993–2018, monitored by satellite altimetry, the Mediterranean Sea level was shown to have risen at a rate of 2.8 ± 0.1 mm yr^{-1}, consistent with the rise in global sea levels (3.1 ± 0.4 mm yr^{-1}) (Cherif et al., 2020, and references therein). Based on estimations from coupled regional climate models, the rise in the Mediterranean Sea level is expected to be close to that of the global mean sea level. The basin-level average sea level will likely increase by 20–90 cm by 2100, compared to the end of the twentieth century, with a small probability of exceeding 110 cm (Cherif et al., 2020; Oppenheimer et al., 2019, and references therein). Near-future mean sea-level projections for the region, based on CMIP6 models (Table 1), suggest that for both SSP1-2.6 and SSP5-8.5

pathways the rise will be limited to 0.1 m. Nevertheless, toward the end of the century, the high emission pathway (SSP5-8.5) could exceed 0.7 m with respect to the 1995–2014 reference period. In this context, there is a growing concern for the higher values and a multi-century lock-in that cannot be mitigated. Extreme sea-level events are water-level heights that consist of contributions from mean levels, storm surges, and tides. Such events in the Eastern Mediterranean are projected to increase. For example, in Alexandria, Egypt, extreme sea level events with return periods of 100 years in the recent past will likely become annual or even more frequent (Oppenheimer et al., 2019).

4.5.3. Red Sea

The Red Sea is located between the African and Asian continents, oriented from the north-northwest to the south-southeast. It is a semi-enclosed basin, with a length of about 2,000 km, an average width of 280 km and an average depth of about 500 m. The sea-level variability is mainly influenced by the exchange between the Red Sea and the Gulf of Aden. The Red Sea is one of the warmest and most saline water bodies in the world, due to the high evaporation rates and near-zero precipitation (Abdulla & Al-Subhi, 2020). Several studies have investigated the annual sea level variation and characteristics of the seasonal cycle and circulation at certain locations in the Red Sea (Abdulla & Al-Subhi, 2020; Alothman et al., 2020; Pugh & Abualnaja, 2015). A recent study based on satellite altimetry sea-level data for 1993–2020 investigated sea-level variability of the Red Sea (Abdulla & Al-Subhi, 2021). Consistent with the global rates, the annual mean sea level was estimated at a rate of 3.88 mm/year from 1993 to present, highlighting the role of the El-Nino Southern Oscillation in the interannual sea-level fluctuations. However, a noticeably faster significant rate (6.40 mm/year) is estimated if data were limited to 2000-present. For the twenty-first century, limited estimations are available since the Red Sea is not fully resolved in global Earth system models. The expected SLR is 15.2, 17.0, and 34.5 cm for pathways RCP2.6, RCP4.5, and RCP8.5, respectively (Abdulla & Al-Subhi, 2021).

5. Special Topics

5.1. The Interplay Between Atmospheric Composition and Climate

Global warming has strong impacts on the arid and semi-arid regions of the Middle East, which have physical geography and atmospheric conditions that make them particularly vulnerable to climate change (Klingmüller et al., 2016; Masoudi et al., 2018; Notaro et al., 2015). Several studies have investigated trends in dust activity as the major factors behind degraded air quality in the region (Achilleos et al., 2020; Mashat et al., 2018; Pozzer et al., 2015; Rashki et al., 2018; Rezazadeh et al., 2013). Figure 14 illustrates the high contribution of particulate matter with a diameter less than 2.5 microns ($PM_{2.5}$), revealing the southern Arabian deserts, the Iraqi Plains and regions in southeast Iran as major dust sources and regional contributors to air pollution. Chemical analysis of airborne dust is essential for questions related to emission inventories, source apportionment, climate modeling, air pollution monitoring and mitigation strategies. The majority of such studies emphasized on trace metals, organics and micro-organisms in total suspended particulates or PM_{10} and $PM_{2.5}$ samples (Al-Khashman, 2013; Gat et al., 2017; Heidari-Farsani et al., 2013; Lang-Yona et al., 2020; Mazar et al., 2016; Rashki, Eriksson, et al., 2013; Shahsavani et al., 2012). Declining precipitation and evapotranspiration increases may lead to a decrease in vegetation, expanding the bare surface, which becomes more susceptible to wind erosion, causing an increase in dust activity, and the frequency and intensity of dust storms (Gholami et al., 2020; Middleton, 2019; Rashki et al., 2021; Shaheen et al., 2020). In addition, projected synoptic variations during the twenty-first century that include increases in the frequency of Red-Sea trough days were associated with dust storms in the Middle-East (Elhacham & Alpert, 2020).

The Middle East is undoubtedly an aerosol and pollution hotspot, where aerosols from both natural and anthropogenic origins co-exist. As previously discussed, the EMME region would be highly impacted by climate change increase in temperature and changes in precipitation. These scenarios imply increased evapotranspiration, freshwater shortage, and expansion of desert areas due to desiccation of ephemeral water bodies (Ahmady-Birgani et al., 2020; Darvishi Boloorani et al., 2021; Rashki et al., 2017). This will likely increase dust emissions, as the dried lake beds lying in topographically low basins are highly susceptible to aeolian erosion. In addition, the saline material left in the upper soil crust after lake desiccation likely contributes to an increase in aerosol particle concentrations and saline dust storms with adverse effects on vegetation and human health (Ahmady-Birgani et al., 2020; Golreyhan et al., 2021). Since aeolian dust is the dominant aerosol type in the region (Shaheen

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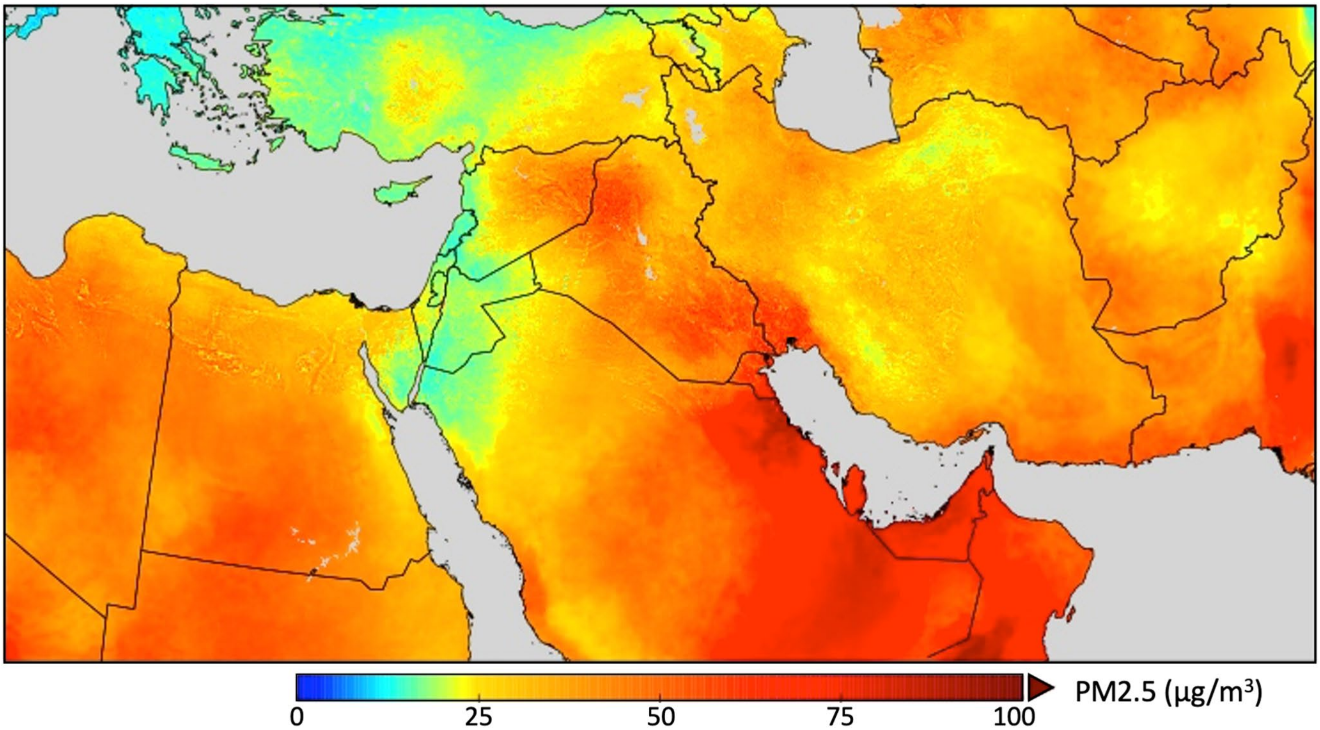

Figure 14. Annual mean distributions of $PM_{2.5}$ over the Eastern Mediterranean and Middle East, derived from satellite observations. (Source: Updated data from Van Donkelaar et al. (2016)).

et al., 2020; Xu et al., 2020), future trends will likely be associated with changes in meteorological processes (i.e., droughts, modulation of synoptic weather and winds), including the effect of large-scale teleconnection patterns that are found to affect atmospheric dynamics and dust activity in the Middle East (Yu et al., 2015).

On the other hand, a projected increase in population, gross domestic product, and industrialization, along with an expansion of oil refineries and petrochemical activity over the EMME region, will increase pollution emissions, such as NO_2, SO_2, potentially toxic elements, and $PM_{2.5}$ on the coming decades. Thus far, there are no important actions for desulfurization or decreases of trace gas emissions in the Middle Eastern countries, coincident with greenhouse gas emissions and intensification of climate warming. The Persian Gulf is a hotspot of photochemical smog and tropospheric O_3 pollution (Lelieveld et al., 2009), also exhibiting the highest sulfate concentrations among the marine regions in EMME. The results of the AQABA (Air Quality and climate change in the Arabian BAsin) cruise campaign, conducted in the summer of 2017 from the central Mediterranean to the Persian Gulf, improved our knowledge on atmospheric gases and chemistry in the marine boundary layer of the EMME region, exploring sources and sinks of non-methane hydrocarbons, ozone chemistry, OH reactivity, emissions of NO_x, methane sulfonamide, and formation of $ClNO_2$ (Bourtsoukidis et al., 2019, 2020; Edtbauer et al., 2020; Eger et al., 2019; Pfannerstill et al., 2019; Tadic et al., 2020).

Scattering and absorption of solar radiation by atmospheric aerosols (such as dust and soot from the burning of biomass and pollution) can modify the radiation budget, atmospheric stability, heat fluxes and thus affect cloud formation, microphysics (albedo, droplet size distribution, and lifetime) and precipitation. In this respect, several studies focused on the indirect climate implications of aerosols and trace gases via their effect on cloud properties and convective precipitation processes over the EMME region (Bougiatioti et al., 2016; Kallos et al., 2014; López-Romero et al., 2021; Ramanathan et al., 2001; Rosenfeld et al., 2001; Solomos et al., 2011; Tang et al., 2018). On a global scale, desert dust exerts an estimated top of atmosphere (TOA) radiative forcing in the range of −0.6 to 0.4 Wm^{-2}, while in the EMME region, the forcing, both at the TOA and surface, is much more intense due to high surface reflectivity and enhanced aerosol loading, especially during the summer season (Alpert et al., 1998, 2005; Alpert & Kishcha, 2008). Several studies have assessed the dust-induced radiative forcing over the region, revealing large surface radiative cooling at the surface, especially during intense dust events

(Gkikas et al., 2018; Jish Prakash et al., 2015; Mishra et al., 2014; Nabat et al., 2015; Papadimas et al., 2012; Saeed et al., 2014; Spyrou et al., 2013; Tsikerdekis et al., 2019). Over areas not systematically affected by intense dust plumes, the surface cooling due to aerosols is mostly attributed to light absorption (atmospheric heating) due to absorbing aerosols, for example, black carbon over the Eastern Mediterranean (Klingmüller et al., 2019; Mishra et al., 2014). When dust is mixed with anthropogenic aerosols, atmospheric heating can account for 17 ± 8 Wm^{-2}, influencing the ambient temperature in the lower atmosphere with heating rates ranging from 0.1°C to 0.9°C/day (Mishra et al., 2014). The uptake of acids from the gas phase by the alkaline dust particles influences atmospheric composition, for example, by reducing nitrate, which in turn decreases the formation of ammonium nitrate aerosols (Karydis et al., 2016). The uptake of acids tends to reduce the lifetime of dust particles by enhancing the deposition and cloud scavenging efficiency (Abdelkader et al., 2015). Since aerosols act as cloud condensation nuclei, dust-pollution-cloud interactions cause cloud adjustments, which reduce the condensed water path, leading to a positive (warming) radiative forcing of climate (Klingmüller et al., 2020).

Absorbing dust aerosols stabilize the lower atmosphere via localized diabatic heating and may lead to the accumulation of aerosols over the region and the formation of a "pollution pool" (Mishra et al., 2014). Shortwave and longwave radiative forcing assessment over the arid Middle East was also performed via numerical model simulations (Jish Prakash et al., 2015; Saeed et al., 2014). A considerable radiative effect of dust aerosols was found at the surface due to strong light scattering, with significant warming during the night and cooling during the day. By modifying the radiative balance and Earth-atmosphere fluxes, dust aerosols affect local climatic parameters such as temperature, wind and precipitation over the Middle East (Francis, Chaboureau, et al., 2021; Klingmüller et al., 2016; Yu et al., 2016). A severe dust storm over Arabia in March 2009 caused a strong temperature decrease (~6°C) over Riyadh (Alharbi et al., 2013; Maghrabi et al., 2011). Similarly, Jish Prakash et al. (2015) estimated a large reduction of 6.7°C in surface temperature over the Middle East during a severe dust storm in March 2012.

The vertical distribution of dust is particularly important for the radiative effects over the arid regions. Several studies have shown a strong linkage between elevated dust-induced atmospheric heating over the Arabian Sea and modulations in the monsoon circulation pattern and rainfall over the downwind Indian sub-continent (Kaskaoutis et al., 2018; Q. Jin et al., 2016; Solmon et al., 2015; Vinoj et al., 2014). This interaction, which may be a regulatory climatic factor in South Asia, has been investigated via satellite observations, ground measurements and numerical simulations. Radiation absorption by elevated dust layers can enhance cyclonicity over the western Arabian Sea, and therefore modulate the pressure gradient across the north Indian Ocean that influences the monsoon circulation. One result is the intensification of the southwesterly summer monsoon flow over the Arabian Sea and increased rainfall over western and central India (Lawrence & Lelieveld, 2010; Q. Jin et al., 2021). Therefore, short- or long-term changes in dust activity in the Arabian Peninsula may modulate the climate system over the whole of South-West Asia. Even small changes in the absorbing capability of dust may significantly affect the precipitation rates and distribution (Das et al., 2015).

Changes in pressure gradients between the Caspian Sea and the Hindu Kush-Pamir mountainous range may strongly affect the wind regime and dust activity over the eastern parts of Iran (Kaskaoutis et al., 2016, 2017). This area is strongly affected by the Levar seasonal or "120-days" winds blowing with great intensity from mid-May to mid-September (Hamidianpour et al., 2021). Warmer conditions and desertification over Central Asia can affect the Caspian Sea High that mostly modulates the Levar wind and dust activity, hence influencing the weather and climate forcing (Li et al., 2021). High-resolution satellite data and in situ observations were also analyzed to estimate the direct and semi-direct radiative effects of dust over the southern Arabian Peninsula during an intense dust storm (Francis, Chaboureau, et al., 2021). Apart from the reduction in incoming solar irradiance, the dust-induced radiative forcing was found to enhance cyclonicity over the region due to intense lower atmospheric heating, which in turn, can trigger new dust-storm formation and convective clouds. It should be mentioned that regional climate model projections usually do not account for radiative feedbacks associated with desert dust and other aerosol types, including those from biomass burning, and further integration of these processes in models is needed.

5.2. Land-Use Change and Climate

5.2.1. Urbanization

The population of the wider Middle East and North Africa region is expected to grow to over 1 billion inhabitants by 2100. This demographic trend, in a region with scarce arable land and water resources, poses significant socio-economic challenges and environmental stress (McKee et al., 2017). The region's population has increased fivefold since the 1950s, from just under 85 million to about 432 million in 2020, and is expected to grow to nearly 600 million by 2050 (United Nations, Department of Economic and Social Affairs, Population Division, UNDESA, 2018). The corresponding urban population has risen ten-fold in the past seven decades. By 2050, the urban population is projected to account for 76% of the total. Some countries already have very high urbanization levels (>80% in Kuwait and close to 100% in Qatar). One of the first order effects of urbanization on the local climate is the UHI phenomenon by which temperatures over a city are higher than the surroundings due to differences in the urban/rural energy balance, brought about by radiative and heat flux changes from the altered land cover and anthropogenic activities (Oke et al., 2017). This effect should be considered when deriving temperature trends from station-based data sets (Kalnay & Cai, 2003); however, it contributes little to the observed global warming (Jones, 2016). Only a few studies of the connection between urbanization and warming have focused on the EMME region. An analysis in Saudi Arabia showed that the observed increase in air temperature (~0.56°C/decade) is likely not due to urbanization changes (Almazroui et al., 2013). Another analysis of observations from more than 200 stations in the Middle East and North Africa corroborated the above mentioned annual temperature trend of about 0.4°C/decade and a discernible, but small urbanization effect. The city of Dubai, for example, is experiencing remarkable temperature increases associated with rapid urbanization (Elhacham & Alpert, 2021).

The synergistic interaction of UHI effects and heatwaves has been studied for Eastern Mediterranean cities. This interaction over Athens, Greece, results in a pronounced amplification of nocturnal UHI intensity (by 3°C) under exceptionally hot weather (Founda et al., 2015). UHI effects in Nicosia, Cyprus, increase the temperature by more than 1°C during daytime under heatwave conditions due to urban/rural moisture contrast (Pyrgou et al., 2020). In Nicosia, urban warming has been linked to an increased probability of heat-related mortality during heatwaves (Pyrgou & Santamouris, 2018). It is thus important to be able to estimate local urban warming, in addition to the regional manifestation of global, large-scale warming, to assess the impacts of their combined magnitude on human health. The accurate projection of urban heating in the context of global warming is a great challenge (Hamdi et al., 2020). Few estimates are available for the EMME. A population-driven urban warming estimation in four Israeli cities suggests that from 2015 to 2060, the UHI intensity will increase further by 2°C–4°C (Itzhak-Ben-Shalom et al., 2016). Another approach uses coupled global climate simulations and reduced-order urban modeling to project local urban climates (L. Zhao, Oleson, et al., 2021). For a high-emission scenario, cities in the Middle East may experience additional warming of 4°C, on top of the regional warming due to anthropogenic climate change. For Thessaloniki in Greece, limited changes in UHI intensity were estimated to occur in the future (Keppas et al., 2021). It will be needed to account for urbanization trends and the UHI effect in future climate projections.

The intense urbanization in the EMME region leads to severe, regionwide air pollution. Urban areas in hot and dry environments are prone to high levels of fossil fuel combustion by-products and elevated emissions of pollutants, GHGs and primary aerosols (Kanakidou et al., 2011; Lelieveld et al., 2002). Reactions of emitted organic and inorganic pollutants contribute by forming secondary aerosols, while photochemical reactions of organic pollutants, in the presence of nitrogen oxides, can add to ozone pollution (Tutsak & Koçak, 2019; Vrekoussis et al., 2006). These interactions are estimated to increase in the region, especially the Middle East, with harmful effects on people and vegetation in urban centers and further downwind (Lelieveld et al., 2009). Figure S15 in Supporting Information S1 illustrates the strongly enhanced levels of NO_2 in urban areas like Tehran, Cairo, Riyadh, Tel Aviv, and Istanbul. The dry and hot conditions also promote wildfires, which, together with chronic exposure to urban air pollution and high dust levels, deteriorate air quality and contribute to respiratory and cardiovascular diseases in synergistic ways.

5.2.2. Forest Fires

Wildfires are an integral component of Mediterranean landscapes and ecosystems. Their occurrence has markedly increased since the 1970s due to land use and climate change, but also changes in fire management (Wittenberg & Kutiel, 2016). Forest fires are most common during summertime and they are often intensified by the combined effect of droughts, high temperatures and strong winds (Koutsias et al., 2013). Eastern Mediterranean countries with relatively temperate climates that favor forest and shrubland biomes (e.g., Cyprus, Greece, Israel, Lebanon, and Turkey) are among those most affected by forest fires. Severe drought events can pre-condition the area for forest fires, predominantly during the warm and dry part of the year. Summer fires frequently rage across the Mediterranean landscapes, while their impact is augmented by extraordinary high temperatures, as well as droughts that are found to regulate the fuel moisture (Turco, VonHardenberg, et al., 2017). For example, an increasing trend and a positive correlation are identified between the measures of fire activity (number of fires and area burned) and annual drought episodes in Greece (Dimitrakopoulos et al., 2011). Nevertheless, droughts also control fuel availability, making the relationships between fire activity and weather conditions more complex (Turco, Levin, et al., 2017).

High-impact wildfires were extensive in the summer of 2007 in southern Greece (Kaskaoutis et al., 2011; Turquety et al., 2009). It was the hottest summer on record for the country at the time, with temperature anomalies in Athens exceeding 3.7 standard deviations off the long-term mean (Coumou & Rahmstorf, 2012; Founda & Giannakopoulos, 2009). This coincided with massive forest fires that burned thousands of hectares of forested and agricultural land and caused the loss of 67 lives (Koutsias et al., 2012). It was considered the most extreme natural disaster in the country's recent history, until the August 2021 wildfires in Greece, which also followed a severe and long-lasting (~8 days) heatwave. The December 2010 Mount Carmel forest fires in Israel (Paz et al., 2011) occurred following an unusually warm and dry autumn. More recently, extreme heat conditions in early October 2019 in Lebanon coincided with massive wildfires, indicating that the fire season has expanded towards the autumn months.

Attribution studies suggest that the risk of extreme fire-weather conditions in the Mediterranean has already increased by 50%, due to anthropogenic activities (Touma et al., 2021). By the end of the century, human-induced changes in temperature, relative humidity, and surface wind speed can more than double the risk of extreme fire-weather conditions in the region. Across most EMME forests, days of critical fire risk, the length of the fire season and the extent of burnt areas have increased significantly in the past decades and are expected to continue doing so in the twenty-first century, especially under business-as-usual pathways (Çolak & Sunar, 2020; Dupuy et al., 2020; Karali et al., 2014; Levin et al., 2016; Palaiologou et al., 2018). This will be due to the combined warming and drying of the region, associated with more frequent and extreme heatwaves and drought events, which are projected to intensify (see Sections 6.1 and 6.2). For parts of the Eastern Mediterranean (e.g., Greece), under high warming scenarios, the burnt area will likely increase proportionally, ranging from about 40% to 100% (Turco et al., 2018), underlying the significant benefits of limiting GWLs to well below 2°C.

6. Impacts on Critical Sectors

6.1. Human Health and Heat Stress

Warming, drying, more prolonged and frequent extreme heat events will all exert substantial stress on the health and well-being of people in the EMME region. Exposure to elevated ambient temperatures, already commonplace in the region, is linked to heat cramps, heat syncope, heat exhaustion, and heat stroke, especially among individuals with pre-existing illnesses, such as cardiovascular and respiratory diseases (McGeehin & Mirabelli, 2001). Associations between high temperatures and excess morbidity and mortality have been identified in several countries of the region, including Cyprus, Greece, Kuwait, Lebanon, and Syria, while this is more evident along the coasts and in large urban centers (Alahmad, Khraishah, et al., 2020; Alahmad, Tomasso, et al., 2020; El-Zein et al., 2004; Kouis et al., 2019; Lubczyńska et al., 2015; Nastos & Matzarakis, 2012; Paravantis et al., 2017; Peretz et al., 2012). Continued exposure to extreme heat throughout the night is associated with sleep disturbances, mental health issues, exhaustion, and hyperthermia (Pal & Eltahir, 2016). Heat stress hotspots may result from the interaction of hot desert air masses with onshore moisture advection from warm water bodies (Coffel et al., 2018). In parts of the region, mainly in the Middle East, the climatic conditions during summer (but also late spring and early autumn) are expected to become particularly harsh. Notably, under business-as-usual scenarios, heat stress will intensify greatly, and in combination with high humidity, ambient environmental conditions are likely to approach and exceed critical thresholds for human adaptability (Pal & Eltahir, 2016). Augmentation of heat stress conditions, particularly during extreme heatwaves (Lelieveld et al., 2016; Varela et al., 2020; Zittis, Hadjinicolaou, et al., 2021), has the potential to substantially increase heat-related mortality by eight to 20 times the historical values (Ahmadalipour & Moradkhani, 2018). Vulnerable populations that include the elderly, children, pregnant women, and people with chronic or pre-existing medical conditions are expected to be the most affected. The extreme environmental conditions are also expected to augment differences and inequalities between the more affluent and impoverished populations of the EMME region. The increasing temperatures may affect some cities in the region (e.g., megacity Cairo) more than others, with different adaptive capacities to cope with hot weather (Habib et al., 2010). At the rate of projected climate change over the next 50 years, heat-related stress in the region is unlikely to be offset by any cold-related gains (El-Zein et al., 2004). Outdoor labor activities, such as construction and agriculture, are already challenged (Al-Bouwarthan et al., 2019). Environmental heat stress has reduced labor capacity to 90% in summer months over the past few decades in many parts of the world. Thermal stress will further aggravate in many parts of the EMME (Casanueva et al., 2020; Dunne et al., 2013). Local industries should adapt to the projected changes to prevent major impacts on the health of workers and, at the same time, preserve economic productivity. The degree to which heat-related morbidity and mortality rates will increase in the next few decades will depend on the adaptive capacity of EMME population groups through acclimatization, adaptation of the urban environment to reduce heat stress and UHI effects, implementation of public education programmes and the preparedness of health care systems.

6.2. Water Resources and Agriculture

Water resources in the EMME are scarce, unevenly distributed, and often do not match human and environmental needs (Fader et al., 2020). The dominance of evaporation over precipitation means that most of the region lacks surface and groundwater resources (Cullen et al., 2002). Many regions consistently experience less than 100 mm of precipitation per year (Hemming et al., 2010). Climate change-driven alterations in precipitation patterns and seasonality, combined with warmer temperatures, stronger evapotranspiration, reduced snow cover in upstream areas, SLR, as well as, increasing water demand, will further limit the access to freshwater resources (Chenoweth et al., 2011; Chowdhury & Al-Zahrani, 2013; Croke et al., 2000; Fader et al., 2020; Fujihara et al., 2008; Oroud, 2008; Rajsekhar & Gorelick, 2017; Schewe et al., 2014; Shaban, 2008). Surface and groundwater resources in most of the EMME are projected to be further limited under climate change conditions and particularly when considering pathways of strong radiative forcing such as business-as-usual scenarios (Al Qatarneh et al., 2018; Chenoweth et al., 2011; Givati et al., 2019; Hartmann et al., 2012; Yıldirim et al., 2021). For example, climate projections for parts of the region suggest an increase in the average seasonality, affecting hydrologic regimes due to shorter wet seasons and earlier snowmelts (Allam et al., 2020). Particularly in the drier parts of the region, the rising temperature appears to be the principal reason for water availability responses (Ajjur & Al-Ghamdi, 2021). Moreover, freshwater demand is expected to intensify due to population increases and changes in the standard of living. Countries of the region where the required adaptation is likely to be particularly challenging include Turkey and Syria because of their reduced runoff projections and major agricultural activity, Iraq because of its downstream location and Jordan because of its minor per capita water resources coupled with limited options for desalination (Bozkurt & Sen, 2013; Chenoweth et al., 2011). The projected transition to warmer and drier bio-climatic conditions can be expected to severely affect agriculture and thus food production. Key Mediterranean crops (e.g., olives, vines, legumes, wheat, barley, and maize) will be strongly affected by the combined effect of prolonged drought periods and increased thermal stress (Al-Bakri et al., 2011; Constantinidou et al., 2016; Giannakopoulos et al., 2009; Kitsara et al., 2021; Lazoglou & Anagnostolpoulou, 2017; Papadaskalopoulou et al., 2020; Sen et al., 2012; Varotsos et al., 2021; Verner et al., 2018). This is mostly relevant for summer crops in the region. For example, a significant correlation between crop yield decrease and temperature increase is evident, regardless the effects of CO_2 fertilisation or adaptation measures (Waha et al., 2017). Other types of crops, such as nut trees, sensitively respond to climate change. For example, the increasing air temperature has shown to have negative consequences for pistachio cultivation in Iran, such as reduced yield, increased pest infestation and increased evapotranspiration and water requirements (Ahmadi et al., 2021). Interestingly, for some crops (e.g., grapevines and cereals) in higher-altitude or higher-latitude regions, agricultural production might benefit from climate change (Giannakopoulos et al., 2009; Lazoglou & Anagnostolpoulou, 2017; Koufos et al., 2018, 2020). For other species and agro-ecosystems in the EMME, the projected climatic pressure will exceed the limits of resilience; vegetation will either adapt to the new conditions or be succeeded by cultivars more tolerant of heat and water stress (Daliakopoulos et al., 2017).

6.3. Impacts of Sea-Level Rise

The impacts of SLR mainly include beach erosion, loss of wetlands and lagoons, damage to coastal infrastructure and saltwater intrusion into coastal aquifers. These influence ecosystems and a range of socio-economic activities such as agriculture, tourism, water and energy management, and urban planning. Low-elevation regions, flat sandy beaches, and deltaic sediments, commonly found in the EMME coastal zones, are less resistant to SLR than elevated, hard and cliffy shores (Kumar et al., 2010). A hotspot where such impacts may be particularly severe is the Nile Delta. The land elevation of approximately 25% of the deltaic region is equal to or beneath present-day sea levels (Shaltout et al., 2015). Even a moderate mean SLR increase can dramatically impact the coastal regions, which include large lakes, tourist resorts, historical sites, fertile agricultural land and populous cities. Egypt mainly depends on the Nile water for agricultural irrigation and economic use (Agoubi, 2021). However, the coastal areas, where economic activities are intensifying, depend on groundwater, which ranks second in terms of water resources (Mabrouk et al., 2013). If the SLR will range between 0.5 and 1 m, large areas of the Nile Delta will likely be submerged by the sea, and the coastline will shift landinward by several kilometres (Sefelnasr & Sherif, 2014). Moreover, about 31% of the 1,200 km Red Sea coast in Egypt, mainly in the south, is highly sensitive to SLR (Hereher, 2015). This includes coastal flats, estuaries and bays over which most coastal cities, harbors and resorts are located. Similarly, in Turkey, numerous coastal cities and villages are located within the 0–10 m elevation zone and are vulnerable to SLR (Kuleli, 2010). In terms of potential land loss, the Mediterranean coast of Turkey is the most vulnerable, with islands of the Eastern Mediterranean being particularly affected. In case of moderate SLR (~0.25 m), about 80% of the beaches in eastern Crete, Greece, are predicted to retreat by more than 20% (Monioudi et al., 2016). In the worst-case scenarios of a SLR greater than 1 m, almost all beaches will retreat by about 50%, while a large number of them will likely disappear. Other parts of the Middle East will also be negatively affected. For example, in Oman, coastal regions that are vulnerable to SLR account for 805 km of the coast, mostly along the Al-Batinah plain in the north of the country (Hereher et al., 2020). Major settlements and key infrastructures (water desalination and power production plants, harbors, and refineries) are located along this coastline. In the United Arab Emirates and Abu Dhabi in particular, nearly all human settlements are concentrated along the coastlines. In a scenario of 0.5 m SLR, about 1.5% of the urban areas will be affected (Ksiksi & Youssef, 2012). This percentage will increase tenfold if the SLR would reach 2 m. Besides infrastructure and human activities, the projected SLR scenarios for this century will deeply affect the fragile coastal ecosystems of the Eastern Mediterranean, especially within the context of more intense drought stress, increased human activities and diminished sediment supply by local rivers (Kaniewski et al., 2014). For example, mangrove forests and plantations in the Gulf region (e.g., in the United Arab Emirates) have significant ecological, social and economic value (Ksiksi & Youssef, 2012). These coastal ecosystems are expected to be significantly affected by the projected SLR.

6.4. Human Security and Conflicts

Climate change can challenge human security by (a) undermining livelihood, culture and human rights, (b) increasing migration, and (c) indirectly influencing armed conflict (Koubi et al., 2020). Climate-driven limitations in water and other resources (e.g., due to prolonged drought events) are found to directly or indirectly trigger or augment disputes and conflicts in the region (Gleick, 2014; Kelley et al., 2015). However, their relative importance, in comparison to other causes, remains controversial. The projected climate changes will likely further increase regional energy demand and may lead to reduced crop yields. Such impacts will increase the existing social contrasts between populations in the region, potentially increasing food insecurity, prices and contributing to malnutrition. Such changes can drive political tensions and instabilities that may ultimately lead to conflicts and humanitarian crises. Regional economic, political, demographic, and social drivers, as well as climate-related environmental stressors (including SLR, droughts, extreme heatwaves, or vector-borne diseases), could contribute to migration flows, with climate change acting as a push factor (Abel et al., 2019; Black et al., 2011; Lelieveld et al., 2016; Tabari & Willems, 2018). The scale and geographic scope of such population displacements could be one of the greatest human rights challenges of our time (Koubi et al., 2020). Migration is not solely driven by climate change but by a combination of environmental, socio-economic, cultural and political factors (Boas et al., 2019). Historically, in the arid to semi-arid areas of the Middle East, such changes have been drivers of human settlement and population migrations (Kaniewski et al., 2012). In historical times, migration may have been the only adaptation option. The additional stress from climate change to prevailing conflicts between countries and populations may have dire consequences for weakened populations, also in refugee camps, exposing them to high risks and contributing to migration, with the associated suffering from malnutrition, poor sanitation and a lack of medical and mental support infrastructure.

7. Adaptation Options and Policy Recommendations

As shown by the assessment of multiple future scenarios in this review, the magnitude of changes strongly depends on the trajectory of greenhouse gas emissions and concentrations, also associated with the presence of natural or anthropogenic particulate matter in the ambient air. This is also the case for the impacts on public health, well-being and several socio-economic activities. Since the EMME region is becoming an increasingly significant global greenhouse gas emitter (mainly for CO_2 and CH_4), decarbonization actions should be rapidly implemented to alleviate the regional impacts of climate change, which are otherwise potentially devastating.

For the countries of the EMME, particular emphasis should be put on decarbonizing the energy and transportation sectors, which dominate regional CO_2 emissions. A significant reduction in energy use and the decarbonization of energy production through renewables are required to achieve these goals, nevertheless, this transition is challenging since the economies of several countries of the region are mostly based on fossil fuel exploitation, while the direct and indirect linkages between economic output and emissions of GHGs need to be fully understood (Giannakis et al., 2020; Giannakis & Zittis, 2021). In terms of technical and economic feasibility, key options for the region include photovoltaics, wind power, and concentrated solar power (Azouzoute et al., 2020; Ciriminna et al., 2019; Hadjipanayi et al., 2016; Shawon et al., 2013). Demand-side measures aiming toward energy conservation and improvements in energy efficiency (e.g., in industry, transportation and buildings) are equally important (Riahi et al., 2017). Additionally, measures in the agricultural sector could support the reduction of CH_4 and N_2O emissions from various sources, including livestock and fertilisers (Riahi et al., 2017).

Besides substantial decreases in emissions, carbon dioxide removal technologies need to be developed and applied to reach net-zero or negative emissions. Existing and potential measures include afforestation and reforestation, land restoration and soil carbon sequestration, direct air carbon capture and storage, enhanced weathering and ocean alkalinization (IPCC, 2018). Relevant technologies differ widely in terms of maturity, potential, cost, risks, co-benefits, and trade-offs. For example, afforestation is considered a cost-effective and readily available climate change mitigation option; however, the arid regions of the Middle East have limited potential as forest growth rates are very low (Doelman et al., 2020). Several Middle Eastern countries have experimented with carbon capture, utilisation and storage, also with oil recovery and industrial facilities, and the integration of energy with other industries (other than oil and gas) (H. Liu et al., 2012; United Nations Economic and Social Commission for Western Asia (UN-ESCWA) et al., 2017). However, none of these applications has been demonstrated to offer the needed gains at the desired scale.

Because of the long lifetimes of most GHGs in the atmosphere, the warming due to anthropogenic emissions will persist for centuries to millennia and continue to cause long-term changes in the climate system. Even if emissions were reduced in the short term, some global warming implications would persist, at least for the coming decades and most likely for the rest of the century. Countries in the EMME have no choice but adapt as environmentally harsh conditions become more challenging and potentially societally disruptive. Making transformational changes toward climate-resilient development will, nevertheless, provide a wider window of opportunity to adapt (IPCC, 2022).

The limited water resources of the region will likely be further reduced. Demand is expected to increase, driven by the growth of population and food production, temperature increases and precipitation changes. Adaptation solutions include the use of non-conventional water resources, the treatment of wastewater, rainwater harvesting for irrigation, policies to reduce water demand, improved leakage detection in urban water distribution systems and more (Charalambous et al., 2019; Lange, 2019; Qadir et al., 2007; Rockström et al., 2010). Water resources, in particular, are frequently managed on a national basis, while cross-border river basins (e.g., the Tigris-Euphrates, Nile and Jordan rivers) additionally require international cooperation (Chenoweth et al., 2011). Some of these rivers are managed partially through international treaties; nevertheless, international cooperation should be maintained and enhanced to increase climate resilience in the region. Adaptation solutions for food production include the introduction of more heat- and water-stress-tolerant cultivars, shifting planting dates, and the adoption of sustainable farming and irrigation, such as saline agriculture in the Nile river delta. Such agro-ecological techniques could increase cropland productivity and satisfy future demand for food in the region (Adamides et al., 2020; Daliakopoulos et al., 2017; Lange, 2019; Malek & Verburg, 2018; Rockström et al., 2010; Tzounis et al., 2017; Walter et al., 2017).

Dust-induced radiative forcing is a regulating climatic factor. The strong interrelation between climate change, dust and precipitation trends over the Middle East calls for further investigations of climate scenarios that may modify this interrelation in the future. Implementing restoration and afforestation projects in suitable areas could reverse land degradation with a possible synergistic improvement of air, soil and water quality, to improve human health and societal indices in the Middle East (Emamian et al., 2021). For the Eastern Mediterranean environments, such restoration projects include mountain terrace rehabilitation, crop diversification and afforestation of abandoned and degraded land (Camera et al., 2018; Zoumides et al., 2017).

Around the world, extreme weather events are progressively becoming the new normal (Singh & Zommers, 2014). This is especially the case for parts of the EMME region, where the increasing severe weather events include droughts, heatwaves, hydro-climate extremes, storm surges, wind- and dust storms. To better cope with more severe and frequent extreme events, the development of accurate early warning systems is vital. Early warning and timely response play a major role in reducing vulnerability, limiting the casualties caused by disasters and enhancing the awareness and resilience of communities (Seng, 2012). This will be important for the EMME, where the perception of climate change and its impacts is still limited. These are key elements of climate change adaptation and disaster risk reduction and aim to avoid or reduce the damage caused by hazards, including extreme weather events and geoclimatic hazards.

Considering the strong urbanization trends in the EMME, sustainable spatial planning and the design of resilient cities are of paramount importance for alleviating the adverse effects of climate change. The synergistic impacts of global and regional warming plus the UHI effect make such measures even more urgent. The substantial coastal developments in most countries are particularly vulnerable to SLR. Adaptation solutions include urban greening, use of cool surfaces, development of sustainable public transportation, improvements in the energy and water efficiency of the built environment, green building projects, coastal erosion protection measures and more (Abubakar & Dano, 2020; Dimitriou et al., 2020; Giannakis et al., 2020; Maggiotto et al., 2021; Salimi & Al-Ghamdi, 2020; Serghides et al., 2022). Urban forestry and the planting of other vegetation could help mitigate climate change while also improving air quality and liveability, with consequent psychological and physical benefits for urban dwellers (Maggiotto et al., 2021).

8. Conclusions and Research Recommendations

We have evaluated the recent scientific literature and analyzed updated observations and regional climate projections for the EMME. We find that the region is warming almost two times faster than the global average and more rapidly than most other inhabited parts of the world. Over the past centuries, precipitation variability in the region was high, with pronounced fluctuations between drier and wetter periods. In recent decades, there are indications of a transition to a drier climate, especially in the Eastern Mediterranean. Greenhouse gas emissions in the region increased sixfold over the past decades. Today, regional emissions are comparable to those of the EU and India, and the region will shortly become one of the world dominant greenhouse gas emitters.

For the remainder of the century, climate projections indicate an overall warming of up to 5°C and more, being strongest in the summer. A strong increase in the intensity and duration of heatwaves is expected. This is a robust outcome of all climate models and scenarios. Heat extremes have the potential to become societally disruptive, especially when considering the additional impact of the UHI effect together with the expected strong urban population growth. Precipitation will likely decrease by up to 20%–30%, particularly in the Eastern Mediterranean. Business-as-usual pathways for the future imply a northward expansion of arid climate zones at the expense of the more temperate regions. Mountainous climate zones with snow will likely diminish by the end of the century. The combination of declining precipitation and strong warming will likely contribute to severe droughts. The regional mean sea level is projected to rise at a pace similar to global estimates. This would imply severe challenges for coastal infrastructure and agriculture, and could potentially lead to the salinization of coastal aquifers, including the densely populated and cultivated Nile Delta.

Virtually all socio-economic sectors will be critically affected by the projected changes, especially under strong climate forcing scenarios. Human health and well-being will be directly affected, especially among underprivileged people, the elderly, children, and pregnant women. The magnitude of climate change and impacts during the second half of the century and beyond strongly depend on greenhouse gas emission scenarios, corroborating the urgency of mitigation efforts. Immediate and effective measures are required, while local communities in urban, rural and coastal areas of the EMME will need to adapt to the increasingly challenging environmental conditions, especially heat extremes, prolonged droughts, and SLR.

While temperature projections are robust, this is mostly not the case for precipitation. Several factors contribute to modeling uncertainties, including (a) the local nature of rainfall events, (b) misrepresentation of orography and coastlines by coarse-grid climate models, and (c) sensitivity of modeled precipitation to the parametrization methods of sub-grid-scale processes (e.g., convection and cloud microphysics processes). An increase in the resolution of climate models (vertical and horizontal) will be an important step forward, yet it implies access to substantial computational resources. Improvements in the parameterization schemes for physical processes, considering the regional peculiarities and in situ measurements of atmospheric properties, are also essential. Most regional modeling efforts in the EMME region focus on the atmospheric component of the climate system. Additional components such as oceans, land and atmospheric chemistry processes are not yet sufficiently considered. The consideration of such components could eventually lead to the development of regional Earth system models, currently not available for the EMME. The region is subject to rapid urbanization. The combined effects of increased population, anthropogenic warming, UHI effect, and poor air quality will introduce additional challenges. However, the current state-of-the-art climate models do not resolve urban scales, except for a few megacities. For developing suitable adaptation strategies and solutions, the representation of urban environments in climate change projections needs to be improved substantially.

Since many of the regional outcomes of climate change are transboundary, stronger collaboration among the countries is indispensable to cope with the expected adverse impacts. Such collaborations will be vital to achieving timely mitigation targets and concurrently ensuring energy security. Educational and research institutions in the region should play a leading role in promoting collaborations, regardless of political, cultural and religious differences. Joint research activities; stronger partnerships between academic institutions; the establishment of research and innovation funding tools; the sharing of data, expertize and resources; and the promotion of climate education are recommended to enhance the adaptive capacity and climate resilience regionwide.

Data Availability Statement

No new data were used. The CORDEX-CORE climate projections are publicly available through the Earth System Grid Federation data portals (e.g., https://esg-dn1.nsc.liu.se/search/esgf-liu/). The gridded observations of the Climate Research Unit, University of East Anglia are available in Harris et al. (2020).

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