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Invited Review

Severe droughts in North Africa: A review of drivers, impacts and management

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ABSTRACT

In the last 50 years, various parts of North Africa (NAF) have suffered devastating droughts, associated with high socio-economic impacts. This arid to semi-arid region is one of the most water-scarce areas in the world. In the context of water scarcity, many studies have focused on droughts approaching their impact from different disciplines and perspectives. However, more integrative studies covering both physical and social aspects are lacking for the region. The present study reviews drought's physical and human drivers, the associated socio-economic impacts in NAF countries, actual adaptation and management options. We summarize and inter-compare management policies implemented by NAF governments to face the severity of such events. Our review highlights a contrasting vulnerability to droughts across the NAF countries, with relatively higher impacts in the western part. Studies show a lack of consistency about the observed increase in meteorological droughts severity and frequency in various regions of NAF. However, more consistent and slightly higher increases in agricultural drought intensity have been revealed, suggesting that the atmospheric evaporative demand due to the increased evapotranspiration has contributed to augmenting the severity of agricultural and ecological droughts compared to meteorological droughts. The North Atlantic Oscillation (NAO) is linked to dry and wet episodes in Northwest Africa from daily to centennial time scales. Changes in the planetary to the regional-scale circulation have been suggested to be responsible for the past and future projected drought increase. Other anthropogenic drivers, such as land use changes, increasing water demand and irrigation, strongly affect the severity of NAF droughts. The analysis of the historical events reveals extensive impacts on agriculture, employment, food security, health and internal migration. The adaptation strategies to drought include irrigation efficiency, groundwater over-exploitation and the use of non-conventional water resources such as desalinated water. Various forms of drought monitoring and early warning operate on several institutional levels under the coordination of different institutions/ministries. An improved understanding of the characteristics of droughts and their impacts in NAF countries is important to guide the transition from emergency response to more proactive policies and long-term planning, but also to assess and identify gaps in drought management capacities.

1. Introduction

Drought is recognized as a natural hazard and has attracted the attention of environmentalists, ecologists, hydrologists, meteorologists, geologists and agricultural researchers (Mishra and Singh, 2010). Droughts refer to periods with substantially below-average moisture conditions in the Earth System (Wilhite and Glantz, 1985), usually covering large areas, during which limitations in water availability result in detrimental impacts on various components of environmental systems and economic sectors (Ault, 2020; Masson-Delmotte et al., 2021; Wilhite and Pulwarty, 2017).

Many of these impacts are associated with meteorological drought (lack of precipitation), hydrological drought (low water levels in rivers, lakes and groundwater), agricultural drought (reduced soil moisture) and ecological drought (loss in plant growth). Recently, AghaKouchak et al. (2021) proposed the concept of anthropogenic drought, which accounts for both natural variation and human actions.

Various parts of North Africa have suffered devastating droughts in

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the last 50 years (e.g. Bhaga et al., 2020; Hoerling and Kumar, 2003; Swearingen, 1992). Evidence from the region suggests that droughts are among the costliest natural hazards in economic and social terms. For example, Moroccan droughts between . and 1985 caused food shortages and civil unrest and drove Morocco's foreign debt to 80% of its gross national product (Swearingen, 1992). The most recent high-impact drought, which occurred in the years 2015–2016, had an impact on all NAF countries and significantly decreased cereal production in Algeria, Morocco, and Tunisia (Bazza et al., 2018), which had an impact on national budgets, export revenues, and import costs (OECD, 2017). All countries of this region are susceptible to drought, but the severity and particularly the impacts vary from country to country. Agriculture in the region is particularly vulnerable to drought, with severe consequences on food supplies and livelihoods, being the most impacted by drought of all economic sectors (Bazza et al., 2018; Schilling et al., 2012). Furthermore, the impacts of drought are prone to be exacerbated by growing water demand due to rapid population increase, strong urbanization trends and climate change (Seneviratne et al., 2021).

In this context, NAF has been the focus of numerous studies in recent years. Global reviews have shown that an overall increase in dryness over North Africa (soil moisture, streamflow, drought indices) resulting from either decreased precipitation and/or increased evaporation have been observed in the 20th century, but the spatial patterns and magnitude are partially dependent on index and calculation method (Dai, 2011, 2013; Sheffield et al., 2012). Masih et al. (2014) reviewed available data and the scientific literature related to drought events in the African continent. They show that the frequency, intensity and geospatial coverage of droughts have significantly increased across the entire continent during the second half of the 1900–2013 period, with a severe drought observed in NAF between 1999 and 2002. Reconstructions back to 1179 CE including tree-ring series for Morocco, Algeria and Tunisia have revealed large-scale regional droughts and a shift towards dry conditions over the region in the recent decades (Touchan et al., 2011). These findings are supported by regional (The World Bank, 2018; Bazza et al., 2018; Bhaga et al., 2020; Spinoni et al., 2014) and country-level studies i.e. Morocco (Ouassou et al., 2007; Zkhiri et al., 2019a), Algeria (Ballah and Benaabidate, 2021; Meddi et al., 2014), Tunisia (Abdelmalek and Nouiri, 2020), Libya (Elhaj et al., 2022) and Egypt (Mabrouk et al., 2020). Most of these studies investigate one or more drought-related subjects i.e., the study of spatiotemporal droughts in a country or in a regional perspective focusing on meteorological droughts using long-term precipitation trends or precipitation-based drought indices, or the impacts of droughts on water resources and agriculture.

The current population of NAF is about 250 million inhabitants ("World Population Prospects - Population Division - United Nations"). Its average annual population growth rate is on average 1.8% (World Bank, 2022) and has one of the world's most rapidly expanding populations. The region is arid or semi-arid and is one of the world's most water-scarce areas aggravated by very high socioeconomic exposure to droughts, likely to be exacerbated in the future due to global warming (Gu et al., 2020). Past droughts have triggered real concern and raised awareness of the need to develop drought preparedness and mitigation strategies. North African countries struggle to enhance their capacities to formulate and implement these strategies with the help of local and international experts, as well as to develop tools and action programmes that integrate drought into the water management policy of each country. Advances are urgently needed on multiple fronts of drought mitigation, including early warning and forecasting, building social resilience, short-term relief efforts, and long-term planning and capacity building. Detailed analysis of drought events and their careful understanding offer opportunities to implement better drought management plans (Vicente-Serrano et al., 2012).

Based on the evidence for local and regional droughts (in the Mediterranean or Africa), there is an urgent need for an appropriate overview of drought studies in NAF. In-depth analysis and discussion of physical conditions, as well as societal, governmental, and stakeholder actions to avert drought impacts are addressed in this study. A thorough analysis of the literature could aid in gathering regional knowledge on the factors that lead to droughts, their impacts, and the mechanisms by which societies and governments respond and contribute to them. We intend to present an update of this knowledge, taking into account the diversity of methods, results and perspectives across disciplines and stakeholders interested in drought in this region.

The studies of Waha et al. (2017) and Schilling et al. (2012) are two examples of a very limited body of integrative literature covering both physical and social aspects of climate change and vulnerability in NAF. To our knowledge, no similar study has addressed drought in this region in such an integrative manner. The present review contributes to this literature by assessing various aspects of drought in NAF. Based on the available literature, past drought events will be reviewed, their natural and anthropogenic causes explained, their impacts discussed, as well as the governmental responses towards drought monitoring, preparedness and mitigation presented. Our sole intention is to present a framework for an integrated assessment of drought in a water-scarce region, and show some of the challenges faced by the governments to propose solutions to their vulnerable populations. For this purpose, our literature review is based on a selection of scientific literature, reports, working papers or government documents and available data relevant to describing all aspects of drought in NAF.

This article is organized as follows: Section 2 presents the geographical and the climatological features of the region, while Section 3 addresses the driving mechanisms of drought in NAF. Section 4 presents the atmospheric circulation drivers, Section 5 the climate variability and teleconnections. Sections 6 and 7 present a catalogue of historical drought events, and the compound drought and heat events respectively. Section 8 discusses past changes and future projections of regional drought. Section 9 focuses on the drought impacts, while Section 10 on adaptation options. Section 11 discusses the drought risk assessment, Section 12 the drought management with an emphasis in Section 13 on the water management options and in Section 14 by the drought management policy. Finally, Section 15 discusses the drought monitoring and forecasting in the region followed by conclusions and research gaps for future studies.

2. Study area

NAF is a region encompassing the northern part of the African continent. There is no singularly accepted definition for the region, and it is sometimes defined as stretching from the Atlantic shores of Mauritania in the west, to Egypt's Suez Canal and the Red Sea in the east. The United Nations definition includes Morocco, Algeria, Tunisia, Libya, Egypt and Sudan. This review focuses on the five northernmost African countries and will be referred to as "North Africa": Morocco, Algeria, Tunisia, Libya, and Egypt. The countries in NAF are grouped in terms of proximity, climate, and hydrology because of their geographical proximity along the North African coast and its environmental characteristics. They also share similar demographic, political, social, cultural and economic structures.

NAF has four main geographic features: the Mediterranean Sea to the North, the Sahara Desert in the south, the Atlas Mountains in the west, and the Nile River in the east. The Atlas Mountains extend across northern Algeria, Morocco and Tunisia, reaching an elevation of 4167 m above sea level in Toubkal in central Morocco. The Sahara Desert covers >75% of the region.

The region is characterized by a Mediterranean climate along a thin strip of land bordering the coasts of Morocco, Algeria, Tunisia, and parts of Libya, with mild, wet winters and warm, dry summers (Csa and Csb climate types in the Köppen–Geiger climate classification system, see Fig. 1) with rainfall of approximately 400 to 600 mm per year. Inland, North African countries have predominantly semi-arid (BSh, BSk) and arid desert climates (BWh and BWk) that regularly display extreme

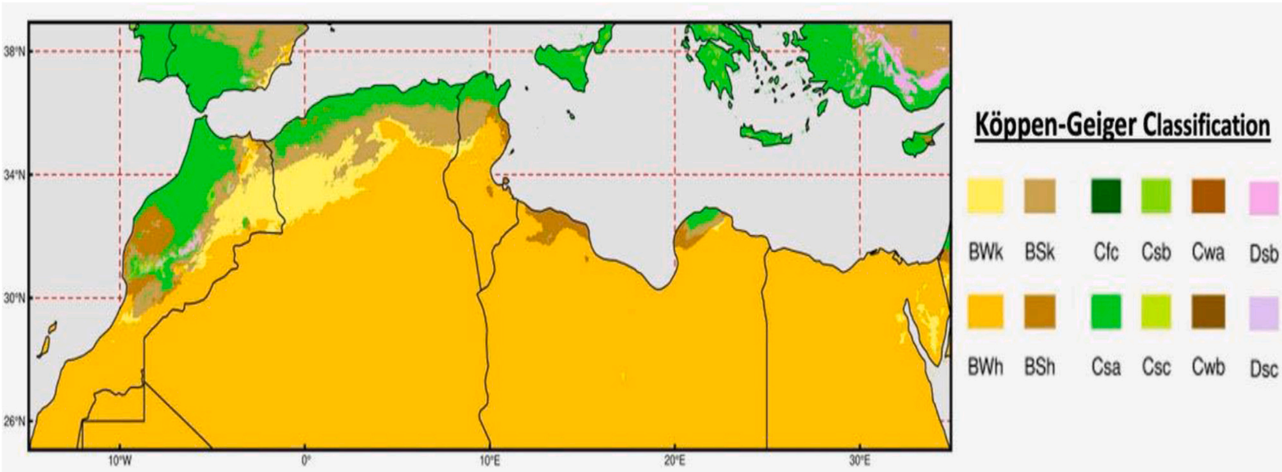

Fig. 1. Climate types over North Africa based on the Köppen–Geiger climate classification system, 1980–2016 (Data source: Beck et al., 2018).

conditions with scorching summers, cold winters, and little rainfall, between 200 and 400 mm per year and < 100 mm per year for desert regions (Babaousmail et al., 2021; Djebbar et al., 2020).

3. Driving mechanisms of drought in NAF

Atmospheric drivers of drought involve thermodynamic processes through heat and moisture exchanges and dynamic processes through atmospheric and oceanic motions. Thermodynamic processes contribute to drought via AED (Haile et al., 2020; Vicente-Serrano et al., 2020b) which is a function of air temperature, radiation, wind speed, and relative humidity. Dynamic processes contribute to droughts via modulating the occurrence, duration and intensity of circulation patterns. While AED generally increases with global warming, regional changes are subject to complex interplay and combined influences of changing land-ocean warming contrast, vegetation feedbacks, regional changes in atmospheric circulation patterns, and internal climate variability (Byrne and O'Gorman, 2015).

In addition to the above-mentioned physical drivers, the anthropogenic influences including anthropogenic climate change and human activities play an important role in enhancing droughts through feedbacks between the growing population and its increasing water demand, and changes in vegetation cover due to land use changes (Van Loon et al., 2016a). These feedbacks exert direct and indirect influences on drought occurrences and create uncertainties for the characterization and prediction of droughts in the future (Tramblay et al., 2020). Fig. 2, presented by (Van Loon et al., 2016a), summarizes the drought propagation in the Anthropocene where the propagation from meteorological drought to soil moisture and hydrological drought (black arrows) is triggered by physical and human drivers. The yellow color depicts the physical drivers, droughts and impacts, while the red-brown the human ones. Drought is modified by hydrological catchment processes that are altered by human activities such as land use changes, irrigation, dam building and groundwater abstractions.

The following sections review the physical drivers of droughts such as the atmospheric circulation patterns, the climate variability modes

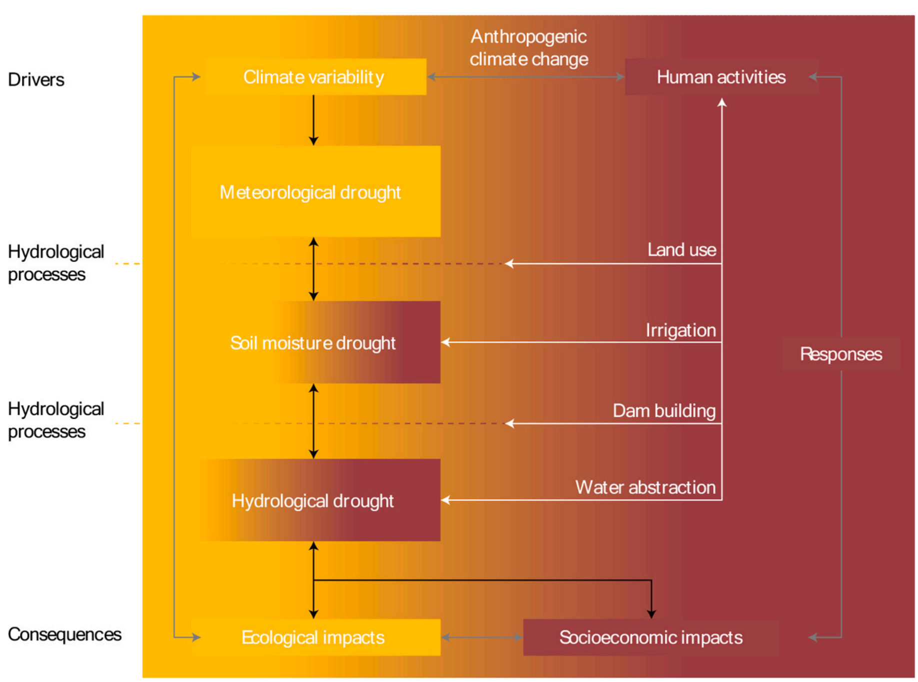

Fig. 2. Drought propagation in the Anthropocene (Van Loon et al., 2016b).

and teleconnections, their changes in the past and projected future, and the physical mechanism of drought increases. This will be followed by the anthropogenic drivers of drought as summarized by Fig. 2.

4. The atmospheric circulation

The atmospheric circulation over NAF is dominated by a mid-tropospheric subtropical anticyclone with the intertropical convergence zone (ITCZ) to the south and the midlatitude storm track to the northwest. Owing to the seasonal cycle of the large-scale circulation, much of North Africa's coast has a Mediterranean climate with hot and dry summers, and temperate, wet winters (Seager et al., 2019). In summer, the center of the subtropical ridge reaches around 25°N and is associated with a pronounced anticyclonic circulation and large-scale subsidence in the middle and upper troposphere, causing dry and hot conditions throughout the region (Fig. 3 – left panel). This circulation pattern results primarily from the remote influence of the South Asian monsoon through a Rossby wave response; the so-called monsoon-desert mechanism (Rodwell and Hoskins, 1996, 2001; Tyrlis et al., 2013). During this season, the midlatitude westerlies are relatively weak and rain bearing extratropical weather systems over the North Atlantic are displaced to the north. The West African monsoon system dominates to the south and the tropical rain belt reaches up to about 20°N, just south of the region of interest. During the cool season, from November to April, the region resides under the downward branch of the Hadley Cell circulation, also leading to dry conditions. However, the subtropical anticyclonic ridge is displaced south along with a strengthening of the midlatitude storm track over the North Atlantic (Fig. 3 – right panel), allowing transient extratropical weather systems to reach northwest Africa. During the winter season, the storm track also appears over the Mediterranean Sea, one of the global hotspots for cyclogenesis (Wernli and Schwierz, 2006).

The atmospheric circulation patterns associated with drought in the region can arguably be best described by the prolonged absence of rainfall-producing weather systems over the region. An early study by Chbouki et al. (1995) speculated that dry and moist conditions in Morocco were linked to (i) the Azores High over the Atlantic, (ii) local cyclogenesis to the southwest, and (iii) pressure perturbations from the Mediterranean to the northeast, later confirmed by Knippertz et al. (2003b). Indeed, weather systems that produce rainfall over NAF vary substantially across the region. The Atlantic coast of northwest Africa receives most rainfall from extratropical weather systems such as extratropical cyclones, fronts, and so-called atmospheric rivers, contributing up to 30–40% of annual precipitation and up to 70% of winter precipitation (Catto et al., 2012; Guan and Waliser, 2015; Hawcroft et al., 2012).

Several regions on the leeside of orographic barriers or farther south into the interior of the continent reside beyond the reach of extratropical weather systems. Sporadic precipitation in these semi-arid to hyper-arid regions often results from so-called tropical-extratropical interactions in the form of tropical cloud bands or local convection (Knippertz, 2007; Knippertz et al., 2003a; Knippertz and Martin, 2005). The much wetter Mediterranean coast - from northeast Morocco to Egypt - receives precipitation from Mediterranean cyclones (Flaounas et al., 2022 and references therein) and upper-level troughs (Argence et al., 2006, 2008; Funatsu et al., 2008, 2009), primarily during the cool season. In summer, the northwest African coast can also receive sporadic precipitation from local convection storms that often form over high topography and in the absence of distinct synoptic-scale weather systems.

Tropical weather systems, such as monsoon lows/depressions and African easterly waves, contribute to precipitation in the southern margins of the region - up to 20°N - during the summer season (Crétat et al., 2015; Hurley and Boos, 2015).

5. Climate variability and teleconnections

Several climate variability modes influence drought and rainfall variability in NAF. The most prominent one is the North Atlantic Oscillation (NAO), and to some lesser extent the atmosphere-ocean coupled El-Nino Southern Oscillation (ENSO). The NAO has a strong linkage to the weather and climate in the western part of NAF, which ceases, and according to some studies, even reverses over the eastern part of NAF, while ENSO has a relatively strong influence in the eastern part of NAF (Donat et al., 2014; Mathbout et al., 2018).

The NAO is defined by large-scale fluctuations of air mass, i.e., sea level pressure, between the Azores High and the Icelandic subpolar low (Hurrell et al., 2003). Lamb and Peppler (1987) were the first to show a negative correlation between the NAO and precipitation in northwest Africa at interannual timescales. Since then, this relationship has been confirmed by numerous studies on monthly (Knippertz et al., 2003b), annual (Djebbar et al., 2020; Mathbout et al., 2020; Seager et al., 2019), decadal (Hurrell, 1995; Mariotti and Dell'Aquila, 2012; Xoplaki et al., 2004), and likely, even centennial timescales (Cook et al., 2016; Touchan et al., 2011). Also, at a country-based level, the relationship

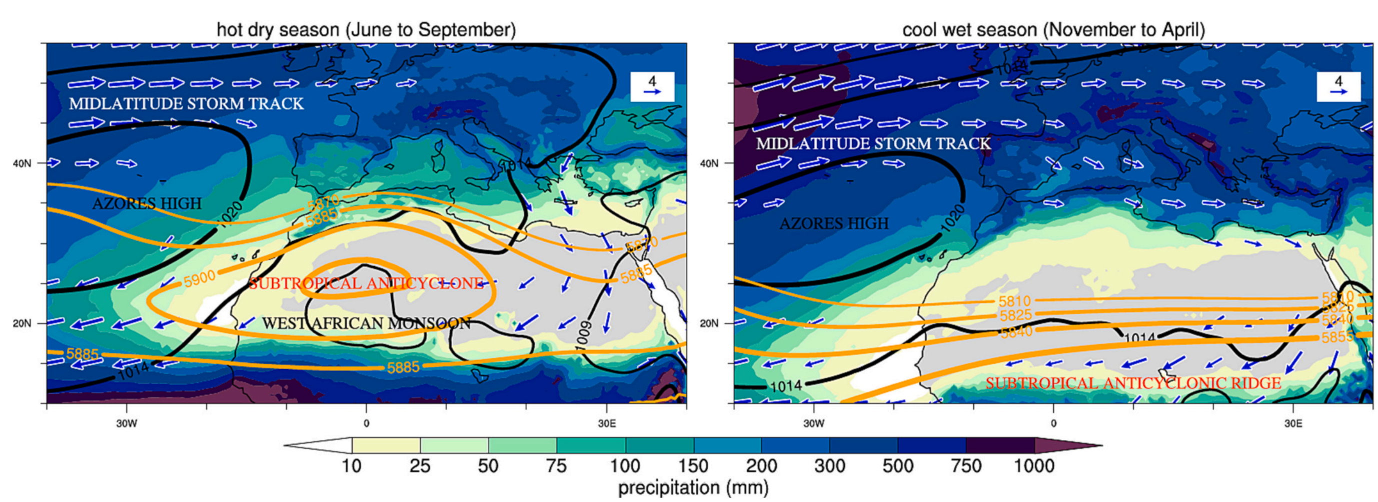

Fig. 3. Precipitation and the atmospheric circulation over NAF during (left) the hot dry summer season, June–September, and (right) the cool wet season, November – April. The data is based on monthly means from ERA5 for the period 1979–2021 and shows accumulated precipitation (mm; shading) and the average monthly means of sea level pressure (hPa; black contours), 500-hPa geopotential height (gpm; orange contours), and the 850-hPa horizontal wind (m s^{-1}; blue vectors where its magnitude >4 m s^{-1}). The atmospheric circulation patterns noted in the figure are discussed in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

between NAO and the hydrological cycle has been demonstrated using observations of precipitation and streamflow in different parts of Morocco (Turki et al., 2016; Zamrane et al., 2016) and northwest Algeria (Meddi et al., 2010; Taibi et al., 2017). A positive (negative) NAO phase favors dry (wet) conditions over northwest Africa through a northward (southward) displaced storm track over the Atlantic going along with reduced (enhanced) westerly winds and moisture transport towards the northwest African coast (Hassan and Nayak, 2020; Hurrell, 1995; Knippertz et al., 2003b; Mariotti and Dell'Aquila, 2012; Touchan et al., 2011; Xoplaki et al., 2004). Consistent with the past drying trends observed over NAF (see section 3.1), the NAO increased during the recent decades, and is projected to further increase in the 21st century (Kelley et al., 2012a).

ENSO has a seasonally varying influence on precipitation in northwest Africa. The warm ENSO phase, El-Nino, is associated with increased (decreased) northwest African rainfall in autumn (spring) season preceding (following) the mature phase of an ENSO event (Knippertz et al., 2003c; Mariotti et al., 2002). This relationship has undergone substantial multidecadal changes during the 20th century with a weakly significant or insignificant relation in the early to mid – 20th century and a stronger, significant relation in the 2nd half of the 20th century. The influence of ENSO manifests by an anomalous atmospheric circulation and moisture transport extending from the Atlantic into the Mediterranean region event (Knippertz et al., 2003c; Mariotti et al., 2002), however, the mechanism as to how the remote ENSO influence impacts the regional atmospheric circulation over NAF remains unclear.

Other, less discussed atmospheric oscillation patterns that influence the hydrological cycle over the region are the Mediterranean Oscillation (MO), the western Mediterranean Oscillation (WeMO), the Scandinavian Pattern (SCAND), the Eastern Atlantic (EA) pattern, and the East Atlantic/West Russia (EAWR) pattern, see also Dünkeloh and Jacobeit (2003), Taibi et al. (2017), Mathbout et al. (2020, 2018), and Djebbar et al. (2020). The role of sea surface temperature (SST) anomalies on climate variability over NAF remains somewhat unclear. Interannual precipitation variability over the Mediterranean, including North Africa's coast, did not relate to substantial SST anomalies across the globe (Seager et al., 2019) nor in the Mediterranean Sea specifically (Xoplaki et al., 2004). However, time-lagged and seasonal analyses suggested that summer SST anomalies of the North Atlantic are followed by anomalous winter precipitation in northwest Africa (Rodriguez-Fonseca and de Castro, 2002), while SST anomalies in the remote Pacific and Indian Oceans have been associated with northwest African rainfall anomalies in specific seasons, being autumn and spring (Mariotti et al., 2002) and winter (Touchan et al., 2011).

6. Historical drought events

Droughts propagate into the entire socio-economic and environmental systems, provoking a cascade of impacts. Such impacts are a result of the drought hazard and an underlying vulnerability of the systems. Subjective and systematic documentation is needed to contextualise historical drought events by impacts and responses and put into perspective the current understanding of the intensity of recent drought hazards.

Several methods have been used to identify past drought events in the region: reconstruction of drought indices using tree rings (see above), the EM-DAT database (The International Disaster Database from the Centre for Research on the Epidemiology of Disasters) which provides country and regional estimates of drought events, people killed and affected and economic damage (Masih et al., 2014) and more recently geospatial data (Bhaga et al., 2020). We use these sources to identify a timeline of drought events, combining all types of droughts and their occurrence and impacts.

Table 1 provides a summary of historical drought events recorded in the EM-DAT database and the scientific literature for North Africa as

Table 1
Occurrence and impacts of major recorded droughts in North Africa from the 1900 to 2020 based on scientific literature (Bazza et al., 2018; Bhaga et al., 2020; Masih et al., 2014).

Country	Number of Events	Drought Years	Droughts impacts
Algeria	2	1981; 2005	Recorded in EM-DAT database. (Masih et al., 2014)
	5	1910–1920; 1945–1947; 1973–1980; 1981–1983; 1999–2002	90% loss of livestock in 1945; decrease in groundwater levels, shallow wells, dry springs, wildfires, crop loss, and production loss causing famine in 1966 (Bhaga et al., 2020)
	14	1910–1920; 1922; 1937 1939–1948; 1945–47; 1961; 1970; 1977–1978; 1975–1998; 1981–84; 1988–1990; 1993–1995; 1997; 1999–2002;	- 'Year of hunger' described by Albert Camus, 3000 deaths south Oran (1945–1947) - Water shortage in major urban centers, such as Algiers and Oran in 2002 (Bazza et al., 2018)
Egypt	4	1972–1973; 1978–1987; 1990–2002; 2010–2011	Unemployment rates increased, as 55% of the population were employed by the agricultural sector and riparian vegetation was severely affected. (Bhaga et al., 2020)
	10	1972; 1979; 1982; 1983; 1984; 1986; 1987; 1990; 2002; and 2010	(Bazza et al., 2018)
Libya	3	1945; 1950s; 1960s	The 1945 drought led to loss of cattle. Details are not available (Bhaga et al., 2020)
Morocco	8	1917–1920; 1930–1935; 1945–1950; 1981–1984; 1991–1995; 1999–2003; 2015–2016; 2018	Disruptions in water supply, agricultural sector, and cereal production. In 1999, approximately 275,000 people were affected, and economic damages were $900 million. (Bhaga et al., 2020)
	5	1966; 1971; 1983; 1984; 1999	Recorded in EM-DAT database. (Masih et al., 2014)
	19	1931; 1945; 1957; 1966; 1975; 1981; 1982; 1983; 1984; 1987;1992;1993; 1994–1995; 1996–1997; 1998–1999; 1999–2000; 2000–2001; 2000–2005; 2006–2007	- General; Reduced incomes due to drought caused GDP to fall by 7.6% in 1995. Cereal production fell from 9.5 million tons in 1994 to 1.6 million tons in 1995. - Reduced incomes due to drought caused GDP to fall by 2.3% in 1997 - Reduced incomes due to drought caused GDP to fall by 1.5% in 1999 - 275,000 people affected. Economic Damages: USD 900 million (1999–2000) - The country imported about 5 million tons of wheat in 2001 (compared to 2.4 million tons in normal years) - Reduced economic growth rate from 3.5 to 1.3% for 2005 - 700,000 people affected. Grain production reached

(*continued on next page*)

Table 1 (*continued*)

Country	Number of Events	Drought Years	Droughts impacts
			only half of the normal year's levels (Bazza et al., 2018) and references therein
Tunisia	6	1961–1969; 1987–1988; 1993–1995; 1999–2002; 2000–2008; 2015–2016	Disruption in water supply, increase in salinity in water retentions, and decreased production of grains and forages. (Bhaga et al., 2020)
	2	1977; 1988	Recorded in EM-DAT database. (Masih et al., 2014)
	2	1920s; 1940s; 1960s and 1980s; 1944–1948; 2000–2008; 2002	(Bazza et al., 2018)

reported by Masih et al. (2014) for the period 1900–2013. No new events were found since 2014 from EM-DAT. This has been completed by the review of Bhaga et al. (2020) of relevant reports on droughts and their impacts that were published between 1900 and 2020 covering North African countries based on remote sensing using several drought indicators. Additionally, (Bazza et al., 2018) is a review of drought characteristics and management in Middle East-North Africa, reporting drought events and their impacts based on country reports and their own expertise related to agriculture.

Caution is required while using these sources due to several limitations. First, in EM-DAT, a much lower number of droughts are recorded for NAF in comparison to other regions of the world. Furthermore, no information is available for many recorded drought events on their impacts (Masih et al., 2014). Second, Bhaga et al. (2020) is a systematic review of remote sensing studies based on mostly meteorological and hydrological indices, while the reported impacts mostly describe agricultural losses not associated with specific drought events. Third, the events reviewed by Bazza et al. (2018)refer to events or periods of rainfall deficits with drought periods affecting one or several regions or generalized to the whole country; and with their duration ranging from one month or season to one year or more. The reported impacts are related to one subregion or watershed over one season or more seasons (for example, the rainy season over two subsequent years), and not the whole country. Further, drought declarations differ among countries, according to the drought management policy. For example, in Egypt, droughts and floods are sometimes declared even when total rainfall or the number of days receiving rain is not very anomalous. This can occur when seasonal rainfall is grossly unevenly distributed over the season, with longer than average dry or wet spells (Nada et al., 2014).

Most NAF countries observe single and multi-year droughts described from a hydroclimatic perspective. While the observed drought events in the Maghreb countries (Morocco, Algeria, Tunisia and partly Libya) are directly related to precipitation deficit and its impacts on surface water and agriculture, drought events in Egypt are explained by fluctuations of the Nile flows, primarily dependent on rainfall fluctuations over the Ethiopian highlands (Mabrouk et al., 2020).

While drought events are more frequently reported after the 1960s for all countries (except for Libya), Morocco shows the highest number of events and reported impacts, followed by Algeria. The drought period 1999–2004 is commonly reported for all NAF countries except Libya (Morocco, Algeria, Tunisia and Egypt), while the droughts of 1943–1945 and 2015–2017 mainly affected Morocco and Algeria. Impacts, as observed by Table 1, will be discussed in detail in Section 9.

7. Compound drought and heat events

The term "compound extremes" refers to the combination of multiple extreme events or multiple drivers that lead to an extreme (Hochman et al., 2022). Compound "hot–dry" events or "co-occurring hot and dry extremes" frequently cause damage to human and natural systems, often exceeding separate impacts from heatwaves and droughts (De Luca et al., 2020). Throughout the Mediterranean, summertime maximum temperature and precipitation have become more strongly coupled over the last 40 years and the persistence of warm–dry days has increased (De Luca et al., 2020). A possible physical process driving increasing coupling with increasing temperature is soil drying. The number of compound warm spells and droughts increased significantly in the Mediterranean Basin over the last four decades, while Morocco is identified as a hot-spot of co-occurring events (Vogel et al., 2021). The main driver of the increasing number of compound warm spells and droughts in the region is the rising temperature and not the lack of rainfall. Extreme temperature projections for the region are quite robust (Lelieveld et al., 2016; Zittis et al., 2021b). Therefore, projections for future compound hot–dry events are mainly constrained by more uncertain precipitation trends (Bevacqua et al., 2022). Nevertheless, given the fact that for parts of NAF (e.g., Morocco), there is higher confidence for a future decrease in precipitation (e.g., Zittis et al., 2019), we expect an increase in the occurrence and impacts of such compound events.

8. Past changes and future projections

North Africa has experienced several dry periods during the last millennium, some with persistent pan-Mediterranean characteristics (Cook et al., 2016). Droughts have increased in the recent past, specifically during the last few decades of the 20th century (Hoerling et al., 2012). The latter half of the 20th century emerged as the driest among the previous nine centuries (Touchan et al., 2011).

Negative trends in mean precipitation were evident over most of NAF between 1971 and 2000 (Donat et al., 2014; Driouech et al., 2013; Nicholson et al., 2018; Tanarhte et al., 2012; Zittis, 2018; Zkhiri et al., 2019b). The frequency of days with >10 mm of rainfall has decreased, and positive trends in the number of consecutive dry days are evident in the eastern parts of the region (Donat et al., 2014). Since the early 2000s, there has been a gradual recovery to normal or wetter-than-normal conditions in Algeria and Tunisia, which has also been observed over Morocco since 2008 (Nouaceur and Murărescu, 2016). However, historical precipitation trends are not statistically significant over the whole domain, as pointed out in Tanarhte et al. (2012), Lelieveld et al. (2016), Filahi et al. (2016) and show pronounced variability within the region, with magnitude and sign of trend in the past century depending on time period (Donat et al., 2014; Mathbout et al., 2018; Seneviratne et al., 2021; Zittis, 2018). Past trends in precipitation have been attributed to internal climate variability, that is, interannual and decadal variability, and anthropogenic radiative forcing, whereby the latter is expected to dominate trends in the future (Hoerling et al., 2012; Kelley et al., 2012a).

Numerous indices, based on different variables, have been developed to identify and quantify drought events. These include, for example, the Standardized Precipitation Index (SPI) (McKee et al., 1993) used to assess meteorological drought, the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), the Palmer Drought Severity Index (PDSI) (Palmer, 1965), used for agricultural drought assessment and many other indices depending on the type of drought and the geographical context. The SPI is the most applied index to analyze meteorological drought defined as temporary lower-than-average precipitation.

An increase in meteorological drought severity and frequency in various countries and regions of NAF was suggested by multiple studies using SPI (Caloiero et al., 2018; Donat et al., 2016; Driouech et al., 2021; Fniguire et al., 2017; Jemai et al., 2018; Sousa et al., 2011). However, low confidence is found for the whole region due to the contrasting signals of precipitation trends depending on the period and region considered (Cramer et al., 2020; Driouech et al., 2021; Seneviratne et al., 2021).

Streamflow data, as a measure of hydrological drought, show a drying trend over the region since the 1990s with a large internal variability due to Pacific Sea Surface Temperatures (Dai and Zhao, 2017) and a hydrological drought intensification in the Mediterranean region in general, attributed to climate change (Gudmundsson et al., 2019, 2021).

Locally, over the Atlas Mountains, several studies report a general decrease in the snow cover and increasing snowmelt, implying a changing contribution to river runoff that could impact the seasonality and magnitude of low flows in some basins influenced by snow (Marchane et al., 2017; Tramblay et al., 2020; Hanich et al., 2022).

Despite the challenges in separating the role of climate trends from changes in land use, water management and demand for changes in hydrological deficits on regional scales, the role of anthropogenic radiative forcing for trends in mean and extreme river flow over the Mediterranean might be dominant as suggested by Vicente-Serrano et al. (2014), and Gudmundsson et al. (2021). Additionally, changes in land use and terrestrial water management contributed to these trends (Teuling et al., 2019; Vicente-Serrano et al., 2019). Over NAF, water demand is already high, thus affecting water resources and, subsequently river flows (Droogers et al., 2012; Milano et al., 2013).

Studies using SPEI and PDSI suggest slightly higher increases in agricultural drought frequency and severity in NAF over the last decades in comparison to the SPI (Dai and Zhao, 2017; Spinoni et al., 2019). For example, more consistent trends in the SPEI are found for the longer periods (50–60 years) in Morocco (Driouech et al., 2021) and the Mediterranean region by Spinoni et al. (2019), which was not the case for the precipitation-based drought index (SPI).

These indices suggest that the atmospheric evaporative demand (AED) has contributed to an increase in the severity of agricultural and ecological droughts compared to meteorological droughts (Seneviratne et al., 2021) and reduced soil moisture during the dry season (Padrón et al., 2020). AED has been defined by Vicente-Serrano et al. (2020b) as the demand of water from the atmosphere (i.e., its drying or evaporating power), and a function of the state and dynamics of the atmospheric boundary layer. AED has stronger relevance to increase drought severity in arid and semi-arid regions where water limitations result in increased AED enhancing the evapotranspiration deficit with negative implications on agricultural (and ecological) drought during periods of low precipitation. In these areas, the interannual climate variability

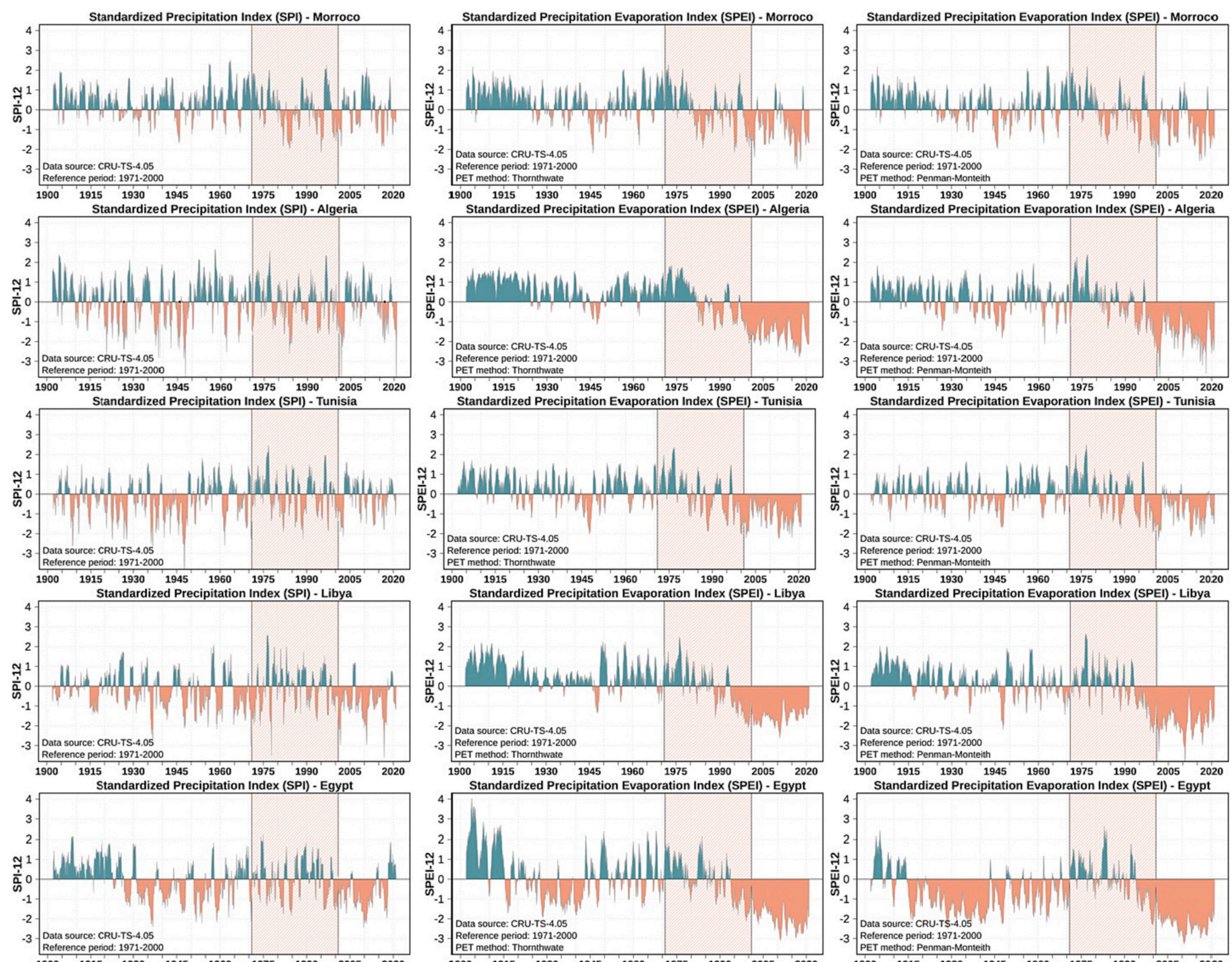

Fig. 4. Observed time series of the Standardized Precipitation Index (SPI-12 – left panels) and the Standardized Precipitation Evapotranspiration Index (SPEI-12 – middle and right panels) at 12-month accumulation periods for five North Africa countries. The SPEI-12 has been calculated using the Thornthwaite (middle panels) and Penman-Monteith methods (right panels).

determines in more depth the vegetation variability than in humid regions (Vicente-Serrano et al., 2013).

For the Mediterranean coast of NAF, studies based on global datasets indicate a historical decrease in soil moisture (Greve et al. (2014)and Greve and Seneviratne (2015)). The soil moisture drying trends identified in both global and regional studies are generally related to increases in evapotranspiration associated with higher AED rather than decreases in precipitation (Seneviratne et al., 2021).

To illustrate the sensitivity to changes in the evaporative demand, we compare both indices for the NAF countries using historical time series of the SPI-12 and SPEI-12 indices, based on average precipitation and temperature in each of the five NAF countries of focus (see Fig. 4), using the Thornthwaite and the Penman-Monteith methods for the calculation of AED (Thornthwaite, 1948; Harris et al., 2014).

These indices are based on the Climate Research Unit dataset CRU v. TS-4.05 gridded observations (Harris et al., 2020) in 12-month accumulation periods. SPIs (and SPEIs) of these time scales are tied to stream flows, reservoir levels, and even groundwater levels at prolonged time scales. The interpretation of the SPI/SPEI values is presented in Table 2. Here, we used the 30-year period 1971–2000 as a reference. Particularly in the eastern part of the region (Libya and Egypt), there is a clear transition towards drier conditions driven by precipitation variability. Considering also the effect of increasing temperature through evapotranspiration (e.g., the SPEI index) highlights the occurrence of multi-year drought conditions throughout North Africa, more pronounced in the most arid countries (Algeria, Libya and Egypt).

This is in line with the results by Vicente-Serrano et al. (2014) and Tramblay et al. (2020), which demonstrate that drought severity increases are a consequence of greater AED resulting from temperature rise, rather than substantial changes in precipitation in the long term in the Mediterranean region. Further analysis of the influence of AED on drought severity in NAF is utterly needed to fully assess the implications on different types of droughts.

Models overwhelmingly project a considerable reduction in precipitation, with enhanced drying of up to −30% to −40% in winter (December to February) precipitation over the region (Planton et al., 2012; Zittis et al., 2019; Zittis et al., 2021a). Nevertheless, the inter-model agreement and robustness of future precipitation changes are low. This becomes most evident in business-as-usual future pathways, and projections towards the end of the 21st century. In summer, significant warming and drying are also projected for northern Africa (Lelieveld et al., 2016; Zittis et al., 2019). Projections from a high-resolution global model (Barcikowska et al., 2018) suggest precipitation changes of up to −50% in some regions of Northwest Africa by the end of the 21st century.

Fig. 5 (top panel) depicts the regional precipitation changes (with respect to the 1971–2000 reference period) for various global warming levels (GWLs). This is based on regional projections for the MENA-CORDEX initiative (Zittis et al., 2021b). The highest GWLs (e.g., 3 and 4 °C since preindustrial) imply an average regional precipitation decrease of up to 20%. Keeping global warming to <2 °C (i.e. meeting the Paris Accord targets) will limit this drying (<5%) and provide wider adaptation opportunities.

The Mediterranean NAF is projected to experience longer meteorological drought duration in 2051–2100 compared to the historical baseline period with increases in drought duration from about two months during the historical period to up to four months in the future, using CMIP6 simulations. Increased drought duration and intensity are primarily driven by declines in mean monthly precipitation (Ukkola et al., 2020).

Table 2
Interpretation of the SPI and SPEI values.

SPI/SPEI Value	Interpretation
SPI (SPEI) ≤ −2	Extremely dry
−2 < SPI (SPEI) ≤ −1.5	Severely dry
−1.5 < SPI (SPEI) ≤ −1	Moderately dry
−1 < SPI (SPEI) ≤ 1	Near normal
1 < SPI (SPEI) ≤ 1.5	Moderately wet
1.5 < SPI (SPEI) ≤ 2	Severely wet
SPI (SPEI) ≥ 2	Extremely wet

Consistent with this decline in precipitation, global and regional climate models project an increase in the duration and intensity of droughts in the Mediterranean during the 21st century, based on different scenarios and metrics, with increases in meteorological droughts already at 1.5 °C of global warming, and further increases with increasing global warming (Seneviratne et al., 2021). Independently from the index used, drought is expected to increase in the region, but with a higher rate in the case of the index accounting for both the effect of precipitation and temperature changes (Driouech et al., 2021). There is high confidence that the broader Mediterranean region (including NAF) is projected to become a global drought hotspot of increased frequency and severity of droughts (Spinoni et al., 2020). For example, the Morocco Atlas Mountains and adjacent Mediterranean coast signal a dramatic increase in drought by the end-century during winter and spring, the seasons more critical for replenishing water resources (Tomaszkiewicz, 2021).

The bottom panels of Fig. 5 depict the projected changes in the number of rainy days per year (bottom-left panel) and the length of dry spells or the maximum number of consecutive dry days per year (bottom-right panel). The number of rainy days is projected to decrease by up to three days per year on average. In addition, the average length of dry spells (CDD) is expected to increase significantly, particularly for the highest GWLs (up to 40 additional days).

Future projections of surface water resources for the largest dams in the region using future climate change show that a decrease in water availability is projected for all basins under all scenarios, with a strong east-to-west gradient (Tramblay et al., 2018).

Several large-scale and regional-scale (thermo)dynamic mechanisms have been proposed to explain past and projected future drying of NAF. From a planetary scale perspective, the Hadley circulation expands poleward (Lu et al., 2007) along with a poleward shift of the midlatitude westerlies and storm track (Yin, 2005). Consequently, subtropical drylands are expected to expand (Feng and Fu, 2013; Grise et al., 2019). However, in contrast to the Southern Hemisphere, this mechanism may have reduced relevance to the Northern Hemisphere due to the pronounced land-sea contrasts and mountain ranges in this hemisphere. As a result, climatic changes show strong zonal differences with a possible wetting in southwest North America due to southward displaced westerlies, while the Mediterranean undergoes strong drying (Seager et al., 2019). It has been argued that changes in stationary waves along with intensifies upper-level subtropical westerlies (Simpson et al., 2016) lead to a strengthening and eastward shift of subtropical anticyclones over the North Atlantic and Mediterranean (Seager et al., 2019; Tuel and Eltahir, 2020), leading to enhanced drought over the Mediterranean, including NAF.

Several generations of General Circulation Models simulations consistently project a future increase of sea level pressure, anticyclonic circulation, and static stability over the Mediterranean (Giorgi and Lionello, 2008; Polade et al., 2017). This change in the regional circulation goes along with a weakening of the Mediterranean storm track and reduced Mediterranean cyclone frequencies, which is to a large extent responsible for the precipitation decline over the northwest African coast (Raible et al., 2010). Seager et al. (2014) explained these changes in the circulation by increased mean flow moisture divergence due to increased atmospheric humidity in regions of mean flow divergence and a strengthening in the mass divergence. Simultaneously with this change in the regional circulation, the Azores High is found to shift or expand eastward (Knippertz et al., 2003b; Raible et al., 2010). Land-sea warming contrasts have also been proposed as a regional driver of precipitation decline. The relatively faster warming of land than ocean may result in (i) relatively increased sea level pressure over the

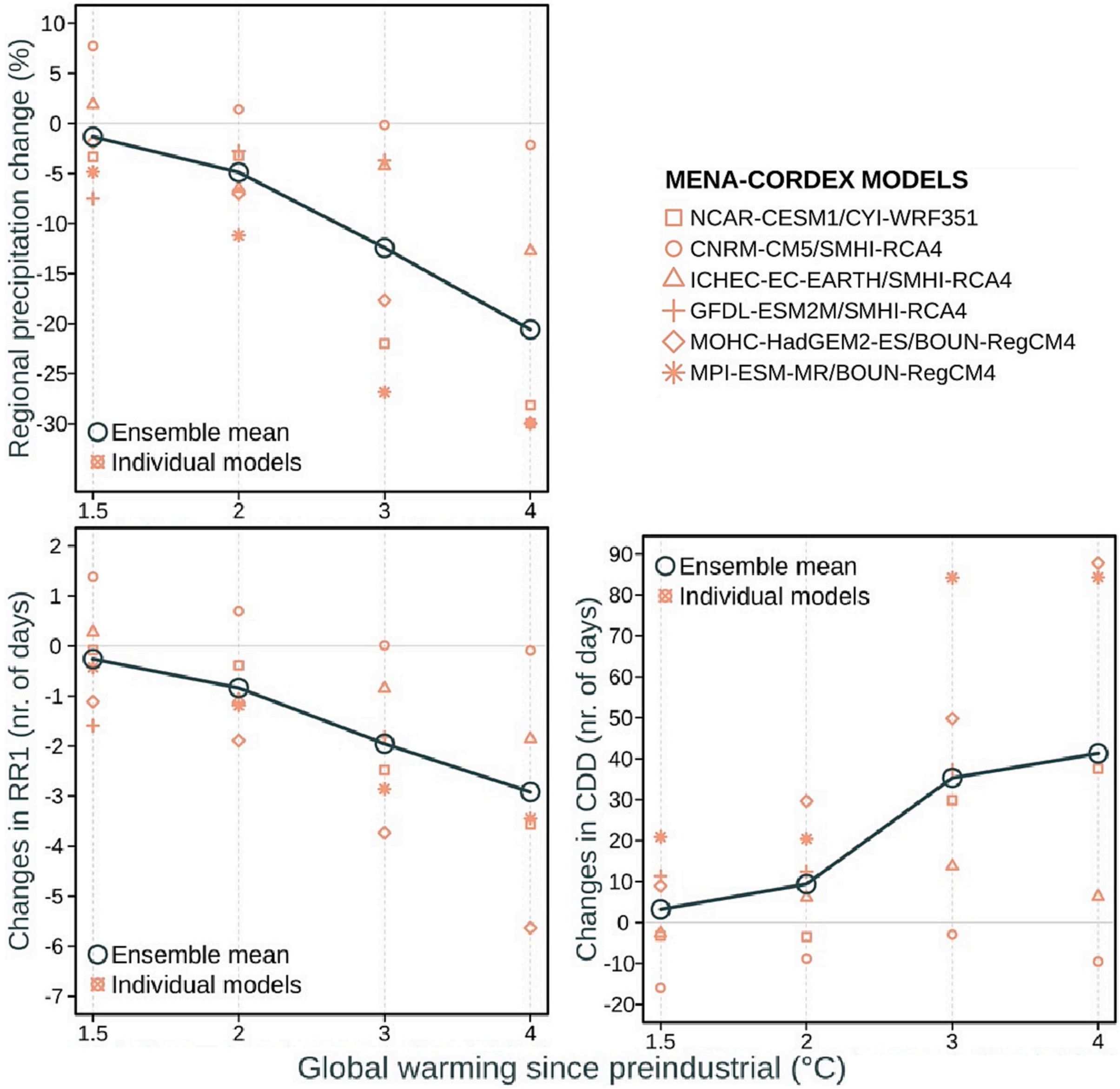

Fig. 5. Precipitation (top panel), RR1 (rainy day per year) changes and Consecutive dry days CDD (with respect to the 1971–2000 reference period) over NAF for various global warming levels.

Mediterranean Sea and reduced baroclinicity during winter (Tuel and Eltahir, 2020), (ii) limited increase in moisture transports from the North Atlantic towards northwest Africa during winter, in particular due to the cold Canary current (Barcikowska et al., 2018), and (iii) thermodynamic effects and enhanced static stability in summer (Brogli et al., 2019).

9. Drought impacts

Droughts can cover extensive areas and can last for months to years, with devastating impacts on the ecological system and many economic sectors (Van Loon, 2015). Examples of affected sectors are drinking water supply, agriculture (rainfed and irrigation), and electricity production (hydropower or cooling water in power plants). Moreover, droughts affect ecosystems through land degradation, deforestation, reduced crop and vegetation productivity (Sheffield and Wood, 2011) and food web structures (Ledger et al., 2013).

The full range of drought impacts and their changes in the NAF region is difficult to assess due to limited records and the strong interannual variability of precipitation (Vicente-Serrano et al., 2020a). Selected impacts related to past drought events for NAF countries have been reported by the review of (Bhaga et al., 2020) and (Bazza et al., 2018) in Table 1. Hunger, food insecurity due to cattle loss and livestock, economic loss due to agricultural losses, water supply shortage or disruption, food import increases and unemployment are the most cited impacts for the historical drought events observed between 1900 and 2020. More recently, an extensive study of user needs for drought monitoring across the MENA region (Fragaszy et al., 2020), including Morocco and Tunisia, revealed a wide range of impacts. The most reported drought impacts from workshop surveys were cited as: water scarcity, overall reduced economic performance and changes in employment opportunities for Morocco and shifting irrigation practices (e.g., to irrigation from rain-fed; from surface to groundwater), increased water demand, reduced crop yields and increased demand for stored surface water.

9.1. Impacts on water availability

Drought has been affecting water resources by reducing water supply and leading to the deterioration of water quality, which further induces crop failure, range productivity reduction, hydropower reduction, and the suspension of economic and social activities (Mishra and Singh, 2010, 2011). In general, reductions in streamflow, groundwater, and reservoir levels are consequences of drought occurrence. These reductions may also result in significant changes in water quality, such as increased salinity due to reduced dilution, increased algal production and toxic cyanobacterial and nutrients decrease (Mosley, 2015). For example, both natural rainfall deficits due to drought and anthropological activities led to the hydrocarbon pollution of the Continental Intercalary aquifer systems, the largest transboundary aquifer in North Africa (Algeria, Tunisia, and Libya) (Hamed et al., 2018).

Many dams and reservoirs have been built in NAF to secure water availability for drinking water, irrigation and hydropower generation. Some of the largest dams of Africa are present in this region, such as the Aswan High Dam in Egypt (reservoir capacity of 132 km^3), Al Wahda (3600 Mm^3) and Al Massira (2760 Mm^3) dams in Morocco and Beni Haroun Dam in Algeria (960 Mm^3). During the dry years, the variation of water flows, rainfall, and evaporation in northwestern Africa caused a significant decline in water levels in the reservoirs. The total water resources in the reservoirs fell to very low levels during the 1990s and 2000s drought periods in Tunisia and Morocco (Tramblay et al., 2018), causing a water supply limitation in urban areas during extreme drought periods in the 1990s (Bhaga et al., 2020). In Morocco, annual hydropower production was 46% below average during drought periods between 1980 and 1985 and 42% fell below average between 1991 and 1995 (Bazza et al., 2018).

9.2. Impacts on agriculture

Agriculture, including livestock and forestry, is particularly vulnerable to drought, with severe consequences on food security and livelihoods, especially for smallholders. It is the first sector to be impacted when drought occurs and also the most impacted of all economic sectors. Agriculture has an important share in the region's Gross Domestic Product (GDP) and is essential for maintaining national food security (see Table 3). For cropping systems in NAF countries, the Nile Valley and the Atlas Mountains are classified as the areas with the highest vulnerability (ESCWA, 2019). Rainfed agriculture is the dominant agricultural system, with irrigation covering <20% of the agricultural area with the exception of Egypt (98%). It is a dominant consumer of water, up to 90% of available water resources in some countries. Irrigation plays a role in producing food crops in the Maghreb that has sufficient surface and groundwater resources available. In Egypt, irrigation is the only possible option for large-scale agricultural production.

In Northwest Africa (Morocco, Algeria and Tunisia), the growing area for cereals is a relatively narrow band that stretches along the coast and into the interior plateaus of all three countries. Each of these three countries relies on a successful annual harvest to reduce their large wheat import requirements. In Tunisia and Morocco, during the dry years 1987–88, 1993–94 and 1996–97, cereal production was poor compared to the average for the period (Abou-Hadid, 2006). The latest drought in the winter of the 2015–16 growing season affected all of Maghreb countries, causing significant reductions (by 43%) in agricultural production in Algeria, Morocco and Tunisia (United States Department of Agriculture USDA, 2016), mainly in cereals production. For example, data analysis by Karrou and Oweis (2014) for Morocco showed that for the period 1988 to 2008, cereal crop yields fluctuated from 150 to 3000 kg/ha with a coefficient of variation of between 30 and 50% in the north and 60 and 70% in the south of Morocco as a result of successive meteorological droughts. Fall and early winter meteorological droughts significantly reduce cultivated areas in rainfed regions, whereas spring droughts tend to decrease cereal yields. The drought of 1982–1985 caused the greatest impacts on livestock in Morocco, with losses of cattle and sheep herds reaching 25% and 40% of the total respective herd sizes (Karrou and Oweis, 2014).

Under 2 °C warming and beyond, rain-fed wheat yield in NAF could decline by 2–59%, depending on agricultural practices (Brouziyne et al., 2018; Chourghal et al., 2016). Under 1.5–3 °C warming and reduced rainfall, barley yield is also projected to decrease mainly due to the shortening of the crop growing season due to higher temperatures. A 15–64% drop in the production of rain-fed olives is also projected in Algeria (Bouregaa, 2019). A lower availability of irrigation water due to drought would lead to further losses (Saadi et al., 2015) or even to the non-viability of vegetable crops in some locations; for example, in Tunisia beyond 2 °C warming (Bird et al., 2016).

9.3. Socio-economic impacts

Drought in NAF has considerable negative impacts on the economy and people in terms of crop production losses, reduction in GDP, and loss in livelihoods. Drought causes considerable loss of seasonal agricultural jobs with its consequence of rural migration to urban areas. In Morocco, in 1997, drought reduced incomes causing GDP to fall by 2.3% and, in 1999, by 1.5%. In 2000–2001, 5 million tons of wheat were imported compared to 2.4 million tons in normal years. In 2004–2005, drought reduced the economic growth rate from 3.5 to 1.3%. In 2007, some 700,000 people were affected, and wheat production fell by 76% compared to 2006. In 1999, approximately 275,000 people were affected, and economic damages were $900 million (Bhaga et al., 2020). In 2011, total cereal harvest was <3.2 million tons, a sharp drop from 8 million tons in previous years (Bazza et al., 2018 and references therein). Therefore, the country faced a large import bill (Schilling et al., 2012). In Tunisia, the 1999–2001 drought caused a significant agricultural trade imbalance, disrupted the rural economy, increased migration to urban areas, and exacerbated rural poverty (Bazza et al., 2018).

The agri-food sector in NAF is also important for global food security because several large producing countries in the region, such as Morocco and Egypt, are net exporters of many essential micronutrients to other low-income countries, which might have economic impacts beyond NAF.

9.4. Impacts on health and migration

The effects of drought are critically dependent on context and

Table 3
Role of agriculture in water resources management and the economic system.

Country	Agricultural water withdrawal as % of total renewable water resources (%)	% of total country area cultivated[1] (%)	Agricultural land [1] (%) (cultivated+pastures)	% of Irrigated land of cultivated land (%)	Agriculture, forest, fisheries added value [2] (% GDP)	Employment/ agriculture (%)[3]
Morocco	31.57	21.33	67.37	16.7 (2011)	12.6	33.25
Algeria	57.18	3.576	17.37	14.5 (2012)	12.3	9.6
Egypt	106.7	3.83	3.85	98.3 (2010)	11.8	20.62
Tunisia	63.54	30.52	62.71	9.3 (2011)	9.1	13.8
Libya	692.9	1.165	8.72	19 (2008)	4.1	16.41

[1] FAO-AQUASTAT, Latest values (2018), accessed on 12/09/2022.
[2] World Bank national accounts data, and OECD National Accounts data files., latest values (2021), accessed on 15/09/2022.
[3] International Labour Organization, ILOSTAT database. Data as of January 2021. https://ilostat.ilo.org.

underlying population vulnerability. The impact on health is particularly dependent on the socio-economic factors that can influence the adaptive capacity of the population. Poor health, poverty, and conflict can be amplifying factors of the impacts of drought (Maskrey et al., 2011). Drought might have a greater impact on people with underlying chronic conditions, such as respiratory diseases, as well as on people with disabilities. Other elements like high food insecurity, displacement and conflicts/political instability render these contexts further vulnerable (Bellizzi et al., 2020).

Some of the drought-related health impacts include nutrition-related effects (general malnutrition and mortality, micronutrient malnutrition, and anti-nutrient consumption), water-related diseases (including *E. coli*, cholera, and algal bloom), airborne and dust-related diseases (including silo gas exposure and coccidioidomycosis), vector-borne diseases, mental health effects (including distress and other emotional consequences) (Stanke et al., 2013).

Drought followed by re-wetting can have a substantial effect on groundwater levels, vegetation, and aquatic predators; all factors which influence mosquito populations. Several studies found an association between a drought during the previous year and West Nile virus incidence, as seen in Algeria, Morocco and Tunisia (Mencattelli et al., 2022; Sekmoudi et al., 2022). Urban mosquito vectors of the Dengue virus and Chikungunya virus are adaptable by nature and are able to exploit a multitude of additional aquatic habitats created as a response to drought (i.e. water storage containers) (Brown et al., 2014). In NAF, the epidemiology of these viruses remains poorly characterized despite increasing reports of outbreaks and transmission in new areas, such as the dengue outbreak in Egypt in 2005 (Humphrey et al., 2016).

A growing body of literature has looked at the association between drought and migration, with most authors concluding that drought-related migration rarely shows a direct linkage (Hermans and McLeman, 2021). Migration decisions are influenced by a wide range of factors, many of which are not related to physical parameters. However, there is a scientific discussion on the fact that climatic factors and their impacts do contribute to migration (Wodon et al., 2014). Such factors include more droughts events and their impacts on agricultural yields and water scarcity, among others. These events act as a threat multiplier (Piguet et al., 2018) in the region by placing additional pressure on already scarce resources and by reinforcing preexisting threats such as poverty and unemployment. In a warmer world, internal migration among the NAF population will continue to be important, but traditional patterns of mobility might be disrupted (Gemenne, 2011). As an illustration, environmental changes due to drought in the oases of NAF reduce income from agriculture and force people to look for additional sources of income, including from migration. In this context, migration may provide financial resources for adaptation (Sobczak-Szelc and Fekih, 2020).

10. Adaptation options

The concept of adaptation gained increasing importance in recent years, particularly in the climate change literature. Most initiatives taken across NAF to build resilience to climate change are mainly focusing on the agriculture and water sectors that are most vulnerable to climate change (Schilling et al., 2020), sectors that are critical for food securityand drought. The spatial and sectoral distribution of recorded adaptation actions for NAF is very limited in the scientific literature in comparison with other African regions (Williams et al., 2021).

Farmers in NAF have been responding and adapting to changes in their environment throughout history. For example, Bronze Age Egyptians used careful planning and policies to adapt to a drought that lasted from around 1250 B·C. to 1100 B.C through efforts of expansion of dry farming in the Canaan region (Finkelstein et al., 2017).

More recently, private adaptation options to drought include agronomic practices such as conservation tillage or irrigation management (Olesen and Bindi, 2002; Oweis and Hachum, 2006). Supplemental irrigation for optimizing the use of the limited water available from renewable resources in rainfed areas, and water harvesting for improved farmer income in drier environment (Oweis and Hachum, 2003) have been cited among the most promising and efficient-proven technologies to improve water productivity and the management of scarce water resources in NAF. However, individual/private coping capacity can be considered moderate because, in most areas, actions are highly dependent on the adaptation actions adopted by the hydrological sector, where public intervention continues to play a key role (Iglesias et al., 2011).

Other adaptation options have been proposed to improve the irrigation efficiency practices by changing surface water irrigation for other techniques (Asseng et al., 2018; Benlhabib et al., 2014; Fader et al., 2016; Malek and Verburg, 2018) and shifting to more sustainable practices (Iglesias et al., 2018). For example, (Fader et al., 2016) have shown that the region could save 35% of water resources through improved irrigation techniques.

In Morocco, most of the strategic steps to adapt to climate change were introduced as part of the Green Morocco Plan for 2008 to 2020. In the background of climate change, the plan was aimed at modernizing agriculture, boosting agricultural productivity and farmers income, and stimulating the development of rural areas. (Benabderrazik et al., 2021) noted that the water demand for irrigation created by the plan has led to overexploitation of the groundwater table causing significant natural resource management challenges. They also raised concerns about the ability of Moroccan agricultural producers to be resilient against drought. Furthermore, maladaptive drip irrigation subsidies and developments proposed as incentives for farmers to buffer drought effects can also result in the unsustainable use of groundwater resources, which might affect the water cycle (and future droughts) and excessive agriculture intensification, indicating the need for careful strategic planning, regulation and monitoring of these options (Venot, 2017).

On the other hand, the use of non-conventional water resources has been used as a means of adaptation to drought in NAF. Countries in NAF have increasingly been investing in desalination to augment supply. Algeria is the region's leader in desalination capacity (see Table 4), where water desalination has been boosted by the oil and gas industry, which uses significant amounts of water at several stages in the production cycle and the cheap cost of energy. Morocco plans to build 20 desalination plants by 2030 building on the low cost of renewable energy to power these plants (The North Africa Post, n.d). Egypt plans to build 14 additional desalination plants to increase the total production capacity.

Drought in NAF impacts some groups disproportionately (e.g., poor farmers, urban migrants, seasonal workers) and livelihoods (Waha et al., 2017). Some of these adaptation options might have side and residual effects, favouring some social groups over others. Adaptation options are those that promote fair solutions for all and take into account region-specific socioeconomic and geopolitical variabilities and vulnerabilities (Iglesias and Garrote, 2015).

11. Drought risk assessment

Drought risk quantifies the likelihood of environmental and socio-economic systems to suffer adverse impacts due to droughts (Blauhut, 2020). Drought risk is defined as the potential for adverse impacts or consequences and results from the interaction of natural drought hazards (e.g., meteorological or agricultural drought), their exposure (e.g. people and ecosystems), and vulnerability (susceptibility of a system and its elements to harm combined with a lack of short-term coping capacity and long-term adaptive capacity). A common understanding of the drivers of drought risk and ways in which drought impacts materialize is crucial and it is an initial step to fostering drought risk management and adaptation options (Blauhut, 2020; Hagenlocher et al., 2019). Several global drought risk analyses have identified NAF as a high-risk area (e.g., Carrão et al., 2016; Guo et al., 2016; Yin et al.,

Table 4
Water resources characteristics of North African countries, FAO-AQUASTAT, Latest values (2018), accessed on 12/09/2022.

Country	Precipitation (10^9 m^3/yr)	Total ren. Water resources (10^9 m^3/yr)	Ren. Surface Water (10^9 m^3/yr)	Ren. Groundwater (10^9 m^3/yr)	Total dam capacity (km^3)	Ren. Water Resources per capita (m^3/inh/yr)	Treated municipal wastewater (km^3/yr)	Water stress (%)	Desalinated (10^9 m^3/yr)
Morocco	154.5	29	22	10	17.96	804.9	0.166	50.75	0.007
Algeria	212	11.67	10.15	1.51	8.61	276.3	0.4	137.9	0.631
Egypt	18.13	57.5	56	1.5	168.2	584.2	4.282	141.2	0.2
Tunisia	33.87	4.615	3.42	1.595	2.691	399	0.274	96	0.0427
Libya	98.53	0.7	0.2	0.6	0.3899	104.8	0.04	817.1	0.07

2014). However, the review of regional drought risk analyses by Blauhut (2020) shows that NAF received little attention from national or regional studies in comparison to other regions in Africa.

Ahmadalipour et al. (2019) assessed drought risk at a national level across Africa. In this study, NAF indicates the lowest risk ratios in Africa (albeit a significant increase in drought hazard), which is mainly attributed to advanced socioeconomic sectors that stabilize the population and decrease drought vulnerability. On the other hand, in their global assessment of drought for agricultural systems, Meza et al. (2019) found that Morocco and Algeria ranked among the ten countries with the highest drought risk in the world for both agricultural systems (rainfed and irrigated). Despite these attempts, the quantification of drought risk might be elusive in this region due to the absence of unambiguous quantified estimates of drought risk, in particular when considering the impacts of droughts on agriculture (Hall and Leng, 2019).

12. Drought management

Drought is a challenging natural hazard to manage because of its spatial and temporal variability. Stemming from the difficulty of classifying such a natural hazard (see definitions above), drought management does not fall under explicit legislation in many countries of the world (Wilhite, 2016). As such, many countries endure droughts with reactive crisis management rather than proactive risk reduction approaches (Sivakumar and Wilhite, 2002; Wilhite et al., 2014).

Demographic processes such as population growth and urbanization are projected to increase in NAF, therefore an increase in agricultural production will be required to satisfy the needs of a growing population. This will inevitably increase water demand and consumption, as well as induce strong changes in land-use and water-use patterns. In this context, the institutional and policy framework might be crucial to attenuate the vulnerability to drought.

An accurate understanding of the characteristics of droughts (as presented above) and how they are managed in NAF countries is important to guide the transition from emergency response to more proactive policies and long-term planning, but also to assess gaps in drought management capacities. For this purpose, we review first the general water resources management and the water governance in the region, then the efforts made by governments to mitigate drought effects by the implementation of a drought policy will be exposed. Finally, the available drought early warning tools to improve drought preparedness are presented for each country.

13. Water management

According to the Food and Agriculture Organization (FAO) AQUASTAT database, the average renewable water resources per capita for 2018 are about 30,000, 12,000, 12,000, 4000, 2000 and 256 m^3 per year for South America, North America, Europe, Sub- Saharan Africa, Asia and North Africa regions, respectively. NAF region is referred to as the most water-scarce region (Taheripour et al., 2020) in the world.

In 2018, the total annual precipitation across North Africa was only 100 km^3. Renewable water resources per capita per year are the highest in Morocco (800 m^3) and the lowest in Libya (100 m^3). While Libya has almost no available renewable water resources and relies heavily on fossil groundwater, other NAF countries, such as Egypt, depend on surface water sources, shared with other East African countries. Morocco, Algeria and Tunisia rely on a mix of both renewable surface and groundwater resources. Non-conventional water resources such as treated wastewater and desalination have also been used as water sources, although they do not contribute significantly to water budgets. Total dam capacity is highest in Egypt due to Aswan High Dam, constructed in the 1960s to control Nile flooding, which provides increased water storage for irrigation and generates hydroelectricity.

Libya and Egypt merit a separate analysis as their water resources origins differ from those in Morocco, Tunisia and Algeria. The presence of the Nile in Egypt and the reliance on fossil groundwater in Libya, present a separate set of regional security and climate-related implications which are not relevant to the same extent for the rest of NA. To meet the Libyan population's water needs, the Man-made River project has been undertaken by drawing water from aquifers beneath the Sahara – mainly the Nubian Sandstone Aquifer System- and conveying it to the Northern coastal cities where most of the Libyan population live and fresh water is considered scarce. This project (not completed to date) was considered to be one of the largest water conveyance systems in the world and was classified as one of the non-conventional water resources, although the transported water is groundwater (Brika, 2019).

Egypt's freshwater resources originate outside of its borders, such as the Nile River and groundwater aquifers. The Nile River provides the country with some 98% of its water requirements (FAO AQUASTAT Country Profile – Egypt, 2019), but shared between nine East African countries, namely, Burundi, Tanzania, Rwanda, the Democratic Republic of the Congo, Kenya, Uganda, Sudan, Ethiopia, and South Sudan. Groundwater resources are closely linked to the Nubian sandstone aquifer and fossil groundwater in the south-west of the country is shared with Libya, Chad and Sudan. The Nile River has been the subject of numerous treaties and agreements over the years. Today, the distribution of Nile water is governed by the Nile Waters Treaty, a bilateral agreement between Egypt and Sudan that was signed in November 1959. This allocated 55.5 km^3/year to Egypt. Therefore, Egypt is affected by the drought in the Horn of Africa countries with an approximately one-month time lag (Nada et al., 2014).

The contribution of snowmelt in the Atlas mountains to Moroccan watersheds varies between 42% and 80% in the different studied areas (Cappy, 2007; N'da et al., 2016). These recharge rates indicate the role of the Atlas Mountains and the significant contribution of snow cover in supplying water resources in surrounding semiarid areas.

Water resources management in NAF is a complex process that involves multiple stakeholders who use water for irrigation, municipal and industrial water supply and hydropower generation. A key problem of water resources management in this region is the imbalance between increasing water demand and limited supply, referred to as "water scarcity", which depends, among other factors, on water management practices, such as those promoting water productivity or enhancements to supply.

The complexities of climate and land use changes, droughts and floods, water quality, transboundary water management, and the management of water in the context of fragility compound the challenge of water scarcity (World Bank, 2018). This combination of already-existing scarcity coupled with higher-than-average hydrological variability makes water management and allocation particularly challenging in this region (Hall et al., 2019). Meeting these challenges depends as much on better governance of water resources as on more and better resource endowments, infrastructure investments, and technologies. Most NAF governments emphasize supplementing water supplies more than managing water demand and view water management primarily as a civil engineering problem (Richards, 2002). Water policy is still limited largely to increasing supply through measures such as desalination, wastewater treatment, and water storage infrastructure.

Water governance refers to the political, social, economic, and administrative systems that influence the use and management of water (OECD, n.d). Good water governance is essential to achieve water security, fairly allocate water resources, and avoid conflicts about water. It has social, economic, political, and environmental dimensions, all of which must be carefully considered and addressed. Water governance in NAF countries is still very state-centered and is characterized by a role distribution between water-related government agencies, laws and regulations, and adopted policy instruments. Most NAF countries have enacted water laws that reflect a number of internationally promoted standard principles and "good practices" (Waha et al., 2017). Centralized systems of planning have rendered governance mechanisms weak in terms of organizational capacities and integration with local communities such as cities, provinces, as well as local non-governmental organizations.

Table 5
Drought declaration policy and reported governmental interventions following past drought events in Algeria, Egypt, Morocco, Tunisia, adapted from Jedd et al. (2021), Verner et al. (2018a), Verner et al. (2018b) and Bazza et al. (2018).

	Morocco	Algeria	Tunisia	Egypt
Drought legal/ technical definitions, physical indicators	No	No	Yes. Seasonal Standardized Precipitation Index values	No
National drought declaration process in law	Yes	No	Yes. Emergency coordination meetings	No
National drought management plan	- Regional formation of local bodies for coordination of interventions - Basin agencies required to develop water allocation and sector management plans for drought	No	- Yes, national level—institutional coordination mechanisms, pre- planned mitigation actions	- In case of high drought impacts, a political action is triggered which results in intervention bill. - Commissions are set up within municipalities in order to give final assessment and priorities for compensation.
Livestock	- Fodder/feed subsidies - Direct fodder/feed provision - Livestock water provision	Supply feed for livestock at subsidized prices	- Fodder subsidy and/or direct provision - Livestock water provision - Subsidies for buying calves to restore cow herds (postdrought) - Shift low-production crop fields to forage	No
Rainfed agriculture	- If fall drought, subsidies, extension services, and preferential loans to switch to spring crops - If winter/spring drought insurance payouts (wheat/barley, delimited areas) - Creation and control of pastoral reserves for transhumant herders	No	- Expanded extension trainings and awareness campaigns to teach coping mechanisms (e.g., soil conservation practices) -Intensify preparedness for next season's crop - Subsidies for tree terraces, moisture barriers, and related equipment - Water trucking for trees and per tree subsidies in delimited areas	
Irrigated agriculture	- Preferential irrigation allocation - Augment groundwater pumping and dig new wells - Speed up new well/well deepening licensing processes	- Augment groundwater pumping and dig new wells	- Surface water mobilization (inter/ intrabasin transfer) - Crop planning in public irrigation perimeters - Preferential irrigation water allocation - Increase reclaimed water use - Extension services/ awareness campaigns to expand irrigation efficiency measures - Irrigation infrastructure rehabilitation	No
Municipal water supply	- Preferential water allocation to municipalities - Awareness campaigns - Campaign to reduce nonrevenue water	No	- Interbasin transfers - Utility rationing - Subsidize home storage infrastructure - Drill new/deepen public groundwater wells - Awareness campaigns - Campaign to reduce nonrevenue water	No
Financial sector	- Credit relief programs from state-owned banks - Job creation programs (focused on water/ electricity/transport infrastructure) - Multirisk climate insurance subsidized (drought for rainfed cereals and other crops in some areas)	Possible Direct compensations - Insurance schemes and special funds to compensate farmers and ranchers	- Extend credit and refinance loans for "bankable" clients (National Agricultural Bank) - Loan rescheduling from agribusiness suppliers (informal financial sector)	Direct compensations, possibilities of tax reductions and exemptions of social costs

14. Drought management policy

The governments undertake a range of drought management responses and intervene in various forms in the main sectors vulnerable to drought, such as agriculture, and municipal water supply. Table 5 compares the drought declaration policy and reported governmental interventions in drought-impacted sectors, e.g., livestock, rainfed and irrigated agriculture, municipal water supply and financial sector for four of NAF countries (no data was available for Libya). It shows that among the four countries in NAF, Morocco and Tunisia have relatively longstanding policies that outline drought management (Bazza et al., 2018; Jedd et al., 2021). They also have multistakeholder coordination mechanisms for drought management at the national and local levels (Louati et al., 2007; Ouassou et al., 2007).

The intercomparison shows that current regional drought management systems in these countries are dominated by crisis interventions rather than risk management, evidenced by the ambiguous bases for drought declaration and the lag in subsequent relief-based programs.

15. Drought monitoring and forecasting

Given the region's inherent severity of drought impacts, drought risk management is a critical endeavor, supported by effective monitoring and early warning systems. The ability to provide early warning forecasts of future drought conditions is an important tool for avoiding or minimizing the possible impacts. This helps to avoid the possible misallocation of resources that could occur when farmers, herders, and other decision makers need to commit such resources before actual annual rainfall levels are known (Verner et al., 2018b).

Drought monitoring involves observing indicators and indices that evaluate changes in a region's hydrological cycle.

In NAF, various forms of drought monitoring and early warning take place on several institutional levels under the coordination of different institutions/ministries, such as those existing in Egypt or in Morocco (Bazza et al., 2018). However, each of these institutions has its own specific dissemination of the information, which makes it largely limited to selected government officials and agencies responsible for water resources and agricultural management.

While efforts have been made to cope with drought events through the engagement of multi-sectoral and interdisciplinary collaborations among communities and across scales as seen in Table 5, strategic drought risk management linked to operational drought early warning systems for the region is not yet in place.

Past assessments have described NAF drought monitoring systems as nascent, overly reliant on precipitation-based indices, and in great need of wider stakeholder involvement and participatory development processes (e.g., World Meteorological Organization (WMO), 2006). In an effort to shape the development of drought early warning systems in MENA (based on Morocco and Tunisia's participation), Fragaszy et al. (2020) developed a Composite Drought Indicator (CDI) approach that combines indicators from different climate variables such as precipitation, soil moisture, vegetation, and evapotranspiration into a single product through a participatory approach method based on engagement with farmers, organizations, and end-users of drought monitoring products. This could serve as a basis for informing enhanced drought monitoring and management in the countries.

Inspired by the U.S. Drought Monitor (USDM) developed by the National Drought Mitigation Center (NDMC) at the University of Nebraska and with technical assistance from NDMC and the International Water Management Institute (IWMI), Morocco has developed an operational Moroccan drought monitoring system based on CDI and published countrywide satellite-based drought maps online for the first time in 2021. The maps visually present satellite data on rainfall, land surface temperature, soil moisture, and vegetation health, which have been compiled into an easy-to-interpret enhanced Composite Drought Index (eCDI) (https://www.iwmi.cgiar.org/2021/03/moroccos-decision-to-publish-drought-maps-could-benefit-the-whole-mena-region/). Furthermore, in recent years a number of scientific studies have developed indices based on time series of remote sensing satellite products tested for this region, using various spatial techniques (optical and microwave measurements) directly related to surface features such as vegetation cover, soil moisture or surface temperature (e.g., (Amri et al., 2012) and references therein).

While significant efforts are underway to develop drought monitoring and forecasting systems globally, the ability to forecast drought is limited due to inherent uncertainties in precipitation forecasts at long lead times (months to years) and under a changing environment resulting from natural and anthropogenic factors (e.g. Livneh and Hoerling, 2016; Sheffield et al., 2014). Statistical drought prediction is achieved by modeling the relationship between drought indices of interest and a suite of potential predictors, including large-scale climate indices, local climate variables, and initial land conditions. Dynamical meteorological drought prediction relies on seasonal climate forecasts from GCMs, which can be employed to drive hydrological models for agricultural and hydrological drought prediction with the predictability determined by both climate forcings and initial conditions (Hao et al., 2018).

Recently, Le Page and Zribi (2019) proposed a statistical approach using multiple remote sensing products (Normalized Difference Vegetation Index (NDVI), Soil Moisture Index (SWI), and Land Surface Temperature (LST)) in the quantification of predictability of drought in Northwest Africa. Another skillful SST indices to predict seasonal rainfall over Morocco have been proposed recently by Tuel and Eltahir (2018). These statistical models could be implemented operationally for seasonal prediction by water policy makers.

16. Conclusions and key issues

This study presents a comprehensive multi-disciplinary literature review on drought in North Africa ranging from their driving processes to their impacts and management. This theme is of outstanding relevance as water is already scarce in this region and is expected to further reduce in the future climate along with an increasing water demand and a growing population. We review the different types of drought types relevant to NAF, physical processes contributing to their occurrence, past events, and the influence of anthropogenic climate change on droughts in the projected future. Also, we discuss their impacts on society and the environment, drought risk, and management and measures that help minimize their impact. Below we present the main conclusions of this review and give recommendations for future research and policymakers.

Our review summarizes the drought events reported by three different sources and shows some discrepancies depending on the selected criteria to report these events and their impacts. The drought period 2002–2005 is common to all NAF countries, except for Libya, where drought events are rare or might not be reported due to a lack of scientific publications or data and/or governmental reports. Data-related challenges in NAF arise due to limited data availability, event definition and recorded impacts. Limited data availability challenges drought studies because it prevents from the description of the full variability of the events. The choice of event definition is also crucial because it can have substantial effects on the outcome of analyses. The recorded impacts are important to define possible vulnerabilities among the population and the livelihoods. To improve data availability, new data sources, such as remote-sensing data and data collected by citizen scientists might be of great potential. Drought monitoring could be enabled through social media, press articles and crowdsourced material such as photos to be used as an interactive information communication platform for drought preparedness, mitigation, response, and recovery.

While precipitation deficits have been reported in the literature for the period 1970–2000, mixed signals are observed over long periods and show pronounced variability within the region, with magnitude and sign of trend in the past century depending on time period. Similarly, the observed increase in meteorological droughts using SPI at the local scale is countered by regional assessments over the Mediterranean region, which show low confidence. More consistent trends were found over longer periods in agricultural droughts using SPEI locally and regionally. This confirms previous scientific results observed over the Mediterranean which demonstrate that drought severity increases are a consequence of greater atmospheric evaporative demand resulting from temperature rise, rather than substantial changes in precipitation in the long term.

Whereas the role of precipitation is an obvious component in the regional water cycle, the role played by the atmospheric evaporative demand in triggering or reinforcing drought episodes is much more complex and needs to be further studied to improve our understanding how it affects drought severity in the southern part of the Mediterranean. The physical dynamics of precipitation and the atmospheric evaporative demand affecting drought are strongly influenced by the large-scale climate and other important thermodynamics drivers as demonstrated above. An important linkage of the NAO to precipitation variability over northwest Africa has been demonstrated from daily to centennial time scales. Dynamical mechanisms that contribute to the past and projected future drought increase involve changes in the planetary-scale to the local circulation, such as the Hadley Cell expansion, poleward shift of the rain-bearing westerlies, a strengthening in the anticyclone over the Mediterranean, and local land-sea contrasts, while their relative contributions remain debated. On the other hand, the very different ways human activity influences the hydrological cycle, from global anthropogenic climate change to very local land use (expansion of agriculture, deforestation, urbanization), and water consumption need to be quantified. The patterns and interactions of these physical and human drivers need further investigation.

In addition, droughts may co-occur together with other types of extremes, such as heatwaves or wild fires. There is a need to better understand the interplay between compounding climate variables such as precipitation, temperature and soil moisture to produce these compound events.

The reported impacts of drought in western NAF reflect the vulnerability of the agricultural sector and the economic system to the consecutive drought events and the exposure of this sector to drought risks. This is in contrast with the eastern part of NAF, where Egypt and Libya show lower vulnerability. Egypt relies on the water allocation provided by the Nile Water Agreement for its water resources management, and therefore tributary of droughts in Eastern Africa and the Nile-powered Grand Ethiopian Renaissance Dam, which might reduce water supplies to downstream Egypt by more than one-third (Heggy et al., 2021) and Libya depends on the fossil groundwater resources for their water needs. Drought risk management supported by effective monitoring and early warning systems is an important tool for avoiding or minimizing the possible impacts.

Among the five countries in NAF, Morocco and Tunisia have relatively longstanding policies that outline drought management and provide early-warning systems to prevent possible impacts of future droughts. However, they remain ineffective because strategic drought risk management linked to operational drought early warning systems are not operational. Furthermore, the development of management strategies to minimize the negative impacts of droughts relies on the ability to assess the drought risk. Planning of emergency responses and early warnings rely on drought forecasts at hourly to seasonal time scales (Mirza, 2010). Development of adaptation strategies requires long-term projections of droughts representing future climate, land use, and water management conditions.

Water management practice is dominated by technocratic, scenario-based approaches that may work well in the short term but can result in unintended consequences in the long term due to limited accounting of dynamic feedbacks between the natural, technical, and social dimensions of human-water systems. To fully understand drought in NAF, disentangling the influence of human-induced changes from those of climate-induced changes to the water cycle is crucial but proved to be challenging. For this purpose, sociohydrological methods and their resulting outcomes have an important role to play in informing policy processes and assisting communities, governments, non-governmental organizations, and the private sector.

Lastly, droughts are spatial phenomena that can affect a larger region, which can span more than one watershed or country. Studies using drought indices that account for spatial extent over the whole NAF are needed to prepare for and adapt to large-scale events, for example, by establishing regional emergency plans. Similarly, most NAF studies typically focus only on a single type of drought or drought index. To comprehensively understand drought events and their corresponding impacts, a general overview is needed. The use of multiple indices to capture the drought event and the associated impacts should be applied more comprehensively.

Author contributions

MT performed writing – original draft and conceptualization. AV and GZ performed writing – review and editing, conceptualization, and data analysis. TC performed conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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