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An assessment of climate change impacts on oases in northern Africa

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ABSTRACT

Oases are vulnerable ecosystems that are affected by climate change. Using high-resolution climate models focusing on northern Africa, we investigate the changes in the agrosystems of oases. Projected air temperature changes under an extreme global warming scenario are statistically significant for all oases studied, with an increase of up to 4–4.5 °C by the end of the century. The impact of the projected warming is likely to lead to an increased groundwater demand, with a parallel trend in reduced precipitation. Combined, these processes endanger the long-term socio-economic prospect of oases.

1. Introduction

Northern Africa is projected to experience the largest increase in air temperature over the African continent and a strong variability in terms of precipitation, with a significant decrease over the Mediterranean area and northern Sahara and an increase over the eastern Sahara (Dosio, 2017; Almazroui et al., 2020). Oases in northern Africa cover around 3,800 km^2 within hyper-arid and arid zones (Schilling et al., 2012). However, their size varies widely, as shown in Table 1 in order of decreasing area.

Oases are fragile natural systems that play a critical role in buffering the advance of the desert and maintaining the human population (Alcalá et al., 2018) by providing several goods and services in the arid and semi-arid ecosystems. The water ecosystem service is one of the most important elements that support human livelihoods. Changes in precipitation influence river flows, which forces local populations to use groundwater to meet the increasing demand (Hamed et al., 2018; Ben Salem et al., 2019). Moreover, some weather extreme events, such as drought, compromise the management of groundwater reserves.

Oases in arid land ecosystems can be considered to be examples of intensive farming practices under adverse climatic conditions that are based on specific water and soil management (Renevot et al., 2009), providing important income to local farmers (Lauri et al., 2019). Dhaouadi et al. (2020) confirm the poor quality of the irrigation water in southwestern Tunisia, where the groundwater is recently facing quantity and quality degradation with a serious salinity hazard. In Tunisia,

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Table 1
Selected northern African oases.

Oasis	Area (km^2)
Kaouar	4,000
Sabha	700
Tafilalt	650
Siwa	400
Adrar	147
Tozeur	53
M'hamid El Ghizlane	44
Skoura	42
Tifariti	6.7
Guelta d'Archei	0.031
Selima	0.025

climate change has caused an increase in irrigation, and consequently, the water salinity of oases has impacted date palms. In Egypt, oases showed variability in salinity attributable to climate change, mainly due to increased evaporation effects (Marks et al., 2018).

Evaporation plays a crucial role in the formation and maintenance of oases in arid regions. The different levels with which it occurs are known to influence not only temperatures (Han et al., 2009) but also soil dynamics since high evaporation rates may result in soil salinization and degradation (e.g. Goldberg-Yehuda et al., 2022). Furthermore, climate projections have shown that the expected warming will increase the required water amount for the date palms from 2019 to 2050, further threatening the oases' water quantity (Haj-Amor et al., 2020). Whereas there is little available literature on changes in the sizes of the specific oases investigated, some studies have shown that the size and dynamics of oases are being influenced by capital projects, climate change, and erratic land use (Wang et al., 2021).

The dynamics of groundwater-dependent economics, such as tourism in oases, is also affected by climate change. According to Alcalá et al. (2015), in the Amtoudi Oasis in southern Morocco, which is attractive for tourism, there is evidence of groundwater degradation. The productivity of these local traditional agrosystems may be hampered by the risk of desertification followed by outmigration. It is therefore urgent to take initiatives for the improvement of their resilience for the benefit of the local populations.

Through the use of high-resolution climate models, we investigate the changes in climate for the end of the century and identify the most crucial factors for the sustainability of the agrosystems of oases. Given that oases preservation depends on the involvement of local people, the human aspect and its resilience in terms of natural resources needs efficient management.

Due to the importance of oases, it is to understand the impact of climate change on their dynamics, and hence ensure their continued ecological, economic, and social benefits.

2. Methodology

To gain a deeper understanding of the impact of climate change on oases, we are examining the effects of climate change in recent decades on oases in nine adjacent countries in northern Africa. At least one oasis is selected from each country (Fig. 1). To determine the magnitude of the recent climate change, we use observed mean air temperature, precipitation, and change in Liquid Water Equivalent (LWE)[7] data. Air temperature and precipitation data are direct climate measurements, while

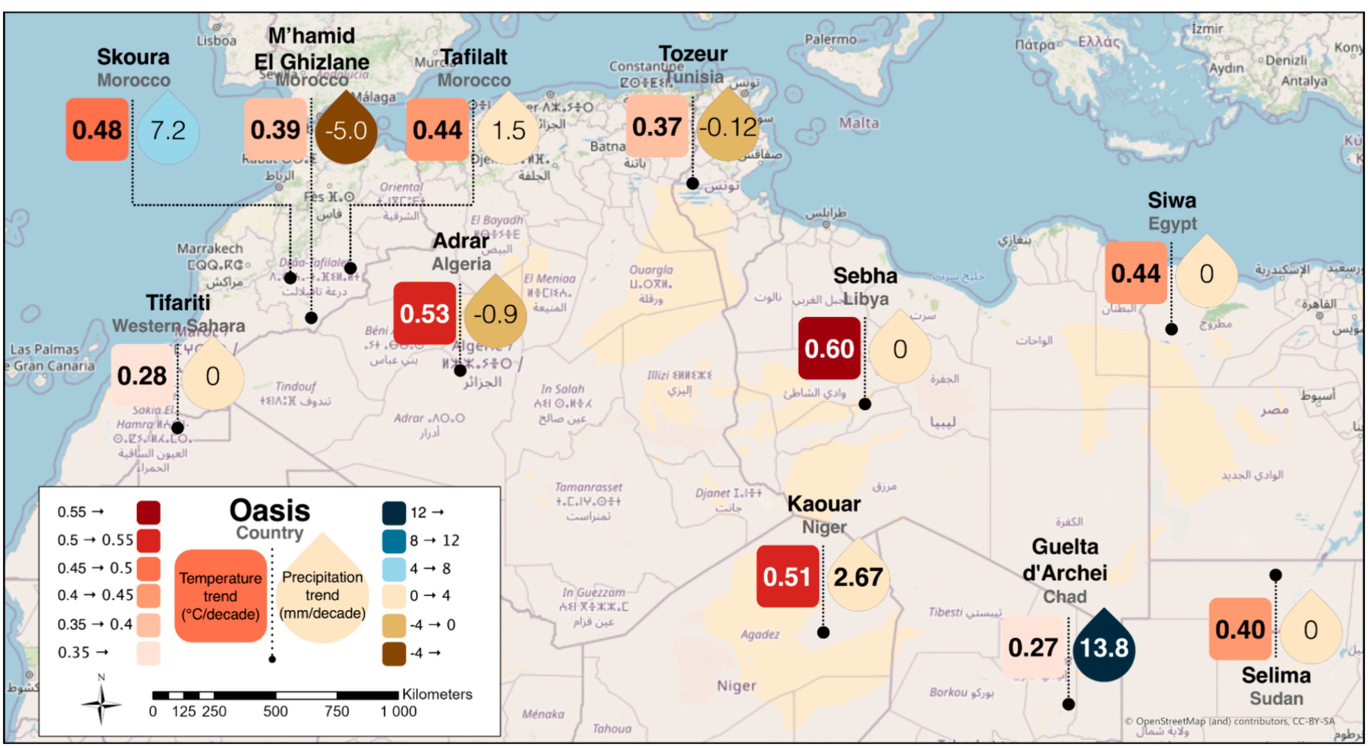

Fig. 1. Observed air temperature and precipitation trends for selected northern African oases. Numbers in squares show the trend in annual air temperatures provided by CHIRTSmax (Funk et al., 2019) for the period 1983–2016. Numbers in the water-drop shapes show the trend in annual precipitation taken from CHIRPS (Funk et al., 2015) for 1981–2020. Bold numbers denote statistical significance at 95% level.

[7] Liquid Water Equivalent is the water storage (in units of height) from soil moisture, snow, surface water (incl. rivers, lakes, reservoirs etc.), groundwater, and aquifers.

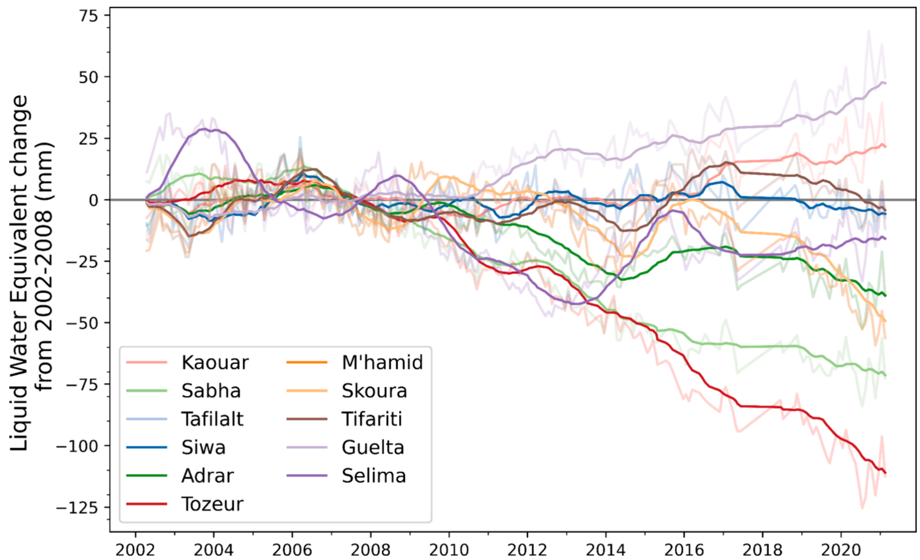

Fig. 2. Observed oases groundwater storage changes. Time series of the monthly liquid water equivalent anomaly, relative to the 2004–2009 period, from the Gravity Recovery and Climate Experiment (GRACE) satellite Monthly Mass Grids: Global mascons (JPL RL06_v02 CRI). Solid thick lines show the 12-yr moving average.

LWE is indirect. The latter quantifies the groundwater storage and is generally influenced by changes in precipitation and runoff. However, in inhabited areas with human presence, it can also be affected by water pumping or storage practices. Therefore, when interpreting LWE changes, it is necessary to remember that they might be unrelated to climate change. Air temperature data used in Fig. 1 are based on $CHIRTS_{max}$ (Funk et al., 2019), on a 0.05° monthly resolution, produced by merging station temperature measurements with geostationary satellite thermal infrared observations.

The areas of the oases were visually approximated by creating polygons representing the land cover of the oases. Several sources of base maps (ESRI World Imagery, Google Maps, OpenStreetMaps) were used to improve the visual approximation. ESRI Sentinel-2 10-meter land use was used to accurately determine vegetation area and population.

3. Data

Precipitation data (same resolution) were provided by CHIRPS (Funk et al., 2014, 2015), which combines satellite information with sparsely gauged locations. For LWE, used in Fig. 2, we utilised mass-concentration (mascon) GRACE data (product JPL RL06_v02 CRI, Watkins et al., 2015; Wiese et al., 2019), directly related to groundwater mass anomalies. GRACE data are monthly, available from 2002 to at latest February 2024.

Future monthly projections of air temperature, precipitation, and actual evaporation for Fig. 3 (and Fig. S1) are provided by nine regional models participating in the COordinated Regional climate Downscaling EXperiment (CORDEX, Giorgi et al., 2009), characterised by 0.44° horizontal resolution (Table S1) and by the Canadian Global Environmental Multiscale (GEM) model (Qaddouri and Lee, 2011) version 4.8, a global atmospheric model run at similar horizontal resolution (0.5°) with the CORDEX experiments.

We selected two 30-year periods for the analysis, 1990–2019 (hereinafter referenced as "baseline") and 2071–2100 based on both the RCP8.5 (henceforth "RCP8.5") and RCP2.6 ("RCP2.6") trajectories. RCP8.5 is the pathway that tracks the recent CO_2 emissions most closely (Schwalm et al., 2020), even though its future emissions' trajectory becomes less likely with each passing year (Hausfather and Peters, 2020). We used both RCP8.5 and 2.6 to explore the spread of possible outcomes and to highlight the effect of mitigation on the modelled changes. In particular, we explored the projected changes between the baseline and the end-of-the-century RCP8.5 and 2.6 scenarios, both in their magnitude and the inter-model robustness. The historical period for the CORDEX models covers the years until 2005, so for our baseline period we combine the 1990–2005 data from the historical runs with the 2006–2019 data from the RCP8.5 scenario. Finally, the RCP2.6 simulation is not provided by the GEM model.

The differences between the model annual means in the future climate under both scenarios and the corresponding model baseline are calculated, and the kernel density of their distributions is reported in Fig. 3, together with the mean differences and the 25th/75th percentiles. The significance of the mean of these differences is compared against the probability distribution, obtained by shuffling the actual annual differences via a bootstrap method consisting of 100,000 runs and computing the corresponding means (Davison and Hinckley, 1997).

For extreme wet and dry years' calculation (Fig. S1), we considered the annual differences between the mean precipitation and evaporation over the period 1950–2100 for all CORDEX models. The 5th (dry years) and the 95th percentile (wet years) of these values are grouped into decades.

Finally, the Mann-Kendall test (Mann, 1945; Kendall, 1975) at 95 % confidence level was used to detect the trend significance and the Theil-Sen estimator (Sen 1968) to quantify the linear slope.

4. Results

Even though the examined oases share many common characteristics, some have distinct climates. One example is the cooler and wetter Skoura in Morocco, due to its high elevation at 1200 m above sea level, differing from the other oases that are mostly at sea level. Another example is the differentiation from the more common dry/warm (summer), wet/cool (winter) climate seasonality to the wet summer and dry winter seasonality for Kaouar in Niger and Guelta d'Archei in Chad. The latter oases are in southeastern Sahara and have a distinct climate due to their lower latitudes and the effect of the West African monsoon.

Despite differences in their climate, all considered oases show a statistically significant mean air temperature increasing trend between 0.27 $^{\circ}C{\cdot}decade^{-1}$ for Guelta d'Archei and 0.6 $^{\circ}C{\cdot}decade^{-1}$ for Sabha during the 1983–2016 period (Fig. 1). Additionally, in the last decades, the climatically distinct Guelta d'Archei and Kaouar oases present a statistically significant increase in annual precipitation, up to 13.8

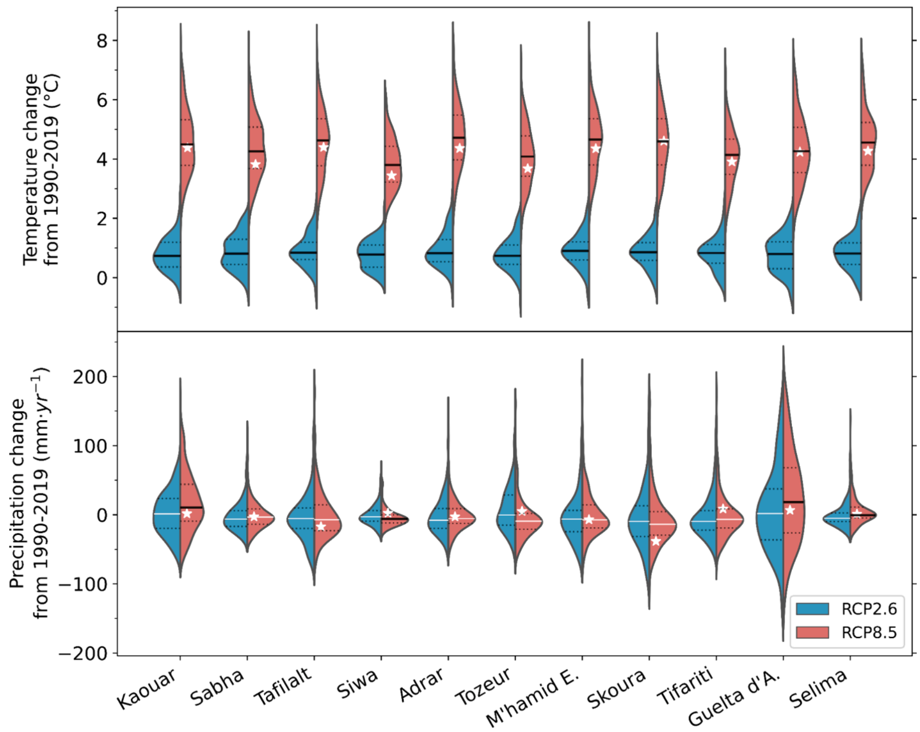

Fig. 3. Projected air temperature and precipitation change for each oasis. Top panel: Kernel density estimation of the distribution of the air temperature differences between all the annual means for the period 2071–2100 simulations and the baseline period (1990–2019) for all CORDEX-RCP2.6 (blue) and CORDEX-RCP8.5 (red) runs. White stars show the corresponding values simulated by the Global Environmental Multiscale (GEM) model run under the high emission scenario (GEM-RCP8.5). 25th and 75th percentiles are indicated with dotted lines, while the black/white horizontal lines show statistically/non-statistically significant differences from the baseline (see Data and Methodology and Table S2 for additional details). Bottom panel: same as top panel, but for precipitation.

mm·decade^{-1} for Guelta (Fig. 1), as well as 20 mm·decade^{-1} and 7 mm·decade^{-1} in LWE, respectively (Fig. 2). Conversely, the other oases have experienced a decreasing trend in LWE, except for Siwa, which shows no significant trend. The decreasing trends for Adrar, Sabha, and Tozeur are in general agreement with the findings of Frappart (2020) and Gonçalvès et al. (2020), who examined the northwestern Sahara aquifer, where the aforementioned oases are located. They also found decreases in the water storage there, with Frappart (2020) stating that 60–70 % of the decrease is climate-related, and Gonçalvès et al. (2020) finding that the aquifer has been exploited unsustainably since the 1980′s, with water withdrawals greatly exceeding the recharge.

Projected changes in air temperature under the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 8.5 are statistically significant for all oases, with more than 4–4.5 °C warming (with the only exception being Siwa with 3.8 °C of warming) and about 25 % of future years in the period 2071–2100 projected to surpass 5 °C warming for the majority of the considered sites (Fig. 3). Similar results were found in the high-resolution global simulations from the Global Environmental Multiscale (GEM) model (please refer to the 'Data and Methodology' section). Other findings for RCP8.5 temperature changes (not shown, averaged over all oases) are that: a) minimum air temperature changes are greater than the maximum air temperature changes by ~ 0.3 °C; b) summer air temperature changes are ~ 1 °C greater than winter. Differences between the low emission scenario RCP2.6 and baseline are much smaller but still statistically significant with mean values between 0.77 °C at Siwa and 0.94 °C at Adrar.

In terms of precipitation, Guelta d'Archei is projected to have the highest increase (30 mm·yr^{-1}) under the high emission scenario, followed by Kaouar (18 mm·yr^{-1}) and Selima (5 mm·yr^{-1}). Siwa shows a projected significant decrease of about 3.5 mm·yr^{-1}, whereas all the remaining oases do not present significant changes. No significant changes are also detected under the RCP2.6 scenario (Table S2 and Fig. S2 for all details). Guelta d'Archei and Kaouar also show the largest positive trends in terms of extreme wet years (Fig. S1), but all trends here are not statistically significant, probably because of the small available sample. Thus, the observed trends from Fig. 1 are mostly projected to continue, with significant warming for all oases, wetter conditions at Guelta d'Archei and Kaouar under a high emission scenario, and no clear signals for the remaining oases. Consequently, the high emission scenario will exacerbate climate change for all oases in terms of air temperature. No significant changes are projected for mean precipitation, except for oases in the southeastern Sahara, an area that could see an increase in precipitation under a high emission scenario, as shown by CMIP6 models too (Alzmaroui, 2020).

Changes in actual evaporation between RCP8.5 for 2071–2100 and the baseline mimic those of precipitation, as expected for water-limited locations. The correlation coefficient between all monthly precipitation and actual evaporation changes is very high (0.87), and the overall average of precipitation change minus actual evaporation change is only −0.04 mm·month^{-1}.

5. Conclusions and recommendations

This study has outlined the connections between climate change and oases dynamics. It has also presented the projected changes in air temperature and precipitation in northern Africa for the end of the century, illustrating the vulnerability of oases to climate change. The projected changes in air temperature under the RCP8.5 scenario are statistically significant for all oases, with more than 4–4.5 °C warming overall, which is projected to surpass 5 °C warming for the majority of the considered sites in the period 2071–2100. Furthermore, as far as mean precipitation is concerned, no significant changes are projected, except for oases in the southeastern Sahara.

The novelty of the study resides in the fact that it not only considers climate issues, but also other drivers which influence oasiś dynamics. It also outlines the risks associated with the growing demands on oaseś resources.

Whereas the observed trends and the projections made are based on climate models and follow a pattern of global warming, a common feature of oases is that their resources are under pressure by increasing resource demands, due to population growth. In this context, there is a need to design and implement strategies that may assist the efforts to limit the degradation of these vulnerable, yet important areas.

Some of these strategies are:

i. Periodical checks on the levels of groundwater, so that changes may be better monitored.
ii. The implementation of measures to reduce the reliance on groundwater for irrigation, such as rainwater harvesting and better control of illegal water pumping.
iii. Encouraging settlements to use water resources more efficiently, keeping people there, and reducing levels of land abandonment.
iv. Encouraging the use of drought-resistant crops and fodder.

Apart from shedding some light on the mechanisms driving ecosystem changes, further efforts are needed to better understand how climate variability in the northern African region affects ecosystems such as oases. Moreover, a closer monitoring of air temperature and precipitation levels across time may be helpful in guiding a more sustainable use of oases.

In the long run, the simulated changes in air temperature and precipitation suggest that oases could be affected in negative ways. This may include a greater demand for groundwater to make up for decreases in precipitation, and a reduction in the levels of groundwater replenishment.

Data availability.

The datasets generated and analysed in this study are available at the following links: CHIRPS: https://data.chc.ucsb.edu/products/CHIRPS-2.0/africa_monthly/bils/ (Funk et al. 2014). CHIRTSmax: https://data.chc.ucsb.edu/products/CHIRTSmonthly/netcdf/ https://www.chc.ucsb.edu/data/chirtsmonthly (Funk et al. 2019). GRACE: https://podaac.jpl.nasa.gov/dataset/TELLUS_GRAC-GRFO_MASCON_CRI_GRID_RL06_V2 (Wiese et al. 2019). CORDEX: https://esgf-node.ipsl.upmc.fr/search/cordex-ipsl/. Version 0.2 of the code used in data processing and visualization is preserved at https://doi.org/10.5281/zenodo.5831115, available via the GNU General Public Licence v3.0. The code is developed openly at https://github.com/matsoukas/oasis-climate. Moreover, the GEMS and CORDEX data used in this research can be found there. Sentinel-2 10-Meter Land Use/Land Cover: https://livingatlas.arcgis.com/landcover/.

CRediT authorship contribution statement

Walter Leal Filho: Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Robert Stojanov:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christos Matsoukas:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Roberto Ingrosso:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **James A. Franke:** Writing – original draft, Formal analysis, Data curation. **Francesco S.R. Pausata:** Writing – original draft, Formal analysis. **Tommaso Grassi:** Writing – original draft, Validation, Data curation. **Jaromír Landa:** Visualization, Software, Methodology, Investigation, Data curation. **Cherif Harrouni:** Writing – original draft.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112287.

References

Alcalá, F.J., Martínez-Valderrama, J., Robles-Marín, P., Guerrera, F., Martín-Martín, M., Raffaelli, G., Tejera de León, J., Asebriy, L., 2015. A hydrological–economic model for sustainable groundwater use in sparse-data drylands: application to the Amtoudi Oasis in southern Morocco, northern Sahara. Sci. Total Environ. 537, 309–322. https://doi.org/10.1016/j.scitotenv.2015.07.062.

Alcalá, F.J., Martín-Martín, M., Guerrera, F., Martínez-Valderrama, J., Robles-Marín, P., 2018. A feasible methodology for groundwater resource modelling for sustainable use in sparse-data drylands: application to the Amtoudi Oasis in the northern Sahara. Sci. Total Environ. 630, 1246–1257. https://doi.org/10.1016/j.scitotenv.2018.02.294.

Almazroui, M., Saeed, F., Saeed, S., Islam, M.N., Ismail, M., Klutse, N.A.B., Siddiqui, M. H., 2020. Projected change in temperature and precipitation over Africa from CMIP6. Earth Syst. Environ. 4, 455–475. https://doi.org/10.1007/s41748-020-00161-x.

Watkins, M.M., Wiese, D.N., Yuan, D.-N., Boening, C., Landerer, F.W., 2015. Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons. J. Geophys. Res. Solid Earth 120, 2648–2671. https://doi.org/10.1002/2014JB011547.

Ben Salem, A., Ben Salem, S., Khebiza Yacoubi, M., Messouli, M., 2019. Ecosystem services demand management under climate change scenarios: use of WEAP software in case of water demand in Ziz Basin, Morocco. In: Karmaoui, A. (edit.) Climate Change and Its Impact on Ecosystem Services and Biodiversity in Arid and Semi-Arid Zones, 45-65. Hershey, PA: IGI Global. http://doi:10.4018/978-1-5225-7387-6.ch003.

Davison, A.C., Hinckley, D.V., 1997. Bootstrap Methods and their Application. Cambridge Series on Statistical and Probabilistic Mathematics. Cambridge University Press, Cambridge, United Kingdom.

Dhaouadi, L., Besser, H., Wassar, F., Kharbout, N., Brahim, N.B., Wahba, M.A., Kang, Y. K., 2020. Agriculture sustainability in arid lands of southern Tunisia: ecological impacts of irrigation water quality and human practices. Irrig. Drain. https://doi.org/10.1002/ird.2492.

Dosio, A., 2017. Projection of temperature and heat waves for Africa with an ensemble of CORDEX Regional Climate Models. Clim. Dyn. 49, 493–519. https://doi.org/10.1007/s00382-016-3355-5.

Frappart, F., 2020. Groundwater storage changes in the major north African transboundary aquifer systems during the GRACE Era (2003–2016). Water 12, 2669. https://doi.org/10.3390/w12102669.

Funk, C.C., Peterson, P.J., Landsfeld, M.F., Pedreros, D.H., Verdin, J.P., Rowland, J.D., Romero, B.E., Husak, G.J., Michaelsen, J.C., Verdin, A.P., 2014. A quasi-global precipitation time series for drought monitoring: U.S. Geol. Survey Data Series 832, 4 p.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. Data 2 (1), 150066. https://doi.org/10.1038/sdata.2015.66.

Funk, C., Peterson, P., Peterson, S., Shukla, S., Davenport, F., Michaelsen, J., Knapp, K.R., Landsfeld, M., Husak, G., Harrison, L., Rowland, J., Budde, M., Meiburg, A., Dinku, T., Pedreros, D., Mata, N., 2019. A High-resolution 1983–2016 Tmax climate data record based on infrared temperatures and stations by the Climate Hazard Center. J. Clim. 32 (17), 5639–5658. https://doi.org/10.1175/JCLI-D-18-0698.1.

Giorgi, F., Jones, C., Asrar, G.R., 2009. Addressing climate information needs at the regional level: The CORDEX framework. WMO Bull. 58, 175–183.

Goldberg-Yehuda, N., Assouline, S., Mau, Y., Nachshon, U., 2022. Compaction effects on evaporation and salt precipitation in drying porous media. Hydrol. Earth Syst. Sci. 26, 2499–2517. https://doi.org/10.5194/hess-26-2499-2022.

Gonçalvès, J., Deschamps, P., Hamelin, B., Vallet-Coulomb, C., Petersen, J., Chekireb, A., 2020. Revisiting recharge and sustainability of the North-WesternSahara aquifers. Reg. Environ. Chang. 20 (2), 47. https://doi.org/10.1007/s10113-020-01627-4.

Haj-Amora, Z., Acharjeeb, T.K., Dhaouadi, L., Bouri, S. Impacts of climate change on irrigation water requirement of date palms under future salinity trend in coastal aquifer of Tunisian oasis. Agric. Water Manage. 228. DOI: https://doi.org/10.1016/j.agwat.2019.105843.

Hamed, Y., Hadji, R., Redhaounia, B., Zighmi, K., Bâali, F., El Gayar, A., 2018. Climate impact on surface and groundwater in North Africa: a global synthesis of findings and recommendations. Euro-Mediterranean J. Environ. Integr. https://doi.org/10.1007/s41207-018-0059-8.

Han, S., Hu, H., Yang, D., et al., 2009. Differences in changes of potential evaporation in the mountainous and oasis regions of the Tarim basin, northwest China. Sci. China Ser. E-Technol. Sci. 52, 1981–1989. https://doi.org/10.1007/s11431-009-0123-3.

Hausfather, Z., Peters, G.P., 2020. Emissions – the 'business as usual' story is misleading. Nature 577 (7792), 618–620.

Kendall, M.G., 1975. Rank Correlation Methods. Oxford University Press, New York.

Lauri, P., Barkaoui, K., Ater, M., Rosati, A., 2019. Agroforestry for fruit trees in the temperate Europe and dry Mediterranean. In: Mosquera-Losada, M.R., Prabhu, R. (Eds.), Agroforestry for Sustainable Agriculture. Burleigh Dodds Science Publishing, Cambridge, pp. 385–418.

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 13, 245–259. https://doi.org/10.2307/1907187.

Marks, L., Salem, A., Welc, F., Nitychoruk, J., Chen, Z., Blaauw, M., Zalat, A., Majecka, A., Szymanek, M., Chodyka, M., Tołoczko-Pasek, A., Sun, Q., Zhao, X., Jiang, J., 2018. Holocene lake sediments from the Faiyum Oasis in Egypt: a record of environmental and climate change. Boreas 47 (1), 62–79. https://doi.org/10.1111/bor.12251.

Qaddouri, A., Lee, V., 2011. The Canadian Global Environmental Multiscale model on the Yin-Yang grid system. Q. J. R. Meteorolog. Soc. 137 (660), 1913–1926. https://doi.org/10.1002/qj.873.

Renevot, G., Bouaziz, A., Ruf, T., Raki, 2009. Pratiques d'irrigation du palmier dattier dans les systèmes oasiens du Tafilalet, Maroc. In Symposium international «agriculture durable en région Méditerranéenne (AGDUMED)», Rabat, Maroc, 14-16 mai 2009. p 16.

Schilling, J., Freier, K.P., Hertig, E., Scheffran, J., 2012. Climate change, vulnerability and adaptation in North Africa with focus on Morocco. Agr Ecosyst Environ 156, 12–26. https://doi.org/10.1016/j.agee.2012.04.021.

Schwalm, C.R., Glendon, S., Duffy, P.B., 2020. RCP8.5 tracks cumulative CO_2 emissions. Proc. Natl. Acad. Sci. 117 (33), 19656–19657.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63, 1379–1389.

Wang, J., Xue, L., Liu, Y., Ni, T., Wu, Y., Yang, M., Han, Q., Bai, Q., Li, X., 2021. The analytical indicators to explain the distribution of oases in arid zones using the Oases Integrated Analysis Model. Ecol. Ind. 127 https://doi.org/10.1016/j.ecolind.2021.107763.

Wiese, D.N., Yuan, D.-N., Boening, C., Landerer, F.W., Watkins, M.M., 2019. JPL GRACE Mascon Ocean, Ice, and Hydrology Equivalent Water Height RL06 CRI Filtered Version 02. Ver. 02". PO.DAAC, CA, USA. Dataset accessed 2021-01-10 at https://doi.org/10.5067/TEMSC-3JC62.