Projections of extreme soil moisture drought in southern Moroccan watersheds under anthropogenic climate warming

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Abstract. The intensification of drought conditions across North-Western Africa is one of the most expected consequences of anthropogenic global warming. However, the effects of 1.5-3°C policy-relevant global warming on soil moisture drought events remain unknown at the catchment scale. This study provides a comprehensive assessment of these events across four semi-arid catchments in Southern Morocco. We use soil moisture simulation from an ensemble of four Land Surface Models (LSMs) forced with bias-adjusted climate projections from four Global Climate Models (GCMs) under three Representative Concentration Pathways (RCPs 2.6, 6.0, and 8.5). The ensemble projects an unprecedented increase in drought events duration, persistence, and severity, driven by global warming intensification, across all catchments. Under 3°C global warming, which is the current track, these catchments are projected to experience decades-long (up to 20 years) mega-droughts compared to a maximum drought duration of 7 years under 1.5°C and 11 months in the historical period (1971-2000). This intensification is accompanied by an increase in drought persistence and order of magnitude (12-16x) of historical drought severity. Given these large changes, historical drought extremes might be considered the new normal conditions in the future. For these reasons, further assessments are needed more urgently than ever to investigate the impact of these extreme events on society and evaluate possible mitigation strategies in the context of uncertainty to provide reliable information to minimize the negative effects of these events.

Key words: drought, soil moisture, global warming, watershed, Morocco

1. Introduction

North-Western Africa is regularly affected by severe drought episodes because of the strong inter-annual variability of precipitation (Driouech et al. 2013; Esper et al. 2007; Knippertz et al. 2003; Lionello 2012; Touchan et al. 2008; Tramblay et al. 2013). These climatic extremes affect ecosystems, the economy, and more importantly human livelihood. The heavy reliance on rainfed agriculture, particularly for rural populations which are mostly poor, leads to the pronounced vulnerability to drought events in the region (Byers et al. 2018; Lerner-Lam 2007; Schilling et al. 2012; Schilling et al. 2020; Waha et al. 2017). For example, about 90% of agricultural land in Morocco depends on precipitation regimes and mainly consists of small traditional farms that produce 70% of agricultural GDP, employ 75% of the rural population, and are responsible for the bulk of the country’s basic food supplies (Bazza et al. 2018). Severe drought, therefore, can be extremely costly and lead to devastating impacts in the country. For example, drought episodes of 1994-1995 resulted in a 7.6% GDP loss reducing rural employment by 60% (Bazza et al. 2018; Verner et al. 2018). The 1999 drought affected more than one million hectares of crops with an estimated cost of...
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900 million $ US, at minimum, reported by the insurance sector (http://www.emdat.be/) as a large number of farmers lacked insurance and only received little compensation for their losses (VERNER et al. 2018). Recent drought episodes caused a decrease in agriculture production which adversely affected more than 700,000 people in 2006-2007 and resulted in a devastating 3% drop in economic growth in 2015-2016 (BAZZA et al. 2018; VERNER et al. 2018).

Society as a whole, and poor populations, in particular, will likely pay the heaviest price for the warming and drying trend across Morocco (ALEXANDER 2016; DRIQUECH et al. 2020b; TRAMBLAY et al. 2013; TRAMBLAY et al. 2020). In upcoming decades, a likely increase in dry spell length and frequency is found in terms of precipitation, soil moisture, and evapotranspiration in the Mediterranean basin due to anthropogenic global warming (DRIQUECH et al. 2020a; GREVE & SENEVIRATNE 2015; GREVE et al. 2014; HOEGH-GULDBERG et al. 2018; HUANG et al. 2016; IPCC 2012; ORLowsky & SENEVIRATNE 2013; POLADE et al. 2017; TRAMBLAY et al. 2018; TRENBERTH et al. 2014). However, the effects of global warming on the characteristics of soil moisture-related drought events are still unknown at the local scale (e.g., drought duration and area). In particular, stakeholders and water managers need solid information about future changes in drought and soil moisture characteristics in the south Moroccan watersheds.

Droughts start with a precipitation deficit which propagates into a reduction in soil moisture and surface and subsurface water depletion (WMO 2018). However, the translation from precipitation deficit into soil moisture is not linear and depends on several processes that control the surface water balance (BERG & SHEFFIELD 2018; KONAPALA & MISHRA 2017). Therefore, soil moisture is considered an integrative indicator for drought because it reflects the balance between rainfall, evapotranspiration, and total runoff (surface and subsurface) (KEYANTASH & DRACUP 2002). In addition, soil moisture persistence was found to be an important driver of projected changes in droughts due to the carry-over effect of soil moisture deficit from one season to the next, which can cause year-round drought events (IPCC 2012; WANG 2005). Soil moisture drying can directly impact crop development and yield, cause vegetation stress, enhance the risk of wildfires, affect biodiversity, and pose great threats to food security and livestock farming (PEICHL et al. 2019; XU et al. 2019a).

Soil moisture drought can be monitored through various metrics that consider precipitation (atmospheric supply) and potential evapotranspiration (atmospheric demand) (BERG & SHEFFIELD 2018). The Palmer Drought Severity Index (PDSI) uses a simple water balance model to measure moisture deficit (DAI 2011). Even though these metrics are appealing and may be accepted for present and past conditions, they come with many shortcomings when applied to analyze future drought trends (BERG & SHEFFIELD 2018; GREVE et al. 2019). The parameterization of potential evapotranspiration in such measurements often depends on temperature. This has been criticized, and we have found that future drought and aridity have been overestimated (SHEFFIELD et al. 2012; TRAMBLAY et al. 2018; TRENBERTH et al. 2014). Furthermore, these metrics are essentially a lumping of many hydrological processes, important to drought development, into a greatly simplified model (BERG & SHEFFIELD 2018). These measurements use potential evapotranspiration as an approximation of actual evapotranspiration. Nevertheless, it neglects soil moisture and vegetation control on evapotranspiration (IPCC 2014). For example, these metrics do not account for the future increases in atmospheric CO₂ on stomatal conductance which was shown to reduce the projected increase in potential evapotranspiration leading to wetter soils, thereby fundamentally changing drought projections (GREVE et al. 2019; MILLY & DUNNE 2016; SWANN et al. 2016; TRAMBLAY et al. 2020; YANG et al. 2019).

Using simulated soil moisture from the recent and more sophisticated land-surface and hydrological models (offline or coupled to climate models) is less problematic for drought analysis than these simplistic metrics. However, there is considerable
variability in future soil moisture projections due to uncertainty in climate projections and hydrologic model parameterizations (BOSSHARD et al. 2013; DONNELLY et al. 2017; GOSLING et al. 2017; LU et al. 2019; MARX et al. 2018; SAMANIEGO et al. 2013; SAMANIEGO et al. 2017; THOBER et al. 2018). Hence, multi-model ensembles are fundamentally required to provide a comprehensive assessment of soil moisture drought. In this study, we assess the impact of global warming on soil moisture drought events using a large multi-model ensemble of 4 general circulation models (GCMs), four land-surface models (LSMs), and three representative concentration pathway scenarios (RCPs). This analysis answers the following research questions:

- What is the magnitude of changes in the characteristics of extreme soil moisture drought events across the southern catchments of Morocco under three policy-relevant global warming levels of 1.5, 2, and 3°C compared to historical conditions?

- What is the implication of future drought extremes in terms of changes in soil water content availability (aridity) over these catchments?

2. Methods

2.1. Study area

The study area covers four semi-arid catchments in southern Morocco, shown in Figure 1. They encompass all rainfed agriculture areas of significant importance for Morocco's economy and are considered the backbone of rural populations. We delineated nine catchments based on the HydroBASINS polygon layers from the HydroSHEDS database (LEHNER & GRILL 2013; LEHNER et al. 2008).

Figure 1: Geographical location, elevation, and precipitation across the four southern Moroccan catchments. The catchments are delineated based on the HydroBASINS polygon layers from the HydroSHEDS database (LEHNER & GRILL 2013; LEHNER et al. 2008). The elevation map is provided by http://www.ngdc.noaa.gov/mgg/topo/globe.html. Precipitation map presents the annual average during the period 1981-2008 computed from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) time-series (FUNK et al. 2015).
Mountainous areas of the Atlas Mountains dominate catchment topography. The pronounced orography strongly influences the distribution of precipitation and separates the hyper-arid conditions of the Sahara Desert in the south from more temperate northern areas. Winter months are the most prevalent wet season with substantial inter-annual rainfall variability in these parts. Climate variability in these areas is connected to large-scale atmospheric circulations, the Atlantic Ocean's influence, and the local impacts of orography and the Sahara Desert (DROUECH et al. 2013; KNIPPERTZ et al. 2003).

2.2. Datasets

This study used an ensemble of monthly soil moisture simulations from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) phase 2b experiment (WARSZAWSKI et al. 2014). The ensemble consists of four state-of-the-art LSMs, presented in Table 1, driven by downscaled and bias-adjusted climate forcing data from four GCMs (GFDL-ESM2M, IPSL-CM5A-LR, HadGEM2-ES, and MIROC5) under historical conditions during 1850-2005 and three RCPs (2.6, 6.0, and 8.5) during 2006-2100 at 0.5° by 0.5° (~50 km at the equator) gridded spatial resolution. Soil moisture is simulated for different depths across LSMs which we integrate into depths of 1 m for the drought analysis.

To evaluate the performance of the different LSMs, we compared simulated soil moisture to observations from the European Space Agency (ESA) Climate Change Initiative (CCI) project (DORIGO et al. 2017; GRUBER et al. 2017; GRUBER et al. 2019). ESA CCI is the first satellite-based soil moisture time-series spanning over 40 years and is currently available globally on a daily basis at 0.25° by 0.25° resolution (~25 km at the equator). ESA CCI dataset is derived by merging active and passive microwave-based soil moisture of the first centimeters of the soil from multiple satellite missions (LIU et al. 2011; WAGNER et al. 2012).

Table 1: Information on the LSMs used in this study

<table>
<thead>
<tr>
<th>Model</th>
<th>Institution</th>
<th>Soil layers</th>
<th>Evaporation Scheme</th>
<th>Runoff scheme</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Community Land Model version 4.5 (CLM45)</td>
<td>National Center for Atmospheric Research, USA</td>
<td>15</td>
<td>Monin-Obukhov Similarity Theory</td>
<td>Saturation-excess</td>
<td>(THIERY et al. 2017)</td>
</tr>
<tr>
<td>Joint UK Land Environment Simulator (JULES)</td>
<td>Met Office, United Kingdom</td>
<td>4</td>
<td>Penman-Monteith</td>
<td>Infiltration-excess, Saturation-excess</td>
<td>(BEST et al. 2011)</td>
</tr>
<tr>
<td>Lund Potsdam Jena managed Land (LPJML)</td>
<td>Potsdam Institute for Climate Impact Research, Germany</td>
<td>5</td>
<td>Priestley-Taylor Method</td>
<td>Saturation-excess</td>
<td>(SITCH et al. 2003)</td>
</tr>
<tr>
<td>Organizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE)</td>
<td>Institut Pierre Simon Laplace (IPSL), France</td>
<td>11</td>
<td>Penman-Monteith Method</td>
<td>Saturation-excess</td>
<td>(GUIMBERTEAU et al. 2018)</td>
</tr>
</tbody>
</table>

The ESA CCI product offers several quality flags and only soil moisture values considered reliable are taken into account (LOEW 2008; PARINUSSA et al. 2011). A comprehensive validation of the ESA CCI soil moisture using in situ observations was done in many parts of the world and shows a close agreement with observations (DORIGO et al. 2015; PASIK 2019). We used The ESA CCI soil moisture in hundreds of hydrological and meteorological studies worldwide. A list of papers using ESA CCI soil moisture is available over https://www.esa-soilmoisture-cci.org/node/137. For example, the ESA CCI dataset is used to evaluate soil moisture from multiple LSMs, hydrological models,

ESA CCI only accounts for volumetric soil moisture in the first centimeters of the soil, representing a somewhat different quantity than LSMs simulated soil moisture. LSMs provide soil moisture content in water stored in different soil layers at given depths due to the other soil representations across LSMs. These differences translate to varying temporal soil moisture dynamics between LSMs, making inter-comparing them challenging. We only considered soil moisture content in the upper soil layer of ≤10 cm (DORIGO et al. 2015; LAUER et al. 2017) to overcome this issue. Even though the upper soil layer in LPJML equals 20 cm, we decided to keep it in the analysis to avoid reducing the ensemble size. We converted LSMs soil moisture content of the upper soil layer to the volumetric unit (m$^3$ m$^{-3}$) to match ESA CCI by dividing by the layer thickness and water density 998.2 kg m$^{-3}$ (20°C). The evaluation period of 1988-2005 is chosen because ESA CCI has poorer observational density before this date (Fig.5 in DORIGO et al. 2015).

2.3. Time sampling

In this study, the period 1971-2000 $T_0$ is selected to represent historical climate conditions. For future conditions, we followed the sampling approach in JAMES et al. (2017) to define global warming periods. First, the offset of global mean temperature between the pre-industrial period of 1881-1910 and 1971-2000 is assumed to equal 0.46°C (VAUTARD et al. 2014). Then, 30-year periods ($T_{∆}$, presented in Table 2) are estimated, per GCM and RCP combination, when global warming reaches or exceeds one of the three policy-relevant warming levels of 1.5, 2, or 3°C minus 0.46°C. This approach provides a large ensemble which is essential for a robust analysis of drought events under different warming levels (SAMANIEGO et al. 2018).

2.4. Soil Moisture Drought Identification and Characteristics

Similar to previous assessments (SAMANIEGO et al. 2013; SAMANIEGO et al. 2018), a grid cell is considered under drought if the soil moisture index (SMI) is less than the value corresponding to the 20th percentile of the historical conditions $T_0$. This threshold reflects moderate drought conditions or even worse according to the US Drought Monitor classification (USDM, http://droughtmonitor.unl.edu/). The SMI is derived from soil moisture $x_t$ of each month t in a given period T (warning $T_{∆}$ or historical $T_0$) as:

$$SMI_t = F_{T_0}(x_t) \forall t \in T \quad (1)$$

$F_{T_0}$ is the cumulative distribution function estimated using the kernel density estimate $F_{T_0}$ of
simulated soil moisture during the historical period $T_0$. $f$ is defined as:

$$f_{T_0}(x) = \frac{1}{nh} \sum_{k=1}^{n} K\left(\frac{x-x_k}{h}\right) \quad (2)$$

$x - x_k$ are soil moisture values of a given calendar month $n$ during the period $T_0$. $K$ is a Gaussian kernel function with a smoothing parameter $h$ which was estimated following Silverman’s rule of thumb for each calendar month, grid cell, and GCM-LSM combinations. Drought events are identified in space and time using a clustering algorithm previously developed and applied to study soil moisture drought in Germany and Europe (SAMANIEGO et al. 2013; SAMANIEGO et al. 2018). In space, all cells below the 20th percentile threshold are consolidated into drought clusters. In time, overlapping drought clusters at consecutive time steps are grouped into spatiotemporal drought events. It is worth noting that we chose to calculate the persistence of moderate (<20th percentile) instead of severe (<10th percentile) drought conditions because they both can have extreme impacts as a result of the high vulnerability and low to absent coping capacity in the study domain.

A drought event can be characterized in terms of its duration and severity (MASIH et al. 2014; SHEFFIELD & WOOD 2008). Duration is the time from the onset until the end of an event and equals the average number of months estimated over all the cells within a drought event. Severity (or magnitude) equals the sum of soil moisture deficit below the threshold value (20th percentile) from the onset until the end of an event. In this study, we only focused on the analysis of the most extreme drought events (that is, the longest, largest, and most severe) per period $T$ and GCM-LSM combinations.

In addition to the characteristics discussed above, we also computed drought persistence which characterizes the level to which an area is prone to remain under drought when it already suffers one (SAMANIEGO et al. 2013). Drought persistence is estimated using a two-state Markov chain ($SMI_t \leq 0.2$ and $0.2 < SMI_t \leq 1 \forall t \in T$) as the probability $\pi_{00}$:

$$\pi_{00} = \Pr[SMI(x_{t+1}) \leq 0.2 | SMI(x_t) \leq 0.2] \forall t \in T \quad (3)$$

$\pi_{00}$ is computed at a monthly time step for each grid cell, period, RCP, and GCM-LSM combinations.

Finally, due to its relevance for water planners, we also estimate the change in available soil water content (aridity) under drought condition as:

$$\Delta x_{T_0} = F_{T_0}^{-1}(0.2) - F_{T_0}^{-1}(0.2) \quad (4)$$

$F^{-1}(0.2)$ is the soil moisture value corresponding to the 20th percentile during a given period (warming $T_0$ or historical $T_0$ for each cell, RCP, and GCM-LSM combinations. $\Delta x$ is reported as seasonal averages of the estimated values for each month. The results are represented by the average over all the cells within a given catchment.

3. Results

3.1. Model Verification

The Multi-model ensemble skill in reproducing multi-year annual means of observed soil moisture across the four catchments is assessed during the period 1988-2005. The ensemble mean shows reasonably good skill in simulating the observed annual soil moisture (Fig. 2) with a correlation value of 0.76 and a mean relative bias of -24%. Similarly, GCM-LSM individual combinations underestimate the observed annual means (by 25-45%), except LPJML showing a positive bias of 13%. These differences are higher approaching desert regions, which is of minor importance due to the small soil moisture content in such environments. We note that the verification performed here is quite rigorous as the layer thickness considered is not consistent across LSMS and between LSMS and satellite observations, which in turn are associated with significant uncertainties. Therefore, this verification can mostly be used as a qualitative assessment of these models.

3.2. Changes in Drought Events Characteristics

From Table 3, a large increase in drought event duration is projected as global warming intensifies. The ensemble median duration of the longest events is estimated at a maximum of 11 months (IQR 6-15 months) in Tensift catchment...
under the historical period (1971-2000). These events become many folds longer at around 87 months (IQR 50-132), or 7 years, as soon as global warming reaches the 1.5°C Paris Agreement target. All the southern catchments are expected to experience mega-droughts that last more than 10 years (120 months) under 2°C global warming and approaches 20 years (240 months) under 3°C warming (Table 3).

![Figure 2: Evaluation of simulated soil moisture of the upper soil layer. (A-E) Scatter plots of multi-year annual means of observed and simulated volumetric soil moisture for all LSM-GCM combinations (A-D) and the multi-model ensemble mean (E). Each circle in the scatter plots corresponds to the annual mean soil moisture in a given year during the period 1988-2005 and a grid cell located within the nine catchments. (F) Relative bias between simulated and observed soil moisture.](image)

Under these decade long events, drought persistence, estimated as the likelihood of drought-prone areas to remain under drought when already suffering one (SAMANIEGO et al. 2017), is greater or equal 0.8 (80% of the time) across all catchments even under the 1.5°C climate mitigation future (Table 3). As global warming intensifies, the catchments are projected to experience high persistent drought extremes, with an average value of \( \pi_{00} \) equals 0.9 (Table 3). Additionally, the exacerbation of these events is accompanied by many folds of their historical severity as global warming intensifies (Table 3). Under the lowest warming level of 1.5°C, the ensemble median severity increases by around 6 folds over the drier catchments of Draa and Ziz-Rheris and around 3.8 folds across Souss-Massa and Tensift compared to the historical period (Table 3). As global warming gets more intense, the increase in drought severity continues and highlights the sensitivity of these catchments as they experience a 5-10x (12-16x) order of magnitude of historical events severity under 2°C (3°C).
3.3. Changes in Available Soil Water Content under Drought

Given this large exacerbation of future drought extremes, historical events “may no longer be classified as extremes” (SAMANIEGO et al. 2018), but rather as the new normal conditions. This points to the crucial question for water managers on what these new droughts imply for adaptation policies across the nine catchments. Similar to previous studies (SAMANIEGO et al. 2018), we answer this important question by calculating the absolute change in available soil water content corresponding to the 20th percentile drought threshold between historical and future conditions. This quantity indicates the change in available soil water content, and thereby aridity, under drought conditions. The absolute change in soil water content is calculated for each season (DJF, MAM, JJA, and SON) and averaged over each catchment.

From the analysis of the ensemble projections, presented in Figure 3, all catchments experience a decrease in soil water content in all seasons and under all global warming levels. Overall, the highest decrease in available soil water content is projected for the winter and spring seasons (Fig. 3). This increase in aridity intensifies with increasing global warming and goes from 12±7 mm (1.5°C) to 15±9 mm (2°C) to 24±8 mm (3°C) soil water content shortage across Morocco. The Souss-Massa and Tensift catchments generally show a higher increase in aridity compared to the Souss-Massa catchment is projected to decrease by 17±9 mm, corresponds to 17,000 km² water shortage. This large decrease is cut by approximately half at 9±7 mm if global warming is limited to the 1.5°C level. Likewise, a

<table>
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<tr>
<th>Detailed Analysis</th>
<th>Draa</th>
<th>Souss-Massa</th>
<th>Tensift</th>
<th>Ziz-Rheris</th>
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<tr>
<td><strong>Drought Duration [months]</strong></td>
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<tr>
<td>1971-2000</td>
<td>13</td>
<td>10</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>1.5°C</td>
<td>162</td>
<td>90</td>
<td>87</td>
<td>135</td>
</tr>
<tr>
<td>2°C</td>
<td>182</td>
<td>110</td>
<td>124</td>
<td>170</td>
</tr>
<tr>
<td>3°C</td>
<td>251</td>
<td>221</td>
<td>217</td>
<td>261</td>
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**Table 3**: Results for drought duration, persistence, and severity averaged over the four catchments under historical (1971-2000) and different global warming conditions. The multi-model ensemble median of drought characteristics is shown along with the interquartile range (25th-75th percentile) as a measure of uncertainty. Drought persistence is expressed as the likelihood (0-1) of drought-prone areas to remain under drought. Drought severity is shown as the ratio of events severity under a warming level to their historical severity.

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<th>Souss-Massa</th>
<th>Tensift</th>
<th>Ziz-Rheris</th>
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<td><strong>Drought Persistence [-]</strong></td>
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<tr>
<td>1971-2000</td>
<td>0.66</td>
<td>0.59</td>
<td>0.57</td>
<td>0.69</td>
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<tr>
<td>1.5°C</td>
<td>0.84</td>
<td>0.81</td>
<td>0.78</td>
<td>0.82</td>
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<tr>
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<td>0.83</td>
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<tr>
<td>3°C</td>
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<td>0.91</td>
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<tr>
<td><strong>Drought Severity [-]</strong></td>
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<tr>
<td>1971-2000</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>1.5°C</td>
<td>6.0</td>
<td>3.8</td>
<td>3.7</td>
<td>6.1</td>
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<tr>
<td>2°C</td>
<td>10.0</td>
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<td>8.5</td>
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<tr>
<td>3°C</td>
<td>13.5</td>
<td>13.7</td>
<td>12.5</td>
<td>15.9</td>
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higher increase of aridity of 22±11 mm at 3°C is projected during winter across the Tensift catchment compared to 11±8 mm under 1.5°C. Catchments of Draa and Ziz-Rheris show a lower decrease in soil water content (Fig. 3) due to lower water supply in these areas. In general, the increase in aridity in all catchments under all warming levels further highlights these environments’ large sensitivity to global warming, regardless of its level.

**Figure 3:** Absolute change in available soil water content (aridity) between different global warming levels and the historical period. Map (top panel) shows the geographical location of the four catchments. Bar plots present the multi-model ensemble mean absolute change (bars) and standard deviation (whiskers) of soil water content during drought events averaged over each catchment for the four seasons (from left to right: DJF, MAM, JJA, and SON). The first bar plot panel (titled Morocco) shows the average across the whole country.

### 4. Discussion

Moroccan catchments are projected to experience drought extremes of unprecedented duration, persistence, and severity due to increasing global warming. Under low climate mitigation, corresponding to 3°C global warming, drought extremes are projected to spread over all catchments, last for decades (10-20 years), with extreme persistence ($\pi_{00} > 0.8$), and many folds ($>10x$) more severe compared to the historical
conditions. This increase in dry spells extremeness appears across generations of climate models based on different scenarios and metrics over the Mediterranean basin. It is deemed very likely with rising global temperature (DAI 2013; DALLAKOPOULOS et al. 2017; DROIUECH et al. 2020a; DUBROVSKY et al. 2014; GREVE & SENEVIRATNE 2015; IPCC 2012; 2013; ORLOWSKY & SENEVIRATNE 2012; ORLOWSKY & SENEVIRATNE 2013; OZTURK et al. 2015; TRENBERTH et al. 2014; WANG 2005; XU et al. 2019b; ZHAO & DAI 2015). Consistent with these projections, reconstructions of past droughts in North-Western Africa also demonstrated that the second half of the twentieth century stands out as the driest among the last nine centuries (TOUCHAN et al. 2011).

This exacerbation of drought extremes is due to the large decrease in soil water availability projected in all seasons, especially in winter and spring, which is mainly a result of the projected decline in precipitation and increase in atmospheric evaporative demand due to high increases in maximum daily temperatures over the Mediterranean (POLADE et al. 2017; SENEVIRATNE et al. 2016). By the end of the 21st century, the projected rainfall reduction is estimated at 38% in Northwestern Africa based on 30 CMIP5 GCMs (POLADE et al. 2017) which is similar to what is projected by the four GCMs used to drive LSMs (Fig. 4). This reduction is deemed very likely and is consistent with the widening of the Hadley Circulation (IPCC 2013). For all catchments, this increase in aridity can be reduced substantially with strong climate mitigation and adaptation, corresponding to the Paris Agreement 1.5°C warming target. Nonetheless, the impact from 1.5°C is still substantial for these southern catchments and highlight their sensitivity to global warming regardless of its degree.

With current policies, the latest data from Climate Tracker (www.climateactiontracker.org) show that the world is on track to warm by 3°C in this century. For the study domain, this comes with a large exacerbation of drought events to a degree that historical extremes may be considered as normal conditions in the future, which was also suggested for the Mediterranean region (NAUMANN et al. 2018; SAMANIEGO et al. 2018). Moreover, the strong decrease in soil water content in all seasons indicates an alteration of the hydrologic regimes toward more arid and hyper-
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81% of projected water scarcity leaving 19% of national water resources for future droughts even if the national pledge under the Paris Agreement succeeds in limiting global warming to the ambitious target of 1.5°C. These measures, however, need to take into account a substantially higher exacerbation of drought extremes under the current track of 3°C global warming. Therefore, further assessments are urgently needed to investigate the impact of these events on society and evaluate possible mitigation strategies in the context of uncertainty in climate projections, land surface and hydrological models, downscaling methods, internal climate variability, and socioeconomic scenarios.

5. Conclusion

Moroccan Southern catchments are projected to face future soil moisture drought extremes with unprecedented duration, persistence, and severity compared to historical conditions (1971-2000). The level of global warming intensification drives the worsening of these extremes. Current policies put the world on track to warm by around 3°C by the end of the century. Under this condition, Southern Moroccan catchments are expected to experience the transformation of historically 11 months lasting events into decades-long (up to 20 years) mega-droughts under 3°C compared to 7 years under 1.5°C. This intensification is accompanied by an increase in drought events persistence and order of magnitude (12-16x) of their historical severity. Given these large implementations of vegetation (e.g., dynamics and response to atmospheric CO₂) and evaporation (e.g., temperature-based, Penman-Monteith, or solving the energy balance) would lead to different evaporative response leaving a wetter or a drier soil and thus can fundamentally change the impact of global warming on droughts (GREVE et al. 2019; MILLY & DUNNE 2016; PRUDHOMME et al. 2014; YANG et al. 2019). Therefore further studies should investigate the merit of these different modeling decisions on drought assessment to reduce uncertainty in future projections of these events. In summary, the results of this investigation highlight the need to adapt to unprecedented drought extremes in the future. Adaptation measures must be taken to minimize the impact of future droughts even if the national pledge under the Paris Agreement succeeds in limiting global warming to the ambitious target of 1.5°C. These measures, however, need to take into account a substantially higher exacerbation of drought extremes under the current track of 3°C global warming. Therefore, further assessments are urgently needed to investigate the impact of these events on society and evaluate possible mitigation strategies in the context of uncertainty in climate projections, land surface and hydrological models, downscaling methods, internal climate variability, and socioeconomic scenarios.

The socioeconomic factors, including population growth, intensive agriculture, and land-use change, were more significant than climate change in North Africa (NIANG 2014). DROOGERS et al. (2012) showed that by 2050, socioeconomic development in Morocco can be responsible for 81% of projected water scarcity leaving 19% attributed to climate change. This emphasized the crucial importance of including land cover and land-use change based on socio-economic scenarios in future projections (TRAMBLAY et al. 2020). Unfortunately, due to the lack of such information in the time of the ISIMIP2b project, human influence (e.g. Dams, reservoirs, irrigation, domestic water use, manufacturing and livestock production) is either absent (ORCHIDEE and JULES) or held fixed at the 2005 level (LPJML and CLM) in LSMs-based projections. Future studies therefore should include socioeconomic-based gridded projections of such influences.

Nonetheless, the consideration of multiple LSMs enables to consider a wide range of process representation, a fundamental requirement to capture the uncertainties originating from the differences across LSMs (DONELLY et al. 2017; GOSLING et al. 2017; MARX et al. 2018; THOBER et al. 2018). The catchments investigated in this study are characterized by a transitional climate regime, under which soil moisture is limited and strongly constrains evapotranspiration (SENDEVIRATNE et al. 2010). Thereby, the representation of soil moisture dynamics, which differ between LSMs, can significantly impact the simulation results. This impact will potentially increase as the catchments transition into drier conditions. For example, the different arid conditions across all catchments, confirming previous works (KOUTROULIS et al. 2019; OZTURK et al. 2018; TRAMBLAY et al. 2018). This change will severely affect vegetation and biodiversity, threaten food security, and increase water abstraction. As a result, it could become increasingly challenging to satisfy the basic needs of a growing population potentially leading to a food crisis, higher inequality levels, social instability, and conflict (GLEICK 2014; GODFRAY et al. 2010; GROLLE 2015; MAHARATNA 2014; SCHILLING et al. 2020; VON UEKULL et al. 2016).

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changes, historical drought extremes can be considered as the new normal conditions in the future. A strong increase in aridity drives these new conditions during all seasons with a soil moisture deficit of up to 17-22 mm under 3°C global warming compared to 9-11 mm under 1.5°C. Even though the intensification of drought conditions is reduced significantly under the ambitious 1.5°C Paris target, it is still substantial further highlighting the high sensitivity of these catchments to global warming regardless of its level. Therefore, adaptation measures must be implemented and must consider the substantially higher exacerbation of drought extremes under the current track to 3°C global warming. Further assessments are needed more urgently than ever to investigate the impact of these events on society and evaluate possible mitigation strategies that consider all uncertainty sources to provide reliable information to minimize the negative effects of these climatic extremes.

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