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Implications of changes in climate and human development on 21st-century global drought risk

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ABSTRACT

Climate change is expected to exacerbate drought conditions over many global regions. However, the future risk posed by droughts depends not only on the climate-induced changes but also on the changes in societal exposure and vulnerability to droughts. Here we illustrate how the consideration of human vulnerability alters global drought risk associated with runoff (hydrological) and soil moisture (agriculture) droughts during the 21st-century. We combine the changes in drought frequency, population growth, and human development as a proxy of vulnerability to project global drought risk under plausible climate and socioeconomic development pathways. Results indicate that the shift toward a pathway of high greenhouse gas emissions and socioeconomic inequality leads to i) increased population exposure to runoff and soil moisture droughts by 81% and seven folds, respectively, and ii) a stagnation of human development. These consequences are more pronounced for populations living in low than in very high human development countries. In particular, Sub-Saharan Africa and South Asia, where the majority of the world's less developed countries are located, fare the worst in terms of future drought risk. The disparity in risk between low and very high human development countries can be substantially reduced in the presence of a shift toward a world of rapid and sustainable development that actively reduces social inequality and emissions. Our results underscore the importance of rapid human development in hotspots of drought risk where effective adaptation is most needed to reduce future drought impacts.

1. Introduction

Droughts are amongst the costliest natural disasters that impact human livelihoods and cause massive economic and ecological damages every year (Keyantash and Dracup, 2002; Mishra and Singh, 2010; Dai, 2011). These losses incur from direct impacts on agriculture, water resources, tourism, ecosystems, and human welfare and differ profoundly depending on a nation's level of development and coping capabilities (Mishra and Singh, 2010; Gray and Mueller, 2012; Masih et al., 2014; Grolle, 2015; Smith and Matthews, 2015; Zhang and Zhou, 2015; Sweet et al., 2017; Vicente-Serrano et al., 2020). The massive socioeconomic and ecological consequences of droughts have motivated large research efforts, leading to an improved understanding of drought response to climate change (e.g., Sheffield and Wood, 2008; Dai, 2013; Prudhomme et al., 2014; Trenberth et al., 2014; Zhao and Dai, 2015; Lehner et al., 2017; Samaniego et al., 2018; Ault, 2020; Cook et al., 2020; Pokhrel et al., 2021). These efforts have revealed likely increases in drought intensity and frequency over many global regions in response to anthropogenic global warming. However, future risk is not only contingent on these climate change-induced trends but also on the societal exposure and vulnerability according to the Intergovernmental Panel on Climate Change (IPCC et al., 2012). Increasingly, studies have shown that the world's most vulnerable populations are disproportionately exposed to the adverse impacts of climate change (Satoh et al., 2017; Byers et al., 2018; Harrington et al., 2018; King and Harrington, 2018; Russo et al., 2019). In this vein, we seek to illustrate how vulnerability would alter future drought risk from a global perspective. Our study builds on substantive previous drought studies reviewed in the following, to provide new insights regarding future drought risk when a proxy of broad vulnerability to climate change is considered.

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The existing body of literature has focused on projecting societal exposure to droughts. Societal exposure is expected to increase globally because of the increased occurrence of droughts in response to higher greenhouse-gas-induced global warming (Smirnov et al., 2016; Liu et al., 2018; Lange et al., 2020). Using a suite of global hydrological models driven by four climate models and historically constant global population (set as in the year 2005), Lange et al. (2020) estimated a 370% increase in population annually exposed to exceptional soil moisture (agriculture) droughts in response to 2 °C global warming. Societal exposure to future droughts is also shaped by the changes in socioeconomic conditions as reflected in the Shared Socioeconomic Pathways (SSPs, Riahi et al., 2017). In a rapid urbanization pathway (SSP1), the exposure of global urban population to severe soil moisture droughts would increase from 350 to 410 million people between 1.5 and 2 °C global warming (Liu et al., 2018). With medium population growth (SSP2), global population in extreme-to-exceptional terrestrial water storage drought is projected to increase from 3% to 8% over the 21st century in a medium population growth pathway (Pokhrel et al., 2021). In a high population growth pathway (SSP3), 60% of the global population is projected to experience more frequent and severe meteorological droughts, mainly in Asia and Africa, in response to 4 °C global warming (Spinoni et al., 2021).

These studies have covered only two (drought hazard and exposure) of the three dimensions that constitute risk. They did not account of vulnerability and hence do not present a complete risk assessment. Consequently, vulnerability has unknown effects on future drought risk globally. Differences in societal exposure between studies also highlight the importance of drought definition. The choice of the drought indicator (e.g., precipitation, soil moisture, and runoff) and truncation level (i.e., a threshold indicating departure from normal leading to drought onset) can affect the magnitude and even the sign of the projected change in drought statistics (Sheffield and Wood, 2007; IPCC et al., 2012; Zhao and Dai, 2015; Cook et al., 2018; Satoh et al., 2021) and thus future exposure and risk. The importance of drought definition necessitated its consideration in this study to address the following research questions: (1) How would the incorporation of vulnerability projections alter future drought risk? and (2) How do climate and socioeconomic changes influence the risk posed by different categories of soil moisture (i.e., agriculture) and runoff (i.e., hydrological) droughts?

We define drought risk as the consequence of drought frequency, population exposure, and human development as a proxy of vulnerability. We project these dimensions globally under plausible pathways of climate and socioeconomic change. We estimate exposure to drought as a result of the projected changes in drought frequency and population growth. Usually, risk estimation consists of applying a robust dose-response relationship to reflect the vulnerability within the exposed population. Given the lack of this relationship and inspired by a recent heatwave risk assessment (Russo et al., 2019), we incorporate projections of the Human Development Index (HDI, Crespo Cuaresma and Lutz, 2016) as a proxy of the broad vulnerability to climate change. The HDI was introduced by the United Nations Development Programme (UNDP) to measure the achievement in key components of a country's human development. The HDI includes income, education, and health, enabling a more comprehensive measure of vulnerability in contrast to the Gross Domestic Product (GDP) used in previous studies (e.g., King and Harrington, 2018). The risk posed by droughts can be driven both by socio-economic and climatic changes, and thus, we examine their individual importance by isolating their contributions under different pathways.

2. Datasets and methods

2.1. Projections of soil moisture and runoff

We use global simulations of soil moisture content and total runoff from the multi-model ensemble (88 members) of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) phase 2b (Frieler et al., 2017). The ensemble consists of eight process-based global Impact Models (IMs; presented in Table S1 in the supporting information and documented in more detail at the ISI-MIP database https://www.isimip.org/impactmodels/). The IMs are: CLM 4.5 (Thiery et al., 2017), ORCHIDEE (Guimberteau et al., 2018), MATSIRO (Takata et al., 2003; Pokhrel et al., 2015; Yokohata et al., 2020), H08 (Hanasaki et al., 2018), PCR-GLOBWB (Wada et al., 2014), WaterGAP2 (Müller Schmied et al., 2016), and LPJmL (Sitch et al., 2003). The IMs are driven by downscaled and bias-adjusted climate forcing data from four Global Climate Models (GCMs: GFDL-ESM2M, IPSL-CM5A-LR, HadGEM2-ES, and MIROC5) of the Coupled Model Intercomparison Project (CMIP5). Climate forcings under historical conditions during 1850–2005 and three Representative Concentration Pathway (RCPs: 2.6, 6.0, and 8.5) during 2006–2100 are used to drive the IMs at the spatial resolution of 0.5° by 0.5° or ~50 km at the equator (Frieler et al., 2017). The baseline period of 1976–2005 is selected to represent near-present climate conditions and the period of 2071–2100 is used to represent long-term future conditions. From the combination of three RCPs, four GCMs, and eight IMs, we obtain a large ensemble with 88 members (note that RCP8.5 simulation were not available from two IMs, Table S1).

The ability of IMs to reproduce various streamflow signatures has been investigated in multiple evaluation studies (Staudinger et al., 2011; Gudmundsson et al., 2012; Velázquez et al., 2013; Giuntoli et al., 2015; Fang et al., 2017; Huang et al., 2017; Vetter et al., 2017; Veldkamp et al., 2018; Zaherpour et al., 2018; Schewe et al., 2019). Recently, we also showed that the IMs capture historical terrestrial water storage (TWS) from Gravity Recovery and Climate Experiment (GRACE) satellite measurements (Pokhrel et al., 2021) and soil moisture drought characteristics from observations (i.e., self-calibrated Palmer Drought Severity Index) and reanalysis in some of world's most drought-prone regions (Elkouk et al., 2021). Consistent with these findings, soil moisture and runoff drought frequency (i.e., percentage of times under drought) shows a high level of agreement between models across the globe during the baseline period (Figs. S3 and S4).

2.2. Projections of drought frequency

Here, soil moisture and total runoff (surface and subsurface) are used to represent agricultural and hydrological droughts, respectively. Agriculture drought corresponds to a period of below-normal soil water content which results in reduced vegetation growth and crop failure. Hydrological drought corresponds to a period when surface water resources, such as river streamflow and water storages in lakes or reservoirs, drop below their local normal conditions (Dai, 2011).

Simulated soil moisture from all models is first integrated across soil layers in the top 1.5 m depth (see Table S1 for details). Then, monthly soil moisture and total runoff are transformed into percentile-based indices, to ensure that their values are comparable between different models and scenarios (Samaniego et al., 2017). The soil moisture index (SMI) and the runoff index (RI) percentile-indices are obtained by fitting a non-parametric function (kernel density estimate) to avoid assumptions about the shape of the distribution which can introduce additional uncertainty in the drought analysis (Samaniego et al., 2013, 2018). The cumulative density function (CDF) is estimated for each calendar month, grid cell, and GCM/IM combination during the baseline period of 1976–2005. The estimated CDF is then used as a reference to draw soil moisture and runoff percentiles during the future period under different RCPs (see Section S1 in the supporting information for further details).

The cells fulfilling $SMI(t) \leq \tau$ and $RI(t) \leq \tau$ during a month t are considered under potential soil moisture and runoff drought, respectively. τ denotes a soil moisture or runoff value occurring less than $\tau \times$ 100% of the time during the baseline period. Drought frequency is then defined as the probability (i.e., percentage of times) when $SMI(t) \leq \tau$ and $RI(t) \leq \tau$, denoted by $\Pr\{SMI(t) \leq \tau\}$ and $\Pr\{RI(t) \leq \tau\}$, for all t. The value of the threshold τ is selected to reflect five drought categories commonly used in drought monitoring systems (Svoboda et al., 2002). The five categories scale from abnormal ($\tau = 0.3$), moderate ($\tau = 0.2$), severe ($\tau = 0.1$), extreme ($\tau = 0.05$), to exceptional ($\tau = 0.02$) drought.

2.3. Projections of population exposure

To estimate exposure to droughts, we use the 0.125° (~12.5 km at the equator) resolution gridded projections of rural and urban population averaged at ten-year intervals during the period 2010–2100 and under SSP1-5 pathways (Jones & O'Neill, 2016; Jones and O'Neill, 2020). These projections were generated by downscaling the national-level SSP-projections of urban and rural population using historical gridded data within a gravity-type model parameterized to reflect the changes underlying each SSP (Jones & O'Neill, 2016). First, we aggregate population projections into the same resolution as IMs. Then, we estimate the number of people located within areas under drought of a given category (defined by τ), at each month, and for each IM, GCM, RCP, and SSP combination. We then calculate the average population affected during a given 30-year period. We use population estimates for 2015 and 2075 (representing the decades of 2010–2019 and 2070–2079, respectively) to calculate the exposure during the 30-year baseline (1976–2005) and future (2071–2100) periods, respectively. Note that we estimate population exposure assuming that soil moisture drought affects rural population the most because of the dependence of their livelihood on agriculture (FAO, 2020), and that the depletion of stored water resources due to runoff drought affects the population in both rural and urban areas (i.e., total population).

While the three RCPs and the five SSPs result in a total of 15 pathway combinations, we select the five most plausible combinations by combining the one climate scenario most plausible for each of the five SSPs (Table S2 presents the reasoning behind these combinations). The pathway combinations consist of 'Sustainability' (SSP1 combined with RCP2.6), 'Middle of the road' (SSP2 combined with RCP6.0), 'Fragmented world' (SSP3 combined with RCP6.0), 'Inequality' (SSP4 combined with RCP6.0), and 'Fossil fuel-based development' (SSP5 combined with RCP8.5). 'Sustainability' is a pathway of rapid and sustainable socioeconomic development and transition toward renewables and reduction of greenhouse gas emissions. 'Middle of the road' is the pathway under which socioeconomic trends follow their historical patterns. 'Fragmented world' and 'Inequality' are pathways of exponential population growth and high socioeconomic inequality. 'Fossil fuel-based development' is a pathway of rapid socioeconomic development as in the path to 'Sustainability' but with a heavy reliance on fossil fuels and high emissions.

2.4. Projections of human development

We use projections of the HDI (Crespo Cuaresma and Lutz, 2016) as a proxy of vulnerability to climate change (Fig. S6). The HDI is estimated as the geometric mean of normalized life expectancy at birth, expected and mean years of schooling, and gross national income (GNI) per capita. The HDI outperforms several measures of national social vulnerability to climate change (Füssel, 2010). It also shows a strong correlation with the Notre Dame-Global Adaptation Initiative Country Index (ND-GAIN) (Russo et al., 2019), an index constructed from 45 indicators of vulnerability and readiness to respond to climate change (Chen et al., 2015). In the absence of ND-GAIN projections, HDI projections thus provide the best alternative to capture countries' broad vulnerability to climate change. We use HDI data from UNDP for the year 2015 and projected HDI values under SSP1-5 for the year 2075 from Crespo Cuaresma and Lutz (2016). It is important to stress that the HDI is not used to measure the actual vulnerability to droughts but rather to illustrate how vulnerability shapes future drought risk.

2.5. Projections of drought risk

Inspired by the risk analysis proposed in Russo et al. (2019), vulnerability can be defined as $1 - HDI$ such that populations with the highest HDI have the lowest vulnerability and vice-versa. An illustrative drought risk index (expressed in %) can be subsequently calculated at each location as the product of drought frequency $Pr\{I(t) \le \tau\}$ using a drought index I of either *SMI* or *RI*, population, and vulnerability ($1 - HDI$):

$$Risk\ index\ (\%) = \Pr\{I(t) \le \tau\}_{hazard} \times Population_{exposure} \times (1 - HDI)_{vulnerability} \times 100$$

Without normalization, the resulting risk index will mainly be driven by population variability because exposure varies more than the values of vulnerability ($1 - HDI$). We normalize exposure using CDF estimates from fitting a Log-Normal distribution to the exposed population during the baseline period (Fig. S7). Similarly, normalized $1 - HDI$ values are drawn from the CDF estimates from fitting a non-parametric kernel density function to $1 - HDI$ in 2015 (Fig. S7). CDF-normalized exposure and $1 - HDI$, therefore, vary within the probability interval [0, 1].

The risk index scores (expressed in %) cannot be interpreted as physical or quantitative estimates of a specific negative drought consequence (Russo et al., 2019), but rather to illustrate how exposure and vulnerability affect the outlook of the future risk. Here, exposure and risk estimates are decomposed into two drivers: climate change and socio-economic change (Jones et al., 2015). Climate change contribution is computed by holding population and vulnerability ($1 - HDI$) constant at the year 2015 and computing exposure and risk under the different RCPs. We do the opposite for socio-economic change, as we hold climate change constant at the baseline period and allow the population and vulnerability to change under the different SSPs. The individual contribution of climate and socio-economic change is then estimated by dividing each one by the sum of the two.

3. Results

The ensemble mean change in drought frequency (Fig. 1a and b) reveals a widespread increase in soil moisture and runoff drought occurrences under RCP8.5 (2071–2100) compared to the baseline period (1976–2005). Areas witnessing an increase in drought frequency include the Mediterranean, Central Europe, the Americas, Southern Africa and Australia, and many parts of Asia as has been reported in earlier works (Prudhomme et al., 2014; Zhao and Dai, 2015; Lehner et al., 2017). Soil moisture droughts show more widespread and higher changes (Fig. 1b). In areas of increase by 20% (Fig. 1b), moderate droughts (occurring less than 20% of the time, $\tau = 0.2$) during the baseline period become twice as frequent during 2071–2100. By contrast, the increase in runoff droughts is lower and less widespread (Fig. 1a). The spatial pattern of changes in drought frequency is generally comparable between the first three drought categories ($\tau = 0.3, \tau = 0.2$, and $\tau = 0.1$ in Fig. S2). However, model agreement on the direction of change decreases when considering drought categories with a small probability of occurrence (small τ-value), especially for runoff droughts (Fig. S2). The weak agreement highlights the substantial GCMs and IMs induced uncertainty in many regions (Prudhomme et al., 2014; Samaniego et al., 2017).

Global population exposure to droughts (Fig. 1c–g) is the highest under the 'Fragmented world' pathway owing to the highest global population and high greenhouse emissions (SSP3-RCP6.0, Fig. 1e). By contrast, global exposure is the lowest under the 'Sustainability' pathway with the lowest global population and emissions (SSP1-RCP2.6, Fig. 1c). Consequently, the shift from the 'Sustainability' to the 'Fragmented world' pathway is associated with an 81% increase in population exposure to moderate runoff droughts (occurring less than 20% of time, $\tau = 0.2$) by 2075. That is an increase from 16% to 29% of the current total population (Table S2). This increase is more pronounced in

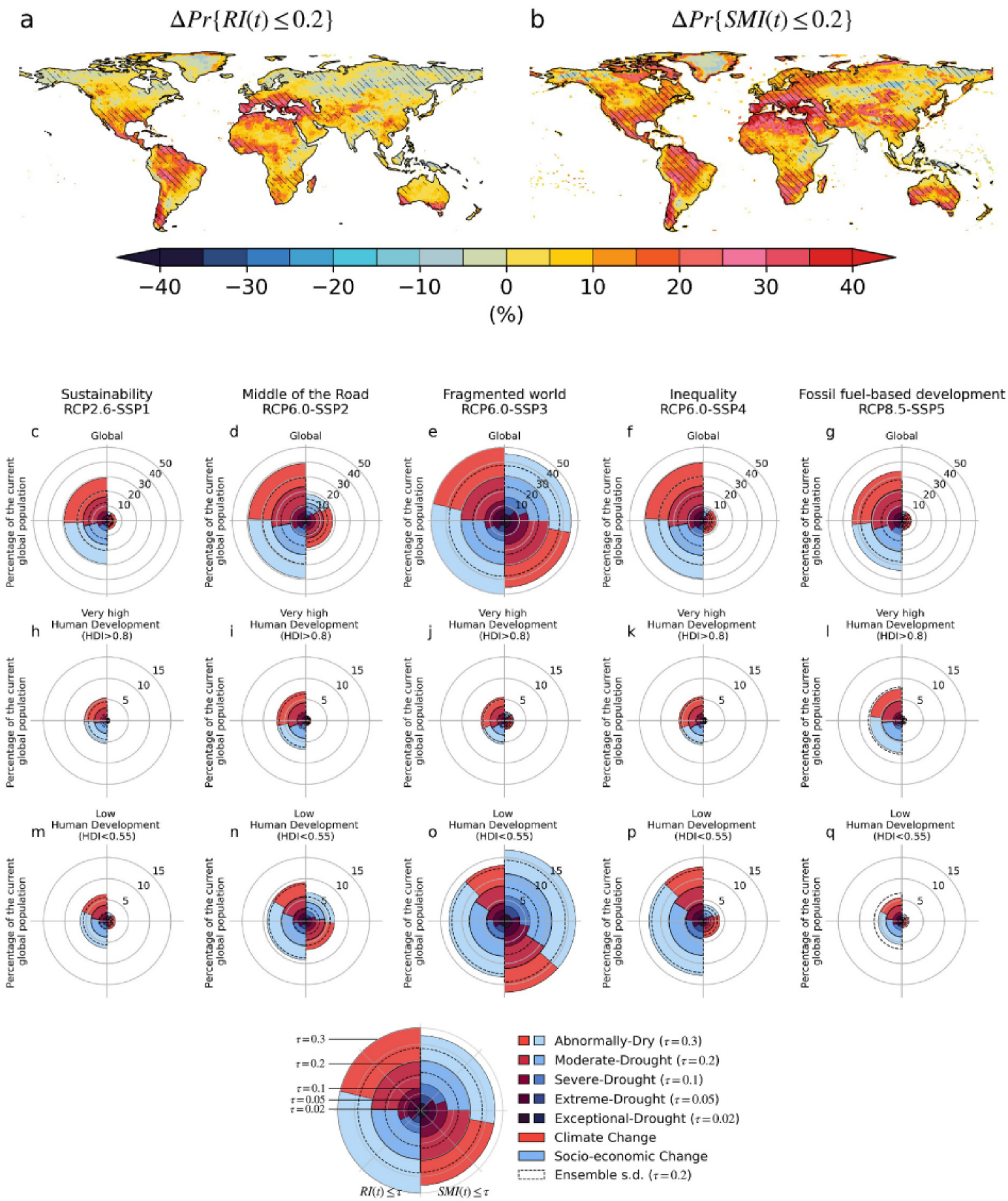

Fig. 1. Changes in drought frequency (a, b), from 1976–2005 to 2071–2100 under RCP8.5, and population exposure (c–q) under plausible RCP-SSP pathways in 2075. Maps show the changes in the percentage of time under runoff (a) and soil moisture (b) droughts (occurring less than 20% of time, $\tau = 0.2$). Maps depict the multi-model ensemble mean change, and hatches mark areas where more than 66% (two-third) of the models agree with the direction of mean change. Panels (c–q) show the ensemble mean population exposure globally (c–g) and for very high (h–l) and low (m–q) human development countries. The left half-circle depicts total population exposure to runoff droughts ($RI(t) \leq \tau$), expressed as the percentage of the current global total population. The right half-circle is same as the left half, but for population exposure in rural areas to soil moisture droughts ($SMI(t) \leq \tau$), expressed as the percentage of the current global rural population. Each half-circle depicts the relative contribution of climate (red portion) and socioeconomic (blue portion) changes. Exposure to five drought categories scaling from abnormal ($\tau = 0.3$) to exceptional ($\tau = 0.02$) drought conditions are depicted by lighter to darker color shadings. Dashed lines represent the uncertainty bounds (± the ensemble standard deviation) in exposure to moderate droughts ($\tau = 0.2$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

rural areas, where the exposure to moderate soil moisture droughts increases by seven folds (~4% versus 30% of the current global rural population, Table S3) from the 'Sustainability' to the 'Fragmented world' pathway. While both climate and socioeconomic change drive exposure to droughts globally, climate change contribution (red portions in Fig. 1) becomes more important when considering drought conditions with a smaller probability of occurrence, particularly for severe droughts (occurring less than 10% of the times, $\tau = 0.1$).

Of the global exposed populations to soil moisture (runoff) droughts, 70% (62%) will be located in South and East Asia, Sub-Saharan Africa, and the Mediterranean under the 'Fragmented world' pathway (Table S4). The shift from 'Sustainability' to 'Fragmented world' has the largest impact in low human development countries (HDI less than 0.55, Fig. S6). Consequently, population exposure within rural areas in low human development countries, mostly located in Sub-Saharan Africa, is projected to increase from 1% to 11% of the current global rural population (Fig. 1m, o, and Table S3). Similarly, an increase in exposure in rural areas by more than six folds is found within many medium human development countries in Africa, Asia, and Latin America (Fig. 2f). By contrast, the population of very high human development countries (HDI greater than 0.8) is affected more by runoff droughts than soil moisture droughts (Fig. 1h-l) because of smaller rural population in these countries. The highest exposure in very high human development countries (~5% of the current total global population) is projected under the 'Fossil fuel-based development' pathway (SSP5-RCP8.5, Fig. 1l). This pathway is the only case where exposure in very high human development countries exceeds exposure in low human development countries (~4% under SSP5-RCP8.5).

Other pathways of high population growth, notably the 'Middle of the road' and 'Inequality' pathways (SSP4 and SSP2, combined with RCP6.0), also lead to substantial increases in total population exposure to runoff drought compared to 'Sustainability' (Figs. 1, 2). However, exposure to soil moisture drought in rural areas follows the global rate of urbanization. The highest exposure in rural areas is found under slow urbanization pathways, the 'Fragmented world' and the 'Middle of the road' with 60% and 80% urbanization rates, while the lowest exposure is found under rapid urbanization pathways, the 'Sustainability', the 'Inequality', and the 'Fossil fuel-based development' with 92% urbanization rate (Riahi et al., 2017).

In comparison to the projections of drought frequency (Fig. 1) and exposure (Fig. S8), drought risk projections (Fig. 3) illustrate that the incorporation of vulnerability ($1 - HDI$, Fig. S9) modifies the pattern of future risk substantially. Normalized drought risk reveals that Sub-Saharan Africa is a global hotspot at an extremely high-risk value of

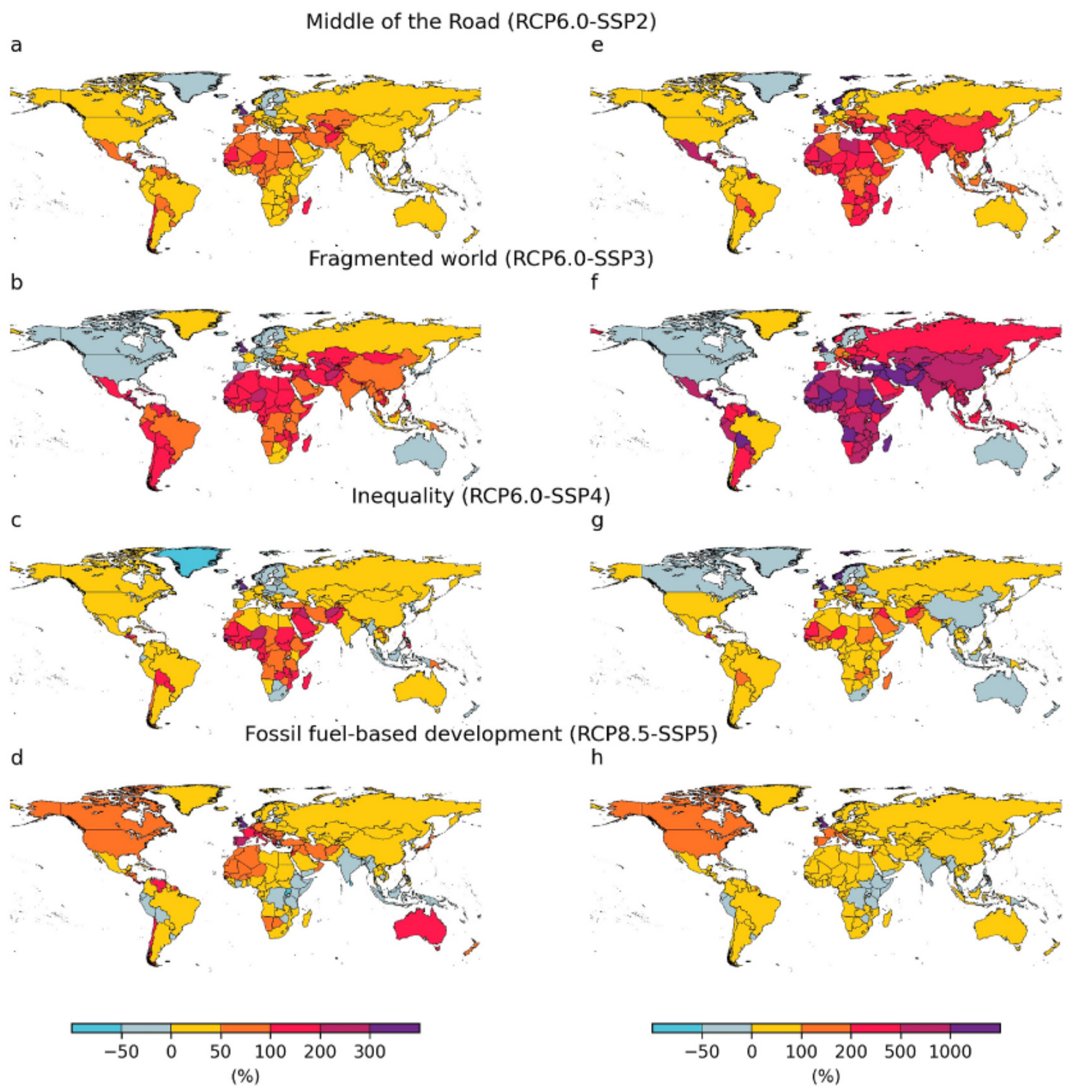

Fig. 2. Relative changes in average population exposed to runoff and soil moisture droughts (occurring less than 20% of the time, $\tau = 0.2$) compared to the 'Sustainability' pathway in 2075. Maps (a-d, left column) and (e-h, right column) show the relative changes in total and rural population exposure to runoff and soil moisture droughts, respectively. Maps depict the multi-model ensemble mean.

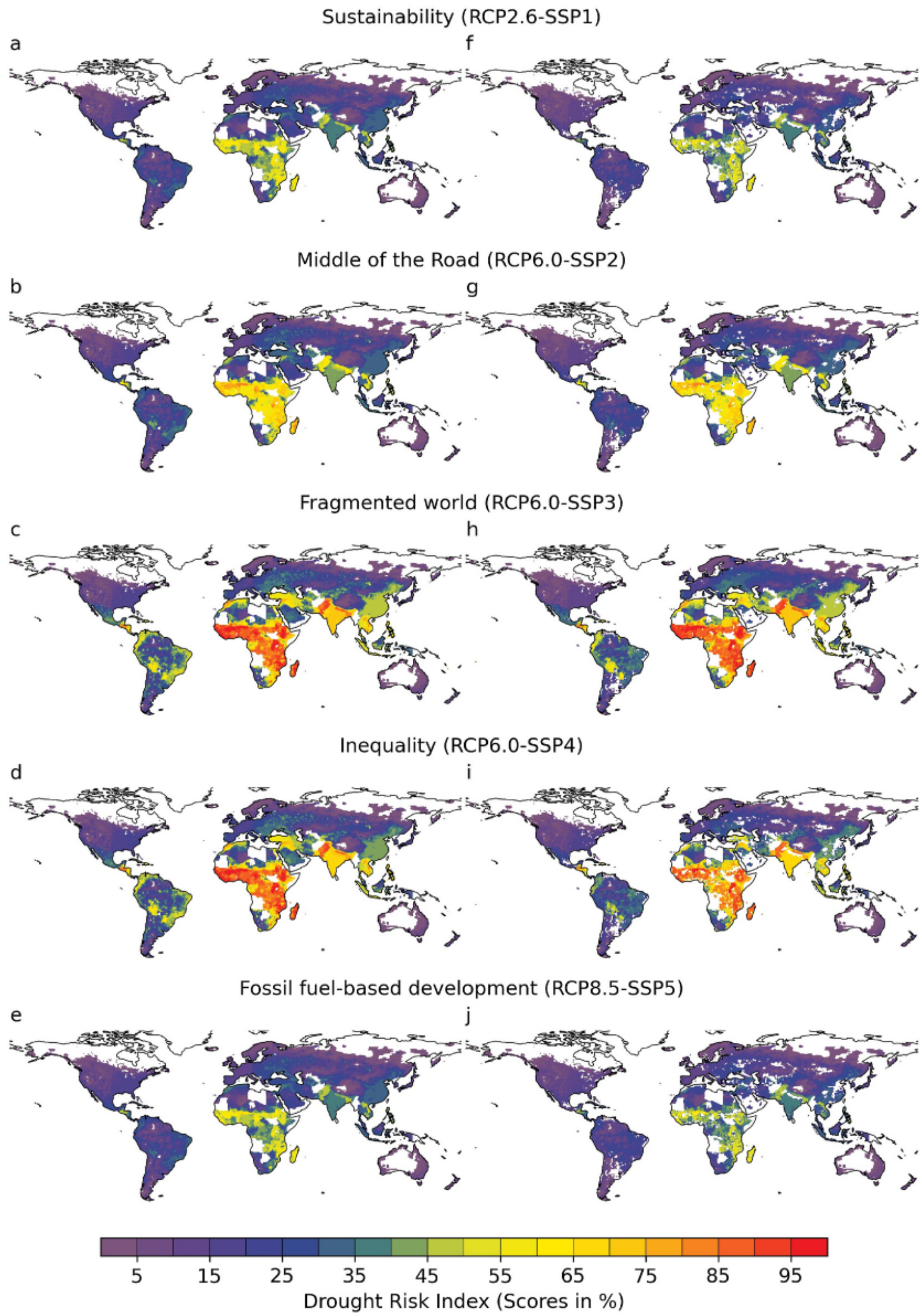

Fig. 3. Illustrative risk index of runoff (a-e, left column) and soil moisture (f-j, right column) droughts (occurring less than 20% of the time, $\tau = 0.2$) under different RCP-SSP pathways in 2075. Maps depict the multi-model ensemble mean.

up to 90% for both soil moisture and runoff droughts under the 'Fragmented world' and 'Inequality' pathways (Fig. 3). Similar high-risk scores are found across South Asia, Middle East, North Africa, and Central America. By contrast, drought risk is the lowest in highly developed countries in Europe, North America, and Oceania under all pathways.

Results show that 26% (24%) of the current global rural (total) population will experience a drought risk value greater than 20% by the end of this century under the 'Fragmented world' pathway (Fig. 4c and Table S5). These figures correspond to 500% (168%) the rural (total) population exposed to the same risk value under the 'Sustainability' pathway (Fig. 4a). Furthermore, 7% of the current global population, located within low human development countries, will experience a drought risk value greater than 70% under the 'Fragmented world' and

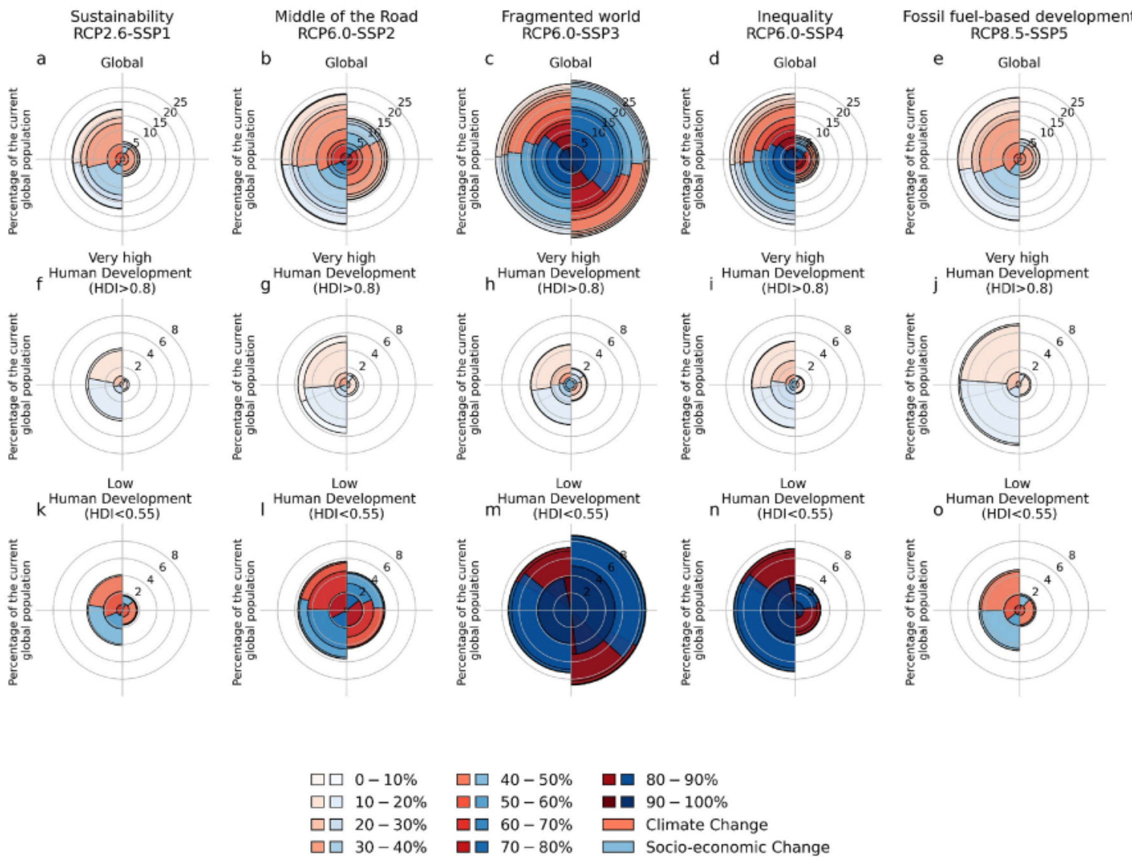

Fig. 4. Changes in the population at risk of moderate droughts (occurring less than 20% of the time, $\tau = 0.2$) under different pathways of climate and socioeconomic change in 2075. Panels show the ensemble mean population at different risk scores (0–100%, depicted by lighter to darker color shadings) globally (a–e) and for very high (f–j) and low (k–o) human development countries. The left half-circle depicts the total population at risk of runoff droughts, expressed as the percentage of the current global total population. The right half-circle is same as the left half, but for the rural population at risk of soil moisture droughts, expressed as the percentage of the current global rural population. Each half-circle depicts the relative contribution of climate (red portion) and socioeconomic (blue portion) changes. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

'Inequality' pathways (Fig. 4m, n, and Table S6), while drought risk nowhere reaches the 70% value in the 'Sustainability' pathway. Socio-economic change drives drought risk under the 'Fragmented world' and 'Inequality' pathways. On the other hand, the contribution of changes in climate to changes in drought risk is more substantial within very high human development countries and under rapid development pathways, namely the 'Sustainability' and 'Fossil fuel-based development'. Most notably, climate change dominates future changes in drought risk when considering drought conditions with a smaller probability of occurrence during the baseline period (Fig. S10).

4. Discussion

Taking the 'Sustainability' pathway of rapid human development (under SSP1) and a reduction in greenhouse gas emissions (under RCP2.6) is the ultimate and most effective way to reduce drought risk. The shift from this pathway into rapid population growth (under SSP3 and SSP4) and high emissions (under RCP6.0), as reflected in the 'Fragmented world' and 'Inequality' pathways, substantially increases population exposure to droughts that is greater in low human development countries (Fig. 1). Our results are broadly consistent with recent works (Byers et al., 2018; Liu et al., 2018; Lange et al., 2020; Spinoni et al., 2021), but provide new findings regarding: (1) population exposure using different drought indicators and categories under a wide range of plausible climate and socioeconomic pathways; (2) how vulnerability can affect drought risk by incorporating projections of the HDI under different SSPs; and (3) the contribution of climate and socioeconomic changes to drought risk.

4.1. Drought exposure implications

The projected increase in population exposure in less developed countries under the 'Fragmented world' and 'Inequality' pathways is expected to exacerbate inequalities in water and food access, especially for rural people. Subsistence agriculture is the major source of income and development for populations in rural areas (FAO, 2020). The increase in rural population numbers and their exposure under the 'Fragmented world' pathway (Fig. 1o) is only indicative of a strong reliance on subsistence farming, and potentially the most exaggerated impacts from soil moisture droughts. In the absence of adaptation, more people, often males, could be forced to migrate, which entails additional burdens for women and can impose long-lasting or even permanent consequences to women's empowerment, and consequently to human development, in less developed countries (FAO, 2020).

4.2. Drought risk and policy implications

The incorporation of human development projections as a proxy of vulnerability widens the disparity in future drought risk between very high and low human development countries. The world's less developed countries, especially across Sub-Saharan Africa and South Asia, are disproportionately at the highest drought risk levels in the 'Fragmented world' and 'Inequality' pathways, a finding that complements prior studies (Byers et al., 2018; Spinoni et al., 2021). Climate mitigation alone is evidently not enough to reduce drought risk in low human development countries. Drought risk there is driven primarily by the increase in exposed population (Fig. 4 and S10) and scarce improvements in human development (Fig. S6). This stagnation in human development is expected to impede the capacity to adapt to changes in climate which in turn impairs human development. Adaptive capacity is manifested by the state of the three pillars of human development: education, health, and income distribution. Educational attainment is a significant contributor to building up adaptive capacity and solutions (Chen et al., 2015). Skewed income distribution leads to exaggerated drought impacts on the poorest (Byers et al., 2018) and worsens the capacity to adapt. Overall health conditions reflect country's internal capacity to face drought-related health shocks (e.g., from malnutrition and unsafe water quality) which can exacerbate poverty and lower educational attainment to the degree that these impacts may be transmitted across generations (FAO, 2020).

Less developed countries will hugely benefit from the rapid human development under the 'Sustainability' pathway. However, the shift into this extremely ambitious pathway can only be achieved if mechanisms such as the Sustainable Development Goals (SDGs) are met and sustained in the long-term (Byers et al., 2018). A very good and sustained progress on poverty, mortality, health, and education (SDGs 1–4) is essential to keep population growth (human development) as low (as high) as projected in SSP1 (Abel et al., 2016). Similarly, inaction on climate change (SDG 13) could make achieving other SDGs more challenging. All SDGs will likely contribute to improving human development, combating climate change, and supporting the other 2030 agenda agreements like the Sendai framework for disaster risk reduction.

4.3. Uncertainties and limitations

Overall, our results underscore the complex response of drought risk to future climate and socioeconomic changes. While both climate and socioeconomic changes influence drought risk, their relative importance differ substantially depending on the level of human development (i.e., vulnerability), socioeconomic pathways, and how drought condition is defined (Figs. 1, 3, and S10). Most notably, climate change is of greater importance when considering drought conditions with a small probability of occurrence. This stems from the fact that a small probability of occurrence in the present period leads to large relative changes in the future, and thus dominates changes in exposure and risk (Fig. 1 and S10). Therefore, discussions on the importance of climate and socioeconomic changes need to take into consideration the extent to which any conclusions depend on how drought is defined (Cook et al., 2018; Satoh et al., 2021).

Drought risk scores (Fig. 3) cannot be interpreted in terms of the probability of a specific negative drought consequence. This important caveat underlines the lack of robust dose-response relationships to reflect the actual vulnerability to droughts within the exposed populations. Nonetheless, projections presented here provide direct estimates of the average population located withing the life span of drought occurrences of different categories in function of a country's level of development. Using national projections of human development as a proxy of vulnerability to climate change enables a more comprehensive risk assessment compared to other measures (e.g., GDP), but it does not consider the heterogeneity of vulnerability within countries. Therefore, hotspots of drought risk will benefit more from further assessment at a smaller scale and development of dose-response relationships relating exposure to specific drought-related impacts in combination with the SSP storylines (Sillmann et al., 2018). Furthermore, efforts to characterize and reduce the uncertainty (from IMs and GCMs) in drought modeling will also be critical to draw more conclusive and relevant recommendations for adaptation (Clark et al., 2016).

5. Conclusions

This study employs the multi-model ensemble (88 members) global hydrological simulations of the ISI-MIP2b under three emission scenarios (RCPs) combined with their corresponding socioeconomic (SSPs) projections of population and human development (as a proxy of vulnerability) to project global drought risk at the end of this century (2071–2100). The shift from the 'Sustainability' pathway (SSP1-RCP2.6) into worlds of high socioeconomic inequality and emissions, as reflected in the 'Fragmented world' (SSP3-RCP6.0) and 'Inequality' (SSP4-RCP6.0) pathways, leads to increased exposure to runoff (by 81%) and soil moisture (by seven folds) droughts. Combined with increased exposure, marginal improvement in human development results in a huge disparity in future drought risk between low and very high human development countries. In particular, Sub-Saharan Africa and South Asia, where the word's less developed countries are located, are projected to endure the worst drought risk. Climate action alone is evidently not enough to substantially reduce drought risk to what is projected under the 'Sustainability' pathway. The shift into this extremely ambitious pathway can only be achieved with rapid human development through mechanisms such as the SDGs. Overall, both climate and socioeconomic changes drive drought risk but their separate contributions differ substantially depending on the level of human development, socioeconomic pathways, and how drought is defined. This underscores the complexity of drought risk response to future climate and socioeconomic changes. An important shortcoming of the risk analysis presented in this study is that it cannot be interpreted as the probability of a specific negative drought consequence. An avenue for further research is therefore to develop dose-response relationships and relate exposure to specific drought-related impacts. Such relationships alongside constraining drought projections uncertainty are crucial to draw more conclusive and relevant recommendations for adaptation.

Authorship contribution statement

A.E. and Y.P. designed the study. A.E. conducted analysis of the data. All authors contributed to interpreting the results and writing the paper.

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.jenvman.2022.115378.

References

Abel, G.J., Barakat, B., Kc, S., Lutz, W., 2016. Meeting the Sustainable Development Goals leads to lower world population growth. Proc. Natl. Acad. Sci. Unit. States Am. 113 (50), 14294. https://doi.org/10.1073/pnas.1611386113.

Ault, T.R., 2020. On the essentials of drought in a changing climate. Science 368 (6488), 256. https://doi.org/10.1126/science.aaz5492.

Byers, E., Gidden, M., Leclère, D., Balkovic, J., Burek, P., Ebi, K., et al., 2018. Global exposure and vulnerability to multi-sector development and climate change hotspots. Environ. Res. Lett. 13 (5), 055012 https://doi.org/10.1088/1748-9326/aabf45.

Chen, C., Noble, I., Hellmann, J., Coffee, J., Murillo, M., Chawla, N., 2015. University of Notre Dame global adaptation index. In: Country Index Technical Report. Retrieved from. https://gain.nd.edu/assets/254377/nd_gain_technical_document_2015.pdf.

Clark, M.P., Wilby, R.L., Gutmann, E.D., Vano, J.A., Gangopadhyay, S., Wood, A.W., et al., 2016. Characterizing uncertainty of the hydrologic impacts of climate change. Curr. Clim. Change Rep. 2 (2), 55–64. https://doi.org/10.1007/s40641-016-0034-x.

Cook, B.I., Mankin, J.S., Anchukaitis, K.J., 2018. Climate change and drought: from past to future. Curr. Clim. Change Rep. 4 (2), 164–179. https://doi.org/10.1007/s40641-018-0093-2.

Cook, B.I., Mankin, J.S., Marvel, K., Williams, A.P., Smerdon, J.E., Anchukaitis, K.J., 2020. Twenty-first century drought projections in the CMIP6 forcing scenarios. Earth's Future 8 (6), e2019EF001461. https://doi.org/10.1029/2019EF001461.

Crespo Cuaresma, J., Lutz, W., 2016. The demography of human development and climate change vulnerability: a projection exercise. In: Muttarak, R., Jiang, L. (Eds.), Vienna Yearbook of Population Research 2015, pp. 241–261 (Vienna, Austria).

Dai, A., 2011. Drought under global warming: a review. Wiley Interdiscipl. Rev.: Clim. Change 2 (1), 45–65. https://doi.org/10.1002/wcc.81.

Dai, A., 2013. Increasing drought under global warming in observations and models. Nat. Clim. Change 3 (1), 52–58. https://doi.org/10.1038/nclimate1633.

Elkouk, A., El Morjani, Z.E.A., Pokhrel, Y., Chehbouni, A., Sifeddine, A., Thober, S., Bouchaou, L., 2021. Multi-model ensemble projections of soil moisture drought over North Africa and the Sahel region under 1.5, 2, and 3 °C global warming. Climatic Change 167 (3), 52. https://doi.org/10.1007/s10584-021-03202-0.

Fang, Z., Ted, I.E.V., Katja, F., Jacob, S., Sebastian, O., Sven, W., et al., 2017. The critical role of the routing scheme in simulating peak river discharge in global hydrological models. Environ. Res. Lett. 12 (7), 075003. http://stacks.iop.org/1748-9326/12/i=7/a=075003.

FAO, 2020. The State of Food and Agriculture 2020. Overcoming Water Challenges in Agriculture. https://doi.org/10.4060/cb1447en. Retrieved from Rome.

Frieler, K., Lange, S., Piontek, F., Reyer, C.P.O., Schewe, J., Warszawski, L., et al., 2017. Assessing the impacts of 1.5 °C global warming – simulation protocol of the inter-sectoral impact model Intercomparison project (ISIMIP2b). Geosci. Model Dev. (GMD) 10 (12), 4321–4345. https://doi.org/10.5194/gmd-10-4321-2017.

Füssel, H.-M., 2010. Review and Quantitative Analysis of Indices of Climate Change Exposure, Adaptive Capacity, Sensitivity, and Impacts. World Bank, Washington, DC. Retrieved from. http://hdl.handle.net/10986/9193.

Giuntoli, I., Vidal, J.P., Prudhomme, C., Hannah, D.M., 2015. Future hydrological extremes: the uncertainty from multiple global climate and global hydrological models. Earth Syst. Dynam. 6 (1), 267–285. https://www.earth-syst-dynam.net/6/267/2015/.

Gray, C., Mueller, V., 2012. Drought and population mobility in rural Ethiopia. World Dev. 40 (1), 134–145. https://www.sciencedirect.com/science/article/pii/S0305750X11001537.

Grolle, J., 2015. Historical case studies of famines and migrations in the West African Sahel and their possible relevance now and in the future. Popul. Environ. 37 (2), 181–206. https://doi.org/10.1007/s11111-015-0237-4.

Gudmundsson, L., Tallaksen, L.M., Stahl, K., Clark, D.B., Dumont, E., Hagemann, S., et al., 2012. Comparing large-scale hydrological model simulations to observed runoff percentiles in Europe. J. Hydrometeorol. 13 (2), 604–620. https://journals.ametsoc.org/view/journals/hydr/13/2/jhm-d-11-083_1.xml.

Guimberteau, M., Zhu, D., Maignan, F., Huang, Y., Yue, C., Dantec-Nédélec, S., et al., 2018. ORCHIDEE-MICT (v8.4.1), a land surface model for the high latitudes: model description and validation. Geosci. Model Dev. (GMD) 11 (1), 121–163. https://doi.org/10.5194/gmd-11-121-2018.

Hanasaki, N., Yoshikawa, S., Pokhrel, Y., Kanae, S., 2018. A global hydrological simulation to specify the sources of water used by humans. Hydrol. Earth Syst. Sci. 22 (1), 789–817. https://doi.org/10.5194/gmd-11-121-2018.

Harrington, L.J., Frame, D., King, A.D., Otto, F.E.L., 2018. How uneven are changes to impact-relevant climate hazards in a 1.5 °C world and beyond? Geophys. Res. Lett. 45 (13), 6672–6680. https://doi.org/10.1029/2018GL078888.

Huang, S., Kumar, R., Flörke, M., Yang, T., Hundecha, Y., Kraft, P., et al., 2017. Evaluation of an ensemble of regional hydrological models in 12 large-scale river basins worldwide. Climatic Change 141 (3), 381–397. https://doi.org/10.1007/s10584-016-1841-8.

IPCC, 2012. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge University Press, New York, NY, USA.

Jones, B., O'Neill, B.C., 2020. Global One-Eighth Degree Population Base Year and Projection Grids Based on the Shared Socioeconomic Pathways, Revision 01. https://doi.org/10.7927/m30p-j498. Retrieved from.

Jones, B., O'Neill, B.C., 2016. Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. Environ. Res. Lett. 11 (8), 084003 https://doi.org/10.1088/1748-9326/11/8/084003.

Jones, B., O'Neill, B.C., McDaniel, L., McGinnis, S., Mearns, L.O., Tebaldi, C., 2015. Future population exposure to US heat extremes. Nat. Clim. Change 5 (7), 652–655. https://doi.org/10.1038/nclimate2631.

Keyantash, J., Dracup, J.A., 2002. The quantification of drought: an evaluation of drought indices. Bull. Am. Meteorol. Soc. 83 (8), 1167–1180. https://journals.ametsoc.org/view/journals/bams/83/8/1520-0477-83_8_1167.xml.

King, A.D., Harrington, L.J., 2018. The inequality of climate change from 1.5 to 2°C of global warming. Geophys. Res. Lett. 45 (10), 5030–5033. https://doi.org/10.1029/2018GL078430. 10.1029/2018GL078430.

Lange, S., Volkholz, J., Geiger, T., Zhao, F., Vega, I., Veldkamp, T., et al., 2020. Projecting exposure to extreme climate impact events across six event categories and three spatial scales. Earth's Future 8 (12), e2020EF001616. https://doi.org/10.1029/2020EF001616.

Lehner, F., Coats, S., Stocker, T.F., Pendergrass, A.G., Sanderson, B.M., Raible, C.C., Smerdon, J.E., 2017. Projected drought risk in 1.5°C and 2°C warmer climates. Geophys. Res. Lett. 44 (14), 7419–7428. https://doi.org/10.1002/2017GL074117.

Liu, W., Sun, F., Lim, W.H., Zhang, J., Wang, H., Shiogama, H., Zhang, Y., 2018. Global drought and severe drought-affected populations in 1.5 and 2 °C warmer worlds. Earth Syst. Dynam. 9 (1), 267–283, 10.5194/esd-9-267-2018.

Masih, I., Maskey, S., Mussá, F.E.F., Trambauer, P., 2014. A review of droughts on the African continent: a geospatial and long-term perspective. Hydrol. Earth Syst. Sci. 18 (9), 3635–3649. https://www.hydrol-earth-syst-sci.net/18/3635/2014/.

Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391 (1), 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012.

Müller Schmied, H., Adam, L., Eisner, S., Fink, G., Flörke, M., Kim, H., et al., 2016. Variations of global and continental water balance components as impacted by climate forcing uncertainty and human water use. Hydrol. Earth Syst. Sci. 20 (7), 2877–2898. https://doi.org/10.5194/hess-20-2877-2016.

Pokhrel, Y., Felfelani, F., Satoh, Y., Boulange, J., Burek, P., Gädeke, A., et al., 2021. Global terrestrial water storage and drought severity under climate change. Nat. Clim. Change. https://doi.org/10.1038/s41558-020-00972-w.

Pokhrel, Y.N., Koirala, S., Yeh, P.J.F., Hanasaki, N., Longuevergne, L., Kanae, S., Oki, T., 2015. Incorporation of groundwater pumping in a global Land Surface Model with the representation of human impacts. Water Resour. Res. 51 (1), 78–96. https://doi.org/10.1002/2014WR015602, 10.1002/2014WR015602.

Prudhomme, C., Giuntoli, I., Robinson, E.L., Clark, D.B., Arnell, N.W., Dankers, R., et al., 2014. Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. Proc. Natl. Acad. Sci. Unit. States Am. 111 (9), 3262. https://doi.org/10.1073/pnas.1222473110.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., et al., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environ. Change 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Russo, S., Sillmann, J., Sippel, S., Barcikowska, M.J., Ghisetti, C., Smid, M., O'Neill, B., 2019. Half a degree and rapid socioeconomic development matter for heatwave risk. Nat. Commun. 10 (1), 136. https://doi.org/10.1038/s41467-018-08070-4.

Samaniego, L., Kumar, R., Breuer, L., Chamorro, A., Flörke, M., Pechlivanidis, I.G., et al., 2017. Propagation of forcing and model uncertainties on to hydrological drought characteristics in a multi-model century-long experiment in large river basins. Climatic Change 141 (3), 435–449. https://doi.org/10.1007/s10584-016-1778-y.

Samaniego, L., Kumar, R., Zink, M., 2013. Implications of parameter uncertainty on soil moisture drought analysis in Germany. J. Hydrometeorol. 14 (1), 47–68. https://doi.org/10.1175/JHM-D-12-075.1.

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., et al., 2018. Anthropogenic warming exacerbates European soil moisture droughts. Nat. Clim. Change 8 (5), 421–426. https://doi.org/10.1038/s41558-018-0138-5.

Satoh, Y., Kahil, T., Byers, E., Burek, P., Fischer, G., Tramberend, S., et al., 2017. Multi-model and multi-scenario assessments of Asian water futures: the Water Futures and Solutions (WFaS) initiative. Earth's Future 5 (7), 823–852. https://doi.org/10.1002/2016EF000503.

Satoh, Y., Shiogama, H., Hanasaki, N., Pokhrel, Y.N., Boulange, J.E.S., Burek, P., et al., 2021. A quantitative evaluation of the issue of drought definition: a source of disagreement in future drought assessments. Environ. Res. Lett. http://iopscience.iop.org/article/10.1088/1748-9326/ac2348.

Schewe, J., Gosling, S.N., Reyer, C., Zhao, F., Ciais, P., Elliott, J., et al., 2019. State-of-the-art global models underestimate impacts from climate extremes. Nat. Commun. 10 (1), 1005. https://doi.org/10.1038/s41467-019-08745-6.

Sheffield, J., Wood, E.F., 2007. Characteristics of global and regional drought, 1950–2000: analysis of soil moisture data from off-line simulation of the terrestrial hydrologic cycle. J. Geophys. Res. Atmos. 112 (D17) https://doi.org/10.1029/2006JD008288.

Sheffield, J., Wood, E.F., 2008. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim. Dynam. 31 (1), 79–105. https://doi.org/10.1007/s00382-007-0340-z.

Sillmann, J., Russo, S., Sippel, S., Alnes, K., 2018. From hazard to risk. Bull. Am. Meteorol. Soc. 99 (8), 1689–1693. https://doi.org/10.1175/bams-d-17-0327.1.

Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., et al., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Global Change Biol. 9 (2), 161–185. https://doi.org/10.1046/j.1365-2486.2003.00569.x.

Smirnov, O., Zhang, M., Xiao, T., Orbell, J., Lobben, A., Gordon, J., 2016. The relative importance of climate change and population growth for exposure to future extreme droughts. Climatic Change 138 (1), 41–53. https://doi.org/10.1007/s10584-016-1716-z.

Smith, A.B., Matthews, J.L., 2015. Quantifying uncertainty and variable sensitivity within the US billion-dollar weather and climate disaster cost estimates. Nat. Hazards 77 (3), 1829–1851. https://doi.org/10.1007/s11069-015-1678-x.

Spinoni, J., Barbosa, P., Bucchignani, E., Cassano, J., Cavazos, T., Cescatti, A., et al., 2021. Global exposure of population and land-use to meteorological droughts under different warming levels and SSPs: a CORDEX-based study. Int. J. Climatol. https://doi.org/10.1002/joc.7302, 10.1002/joc.7302, *n/a*(n/a).

Staudinger, M., Stahl, K., Seibert, J., Clark, M.P., Tallaksen, L.M., 2011. Comparison of hydrological model structures based on recession and low flow simulations. Hydrol. Earth Syst. Sci. 15 (11), 3447–3459. https://hess.copernicus.org/articles/15/3447/2011/.

Svoboda, M., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., et al., 2002. The drought monitor. Bull. Am. Meteorol. Soc. 83 (8), 1181–1190. https://doi.org/10.1175/1520-0477-83.8.1181.

Sweet, S.K., Wolfe, D.W., DeGaetano, A., Benner, R., 2017. Anatomy of the 2016 drought in the Northeastern United States: implications for agriculture and water resources in humid climates. Agric. For. Meteorol. 247, 571–581. https://www.sciencedirect.com/science/article/pii/S0168192317302800.

Takata, K., Emori, S., Watanabe, T., 2003. Development of the minimal advanced treatments of surface interaction and runoff. Global Planet. Change 38 (1), 209–222. https://doi.org/10.1016/S0921-8181(03)00030-4.

Thiery, W., Davin, E.L., Lawrence, D.M., Hirsch, A.L., Hauser, M., Seneviratne, S.I., 2017. Present-day irrigation mitigates heat extremes. J. Geophys. Res. Atmos. 122 (3), 1403–1422. https://doi.org/10.1002/2016JD025740.

Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2014. Global warming and changes in drought. Nat. Clim. Change 4, 17. https://doi.org/10.1038/nclimate2067. Perspective.

Velázquez, J.A., Schmid, J., Ricard, S., Muerth, M.J., Gauvin St-Denis, B., Minville, M., et al., 2013. An ensemble approach to assess hydrological models' contribution to uncertainties in the analysis of climate change impact on water resources. Hydrol. Earth Syst. Sci. 17 (2), 565–578. https://hess.copernicus.org/articles/17/565/2013/.

Veldkamp, T.I.E., Zhao, F., Ward, P.J., Moel, H.d., Aerts, J.C.J.H., Schmied, H.M., et al., 2018. Human impact parameterizations in global hydrological models improve estimates of monthly discharges and hydrological extremes: a multi-model validation study. Environ. Res. Lett. 13 (5), 055008. http://stacks.iop.org/1748-9326/13/i=5/a=055008.

Vetter, T., Reinhardt, J., Flörke, M., van Griensven, A., Hattermann, F., Huang, S., et al., 2017. Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. Climatic Change 141 (3), 419–433. https://doi.org/10.1007/s10584-016-1794-y.

Vicente-Serrano, S.M., Quiring, S.M., Peña-Gallardo, M., Yuan, S., Domínguez-Castro, F., 2020. A review of environmental droughts: increased risk under global warming? Earth Sci. Rev. 201, 102953. https://www.sciencedirect.com/science/article/pii/S0012825218306421.

Wada, Y., Wisser, D., Bierkens, M.F.P., 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth Syst. Dynam. 5 (1), 15–40. https://doi.org/10.5194/esd-5-15-2014.

Yokohata, T., Kinoshita, T., Sakurai, G., Pokhrel, Y., Ito, A., Okada, M., et al., 2020. MIROC-INTEG-LAND version 1: a global biogeochemical land surface model with human water management, crop growth, and land-use change. Geosci. Model Dev. (GMD) 13 (10), 4713–4747. https://gmd.copernicus.org/articles/13/4713/2020/.

Zaherpour, J., Gosling, S.N., Mount, N., Schmied, H.M., Veldkamp, T.I.E., Dankers, R., et al., 2018. Worldwide evaluation of mean and extreme runoff from six global-scale hydrological models that account for human impacts. Environ. Res. Lett. 13 (6), 065015. http://stacks.iop.org/1748-9326/13/i=6/a=065015.

Zhang, L., Zhou, T., 2015. Drought over East Asia: a review. J. Clim. 28 (8), 3375–3399. https://journals.ametsoc.org/view/journals/clim/28/8/jcli-d-14-00259.1.xml.

Zhao, T., Dai, A., 2015. The magnitude and causes of global drought changes in the twenty-first century under a low–moderate emissions scenario. J. Clim. 28 (11), 4490–4512. https://doi.org/10.1175/JCLI-D-14-00363.1.