Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment

This item was submitted to Loughborough University's Institutional Repository by the/an author.

Citation: PRUDHOMME, C. ... et al., 2014. Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. Proceedings of the National Academy of Sciences of the United States of America, DOI: 10.1073/pnas.1222473110.

Metadata Record: [https://dspace.lboro.ac.uk/2134/22127](https://dspace.lboro.ac.uk/2134/22127)

Version: Accepted for publication

Publisher: © National Academy of Sciences

Rights: This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) licence. Full details of this licence are available at: [https://creativecommons.org/licenses/by-nc-nd/4.0/](https://creativecommons.org/licenses/by-nc-nd/4.0/)

Please cite the published version.
Hydrological droughts in the 21st century: hotspots and uncertainties from a global multi-model ensemble experiment

Authors: Christel Prudhomme1, Ignazio Giuntoli1,2, Emma L. Robinson1, Douglas B. Clark1, Nigel W. Arnell1, Rutger Dankers3, Balázs Fekete3, Wietse Franssen4, Dieter Gerten5, Simon N. Gosling6, Stefan Hagemann5, David M. Hannah2, Hyungjun Kim10, Yoshimitsu Masaki11, Yusuke Satoh12, Tobias Stacke9, Yoshihide Wada13, Dominik Wisser13,14

1 Centre for Ecology and Hydrology, Maclean Building, Wallingford, Oxfordshire, OX10 8BB, United Kingdom
2 School of Geography, Earth and Environment Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom
3 Walker Institute for Climate System Research, University of Reading, Reading, RG6 6AR, United Kingdom
4 Met Office Hadley Centre, Exeter, United Kingdom
5 Civil Engineering Department, The City College of New York, New York, USA
6 Earth System Science, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, Netherlands
7 Potsdam Institute for Impact Research, Germany
8 School of Geography, University of Nottingham, Nottingham, NG7 2RD, United Kingdom
9 Max Planck Institute for Meteorology, Bundesstraße 53, 20146 Hamburg, Germany
10 Institute of Industrial Science, The University of Tokyo, Tokyo, Japan
11 National Institute for Environmental Studies, Japan
12 Department of Civil Engineering, The University of Tokyo, Japan
13 Department of Physical Geography, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, Netherlands
14 Center for Development Research, University of Bonn, Germany

Submitted to Proceedings of the National Academy of Sciences of the United States of America

Increasing concentrations of greenhouse gases in the atmosphere are expected to modify the global water cycle with significant consequences for terrestrial hydrology. We assess the impact of climate change on hydrological droughts in a multi-model experiment including seven Global Impact Models (GIMs) driven by bias-corrected climate from five Global Climate Models (GCMs) under four Representative Concentration Pathways (RCPs). Drought severity is defined as the fraction of land under drought conditions. Results show a likely increase in the global severity of hydrological drought at the end of the 21st century, with systematically greater increases for RCPs describing stronger radiative forcings. Under RCP8.5, droughts exceeding 40% of analysed land area are projected by nearly half of the simulations. This increase in drought severity has a strong Signal-to-Noise ratio at the global scale, and Southern Europe, Middle East, South East United States, Chile and South West Australia are identified as possible hotspots for future water security issues. The uncertainty due to GIMs is greater than that from GCMs, particularly if including a GIM that accounts for the dynamic response of plants to CO2 and climate, as this model simulates little or no increase in drought frequency. Our study demonstrates that different representations of terrestrial water cycle processes in GIMs are responsible for a much larger uncertainty in the response of hydrological drought to climate change than previously thought. When assessing the impact of climate change on hydrology it is hence critical to consider a diverse range of GIMs to better capture the uncertainty.

Drought | Climate impact | global hydrology | evaporation | CO2

Introduction

The global water cycle is expected to change over the 21st century due to the combined effects of climate change and increasing human intervention. In a warmer world the water holding capacity of the atmosphere will increase, resulting in a change in the frequency of precipitation extremes, increased evaporation and dry periods (1) and intensification of droughts (2). This is represented by most Global Climate Models (GCMs) by increased summer dryness and winter wetness over large areas of continental mid- to high-latitudes in the Northern Hemisphere (3), associated with a reduction in water availability at continental (4) and global scales (6, 7). Because such changes have potentially very serious implications in some regions of the world, identifying areas where there is agreement in the direction and magnitude of changes in drought characteristics (hotspots) in response to climate change is essential information for water resource management aimed at ensuring water security in a changing climate.

Most GCMs, however, are not able to reproduce the fine-scale processes governing terrestrial hydrology (and hence runoff) and suffer from systematic biases (8). As land-atmospheric feedbacks are not yet fully understood and reproduced by global models (9), and because full coupling of GCMs and Global Impact Models (GIMs) is not straightforward, GIMs forced by data from GCMs have been used as tools to quantify the impact of changed climate on the water cycle and droughts (10), despite by definition ignoring important feedbacks and their possible modification with climate change (11). GIMs vary in the types of processes represented and the parameterisations employed. Some GIMs, particularly those designed to quantify water resources, only calculate the water balance (e.g. 12), while others consider coupled water and energy balances, sometimes also representing the dynamic response of plants to changes in atmospheric CO2 and climate (e.g. 13). Until recently the uncertainty in the simulation of the terrestrial water cycle related to the choice of a particular GIM had not been investigated. However, the Water Model Intercomparison Experiment (14) demonstrates that different representations of terrestrial water cycle processes in GIMs to better capture the uncertainty.

Significance

Increasing concentrations of greenhouse gases in the atmosphere are widely expected to influence global climate over the coming century. The impact on drought is uncertain because of the complexity of the processes, but can be estimated using outputs from an ensemble of global models (hydrological and climate models). Using an ensemble of 35 simulations we show a likely increase in the global severity of drought by the end of 21st century, with regional hotspots including South America and Central and Western Europe in which the frequency of drought increases by more than 20%. The main source of uncertainty in the results comes from the hydrological models, with climate models contributing to a substantial but smaller amount of uncertainty.

Reserved for Publication Footnotes

www.pnas.org --- --- PNAS
This study focuses on identifying regions where the impact of climate change on hydrological drought (henceforth simply ‘drought’) shows a strong signal of change between the end of the 20th and 21st centuries. We define drought as occurring when total runoff is less than a given threshold. Drought represents the time-integrated effect of several interconnected processes and stores, including precipitation, evaporation and soil moisture storage (10); because some of these processes are represented by GCMs and some by GIMs, it is vital to quantify the relative uncertainty introduced by both GCMs and GIMs when assessing climate change impacts.

We use outputs from the ISI-MIP multi-model ensemble (MME) experiment (18) of 35 members (for RCPs 2.6 and 8.5; only 27 members available for RCP4.5 and 6.0) in which GIMs of different types were driven by bias-corrected (8) climate from state-of-the-art CMIP5 GCMs (19). These GIMs describe the terrestrial water cycle at global scale and include current understanding of hydrological systems (20). Note that statistical bias-correction can influence the signal of runoff changes but this generally remains smaller than uncertainty from GCMs and GIMs (21). The simulations we used did not consider water management or changes of land use, so they represent the effects of climate change alone. We quantify changes in the space-time variability of drought that are projected to occur under four Representative Concentration Pathways (RCPs) that span a wide range of radiative forcing (from left to right RCP2.6 R2, RCP4.5 R4, RCP6.0 R6, RCP8.5 R8). In each RCP panel, results are organised by radiative forcing (from left to right: HadGEM2-ES; IPSLCM5-ARL; MIROC-HM; pentagon PRCGLOB-WB; down triangle VIC; square WBM.

Project (Water MIP; 14) highlighted that simulated hydrological averages can vary substantially between GIMs, even when driven with the same bias-corrected climatic forcing (14, 15), and uncertainty in future projection due to GIMs can be as large as that from GCMs in some regions (16, 17). While in the climate-to-impact modelling chain much effort has been directed to better understand the uncertainty due to GCMs, studies of the impact of climate change on water availability and drought have often been based on one or a few GIMs, potentially underestimating the overall uncertainty.

This study aims to identify regions where the impact of climate change on hydrological drought shows a strong signal of change between the end of the 20th and 21st centuries. We define drought as occurring when total runoff is less than a given threshold. Drought represents the time-integrated effect of several interconnected processes and stores, including precipitation, evaporation, and soil moisture storage; because some of these processes are represented by GCMs and some by GIMs, it is vital to quantify the relative uncertainty introduced by both GCMs and GIMs when assessing climate change impacts.

We use outputs from the ISI-MIP multi-model ensemble (MME) experiment of 35 members (for RCPs 2.6 and 8.5; only 27 members available for RCP4.5 and 6.0) in which GIMs of different types were driven by bias-corrected climatic forcing from state-of-the-art CMIP5 GCMs. These GIMs describe the terrestrial water cycle at global scale and include current understanding of hydrological systems. Note that statistical bias-correction can influence the signal of runoff changes, but this generally remains smaller than uncertainty from GCMs and GIMs. The simulations we used did not consider water management or changes of land use, so they represent the effects of climate change alone. We quantify changes in the space-time variability of drought that are projected to occur under four Representative Concentration Pathways (RCPs) that span a wide range of radiative forcing.
hotspots where the signal is strongest.

and season scale, with Signal-to-Noise ratios (S2N; MME mean changes in GDI and RDI are examined at the annual (Methods; Figs. S2 and S3 in Supplementary Information SI). The five GCMs are included in the MME for RCP2.6 and RCP8.5 of zero runoff values; hence a total of seven GIMs driven by

for which on average fewer than 75% of the remaining land cells zero more than 90% of time in the reference or future periods

Deficit Index (DI) which is equal to 1 if the daily runoff (not river forcings) with those from a reference period 1976-2005 (historical forcings).

We analyse future droughts by comparing the temporal and spatial patterns of simulated runoff in the years 2070-2099 (RCP forcings) with those from a reference period 1976-2005 (historical forcings). For each land cell and simulation we define a runoff forcing (22) (Methods). We also evaluate the uncertainty associated with both GCMs and GIMs, so as to identify hotspots of change where we have more confidence in the projections of future drought severity.

Results

We analyse future droughts by comparing the temporal and spatial patterns of simulated runoff in the years 2070-2099 (RCP forcings) with those from a reference period 1976-2005 (historical forcings).

Global changes

Under RCP8.5, the MME mean change in the frequency of drought (i.e. DI=1) shows a widespread increase of drought conditions across the globe and in particular in most parts of South and North America, large parts of tropical and southern Africa, the Mediterranean region, South East China and Australia; little change or reduced occurrence of drought conditions are found in northern Canada, North East Russia, the Horn of Africa and parts of Indonesia (Fig. 1). There is strong seasonality across many mid- to high-latitude regions in the Northern Hemisphere, with small changes or reductions in DJF and larger increases in JJA (Fig. S4). For 25 members (i.e. 70% of the ensemble) the frequency of drought increases in 60.3% of unmasked land cells, falling to 44.9% in DJF when there is the largest degree of disagreement between ensemble members as to the direction of changes. Over the whole year, S2N is largest in the Mediterranean and the Middle East, Chile, South East US, and Western Australia (Fig. 1).

In Fig. 2 we calculate the mean change in GDI for the four RCPs. The results show a likely increase in drought severity with a MME mean increase of 3.9% under RCP2.6, 6.3% for RCP4.5, 7.4% for RCP6.0 and reaching 13% under RCP8.5 (see (23) for method and SI for detailed results); changes are largest in JJA (17.6%) and smallest in DJF (10.6%) under RCP8.5. The systematic increase in drought severity with radiative forcing (Fig. 2) is associated with considerable variation in the magnitude of the changes ranging from -1.7% to +11.2% under RCP2.6 and -4.8% to 25.4% under RCP8.5. S2N associated with GCMs and GIMs shows a stronger signal (less uncertainty) for GCMs (mean S2N=2.44) than for GIMs (1.82) primarily due to smaller IQ for GCMs (mean IQ=0.049) than for GIMs (0.070) (SI for details). This indicates that, at the global scale, the variability due to different GIMs is larger than that due to different GCMs.

There is a statistically significant (see Methods) increase in the frequency of severe events (large GDI) for all RCP/GCM/GIM combinations except for JULES which shows a consistently smaller change signal in all simulations but one for RCP 8.5 (Cumulative Density Function CDF, Fig. 3). Under historical forcing, drought affects less than 21% of the global land area at any one time (GDI<0.21; black lines) but this is exceeded for 23 out of 33 simulations under RCP2.6 (dark blue) and for 30 under RCP6.5 (red). Largest increases are seen for RCP8.5, with maximum drought severity exceeding 40% of land in 16 simulations. There is greater temporal variability in the GDI in many simulations of the RCPs (flatter CDFs in Fig. 3), increasing with radiative forcing, and associated with more pronounced variability between GIMs.

Effects of model structure

All the models shown in Fig. 3 calculate the water balance of the land, but only H08 and JULES consider the energy balance (Table 1 in SI), and only JULES represents the effects of CO2 on stomatal opening and includes a dynamic vegetation model that allows vegetation to grow in response to its environment. To examine whether the different behaviour of JULES was at-

Footline Author PNAS
GIM, JULES, that shows systemically lower response to climate change, but remains larger than the uncertainty in GCMs even when excluding it from the ensemble, e.g. GDI S2N is 2.48 from GIMs and 3.01 from GCMs when excluding JULES (Table S3 in SI; numbers in bracket for details).

By investigating JULES simulations further, we show that its outlying signal is largely the result of the inclusion of a description of the plant response to enhanced CO₂, a process that is not represented in most GIMs used to simulate global water resources. The effects of CO₂ and dynamic vegetation on plant evapotranspiration and mean runoff have been studied before (e.g. 24, 25, 33, 34) but the effect on drought and a direct comparison with hydrological models has not been presented before.

When atmospheric CO₂ increases, the stomata can partially close (35) conserving the water and resulting in smaller changes of evapotranspiration in a warmer climate (26, 36). This leaves a wetter soil and thereby a less likely drought occurrence, as found in our results. At the leaf-scale the physiological effect of increased CO₂ is well characterised by laboratory and field studies (37) but models differ substantially in the predicted response of transpiration at the ecosystem level (38) and the net effect of physiological and structural changes is also highly uncertain (39).

Our results suggest that the inclusion of CO₂ and vegetation dynamics can fundamentally change the drought response to climate change but the magnitude of these changes remain uncertain. This underlines the importance of including a diverse range of GIMs describing various processes when designing multi-model experiments, and that more research should be conducted to better understand the response of vegetation water use to CO₂ increase.

Our MME only considered the impact of climate change with no representation of water management or changes in land use. Climate (including CO₂ effects on vegetation) is not the only forcing relevant to assessments of future droughts and water scarcity as water demand can generate water stress (40) and the projected future population increase will likely result in further increases in water stress (41). For a thorough investigation of water availability, the combined effect of climate, land use and water management should be taken into account, using a range of GCMs and GIMs to capture the uncertainty.

Methods

In this paper we have analysed simulations from the Global Impact Models of the ISI-MIP ensemble experiments for which daily runoff data were available. The experiments considered five different worlds: one representative of historical climate and four future worlds. These future scenarios included: a very high baseline (rising radiative forcing reaching 8.5Wm⁻² by 2100, RCP8.5), a very low forcing level (radiative forcing peaking at 3Wm⁻² before declining to reach 2.6Wm⁻² by 2100 RCP2.6), and two medium stabilization scenarios (stabilization without overshoot pathway to 4.5/6.0 Wm⁻² at 2100 RCP4.5/RCP6.0) (22, 42). Each radiative forcing scenario was implemented by five Global Climate Models (GCMs): HadGEM2-ES; IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M and NorESM1-M (18). Transient GCM outputs were re-gridded to a common 0.5° latitude x 0.5° longitude grid and a 2-step bias correction procedure implemented for each month independently (8) based on the WATCH Forcing data (43).

The bias-corrected GCM outputs (8) were used as inputs for nine Global Impact Models: H08, JULES, LPJmL, Mac-PDM.09, MATSIRO, MI-heat, PRCi, GloWb, VIC and WBM (see SI for references). For RCP4.5 and 6.0, VIC and Mac-PDM.09 were only driven by HadGEM2-ES. The GIMs were run on 0.5° grids (except JULES, which was run with grid cell size 1.875° longitude x 1.25° latitude, then regridded to 0.5° for analysis). GIMs were spun up to a quasi steady state by repeated use of detrended meteorology for 1951-1980, followed by a simulation of the period 1981-2005. Simulations for each RCP covered 2006-2099 (2005-2099 for HadGEM2-ES-forced runs). All GIMs considered contemporary patterns of land use, except JULES which modelled natural vegetation only, with no land use. No anthropogenic storage (e.g. dams and reservoir) or water management were represented.

We have not investigated the extent to which the drought results from climate, land use and water management, as no simulations without either were available. However, our best assessment from other work with JULES (not specifically on drought) is that results are generally not very sensitive to the size of the grid cells, at least for modest changes in resolution (say 0.5 to 3 degrees) and for regionally or globally averaged statistics.

Daily total runoff is the sum of surface and subsurface runoff. It is an integrated response to all climate forcings and the useable output of river basins for various water sectors. The daily total runoff outputs from the RCP/GCM/GIM combinations were extracted and analysed for two time slices: 1976-2005 (historical forcing or reference period) and 2070-2099 (future or RCP8.5) (22, 42).

The ISI-MIP dataset also includes experiments of JULES and LPJmL in which CO₂ was allowed to vary only until the year 2000, after which it was kept constant ("noCO₂ runs"), while the meteorological forcing included the climate change signal as before. "RCP" JULES runs were only used in the sensitivity analysis of Fig. 4; all other analysis used JULES runs with varying CO₂.

Following (6), drought episodes were defined relative to a time-varying threshold corresponding to the 10th percentile of total runoff (Q90) simulated under hist (notation follows convention from (44) with Q90 being the runoff value exceeded or equalled 90% of the time). We calculated a detailed partition of the runoff in daily drought deficit indices (Dds), such that Dd1=1 when runoff < Q90 and Dd1=0 otherwise. The drought episodes were represented.

For each land cell of each simulation, we calculated a measure of drier effects per degree of radiative forcing change (ΔF) in the RCP scenario. We quantified an index as the difference between the fraction of days under drought between each RCP and the corresponding historical scenario. We calculated the Signal-to-Noise ratio (S2N) as the ensemble mean change divided by the Inter-Quartile IQ range of changes for the full MME and certain sub-sets of RCP/GCM/GIM combinations (i.e. S2N associated with GCMs is the S2N associated with each GIM driven by all GCMs, then averaged across all GCMs. For S2N associated with each GCM for all GIMs, then averaged across all GIMs). Sensitivity of S2N to the definition of spread was tested (SI). It showed that values based on IQ range are similar but slightly more conservative (i.e. smaller S2N) than those based on Standard Deviation of changes, and so IQ range was used.

Similarly to (46), we removed arid grid cells from the analysis. We defined arid grid cells to be those which had more than 90% of the runoff time series zero and applied an additional threshold to each grid cell of each GCM combination, which discarded days for which the value of Q90 was zero. There were two GIMs (LPJmL and MATSIRO) for which the masking and vetoing removed too many points to be able to calculate global averages (see SI for details), so we did not use these in the global analysis. After applying the masking procedure to the remaining seven GIMs, 82% of the total land cells (55051 out of 67420 grid cells) was included in the analysis. For JULES, this corresponds to 83% of the total grid cells; 3770 out of 10770 grid cells. The days which were kept were based on the effects of model structure (inclusion of dynamic effect of CO₂ on plants) using the two discarded GIMs (LPJmL and MATSIRO) along with JULES, using the GDI metric, which retained only 64% of the total land cells (68% of the JULES land cells; see SI for details). Therefore, these sensitivity tests are not global results.

The global impact of changing drought was studied by calculating a daily Global Deficit Index (GDI) for each GIM/GCM/RCP combination over the un-masked land cells. This is the weighted average of the number of land cells under drought conditions, with weights proportional to the area of each grid cell. It represents the global proportion of land (or spatial extent) under drought and gives a measure of the global severity of a dry episode; it varies between 0 (no land cells under drought conditions that day) to 1 (all land cells under drought conditions that day). The method differs from that of (47) and (48) in that it describes the global severity of a dry event based on the percentage of land cells under drought conditions that day to that of (6) to avoid potential discontinuity introduced by minor events. Seasonal GDI were derived by extracting GDI time series for two specific 3-month periods: December to February (DIF) and June to August (UA). We also calculated a daily Regional Deficit Index (RDI) for 17 of the Geo regions defined in (27). These regions were those for which we could calculate a DI value for at least 50% of the land cells.

We also calculated a daily Regional Deficit Index (RDI) for 17 of the Geo regions defined in (27). These regions were those for which we could calculate a DI value for at least 50% of the land cells.

Daily differences between hist and RCP GIs were assessed using the 1-sided Kolmogorov-Smirnov (48) test which measures the distance between the empirical cumulative distribution functions of two samples of n1 observations (here n1=365x30=10950). Results are presented at the 95% level.

Acknowledgements.

This work has been conducted under the framework of ISI-MIP. The ISI-MIP Fast Track project was funded by the German Federal Ministry of Education and Research (BMBF) with project funding reference number 206.
The work has been part funded by the CEH-NERC water programme. IG was partnership with the Global Organization for Earth System Science Portals. Energy's Program for Climate Model Diagnosis and Intercomparison provides the HadGEM2, IPSL and MIROC climate modelling groups for producing Group on Coupled Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.