Quantifying Extreme Drought Risk using Palaeoclimate and Model Observations from the Last Millennium

Katherine L. Taylor[1], Michael N. Evans[2,1], Andrew Schurer[1], Gabi Hegerl[1]

[1] School of Geosciences, University of Edinburgh; [2]GEPS & ESSIC, University of Maryland

Katherine.Taylor@ed.ac.uk



This presentation participates in OSPP

Outstanding Student & PhD candidate Presentation contest

OSSP Abstract

1. Abstract

- Droughts result from the interaction of climate variability and human intervention, accounting for some of the most complex and costly extreme events of the 20th and 21st centuries[1,2].
- The frequency, severity and persistence of droughts have increased in many regions, and increasingly droughts coincide with high temperatures generating compound hot-dry conditions[3,4,5,6].
- Extreme events are particularly poorly sampled over the instrumental period. Evidence of megadroughts in reconstructions may help to improve understanding of worst-case outcomes and their drivers[7,8,9,10].
- Here, the Palmer Drought Severity Index (PDSI) is calculated globally for the period 850-2014 using CMIP6 last millennia simulations and compared to tree-ring derived reconstructions and instrumental values.
- Simulated PDSI is less variable relative to observations, however can still be used to identify regions which may be particularly vulnerable to extreme drought conditions with warming.
- Future work will quantify the roles of precipitation and temperature in driving the extremes of the last millennia to understand to what extent these events were compound.

2. Research Questions

1. How do extreme droughts in the instrumental period compare to those observed in reconstructions and simulated by models, and how can we ensure a direct comparison?
2. What role did temperature play in the extreme droughts of the last millennia?
3. Is the instrumental period sufficient to assess future vulnerability to droughts?

3. Methods

- PDSI is a compound metric reflecting both precipitation and temperature. In particular regions, PDSI can be used to identify compound drought and heatwave events[11].
- Potential evapotranspiration (PET) was calculated using the Penman-Monteith approach (eq. 1) at a monthly timestep for CMIP6 simulations:

$$PET = \frac{0.408\Delta(R_{\mathrm{Net}} - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

Equation 1: The Penman-Monteith equation for PET

- R_{net}: Net Radiation
- G: Ground Flux
- γ: Pyschrometric constant
- U_2: 2m windspeed
- e_s: Saturation vapour pressure
- e_a: Actual vapour pressure
- Δ: Slope of the vapour pressure curve

- PDSI, a soil moisture water balance model, was calculated using monthly precipitation and PET values using the climate indices python package, and averaged to retain the summer season (JJA) only.
- A 10-year rolling mean of the modelled, reconstructed (drought atlas) and instrumental summer PDSI was calculated for the regions of interest shown in figure 1 to compare the characteristics of and trends in soil moisture between the three datasets.

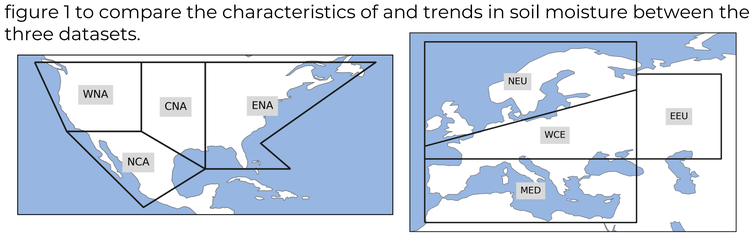


Figure 1 – IPCC regions for North America and Europe used for analysis

4. Observation vs Model PDSI

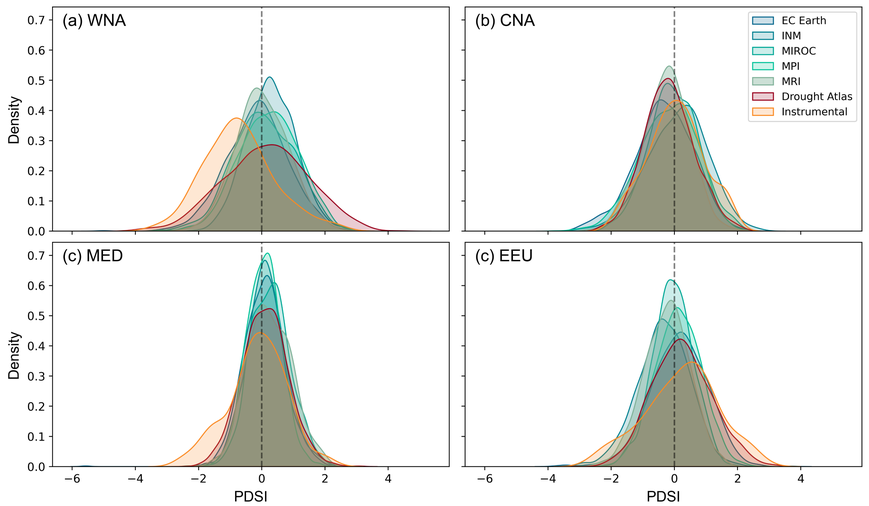


Figure 2 – Distributions of modelled, reconstructed and instrumental annual summer season PDSI for a selection of IPCC regions

- Annual summer PDSI typically lies within the range of -4 to 4. However, the shape of the PDSI distributions vary between the instrumental, reconstructed and model datasets, and between the different regions.
- PDSI is not normally distributed in all regions – this is particularly evident for the instrumental PDSI dataset in WNA and MED raising questions over the ability of PDSI to accurately capture variation in soil moisture across regions of varying climate.
- Both the drought atlas and instrumental datasets show a greater frequency of extreme soil moisture values relative to the model datasets in WNA and EEU – in these regions models may not be able to accurately reproduce the variability of extremes.

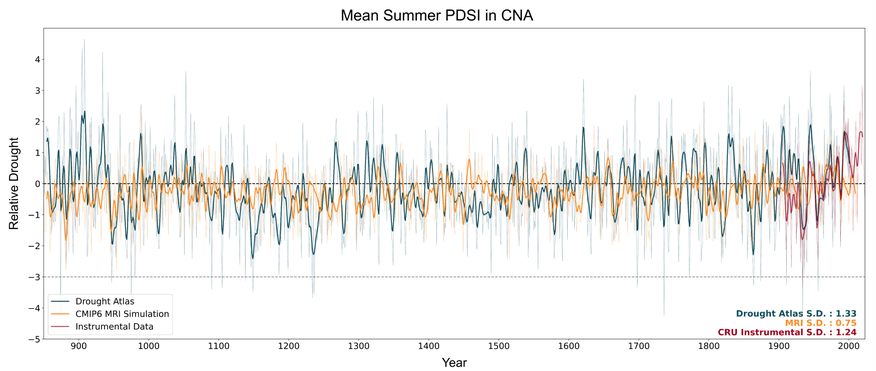


Figure 3 – A comparison of average reconstructed, instrumental, and CMIP6 last millennia (MRI) summer season PDSI across Central North America for the period 850-2015

- Model PDSI is less variable in comparison to reconstructed PDSI from the drought atlas, particularly during the first 200 years of the analysis during which particularly high magnitude extremes are observed in the reconstruction.
- Extended periods of negative soil moisture anomalies can be observed in the reconstructed PDSI corresponding to known periods of 'megadroughts'[7]. Their magnitude can exceed those of the extremes observed in the instrumental data.

5. Frequency of Extreme Drought

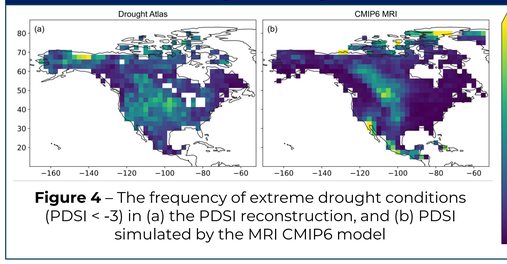


Figure 4 – The frequency of extreme drought conditions (PDSI < -3) in (a) the PDSI reconstruction, and (b) PDSI simulated by the MRI CMIP6 model

Extreme drought occurs more frequently in the modelled PDSI in the southwest and central areas of the US. However, some areas do not observe a PDSI value of -3 at all, demonstrating that the modelled PDSI does not exhibit a common distribution across space.

6. Which Regions Face Future Drought Risk?

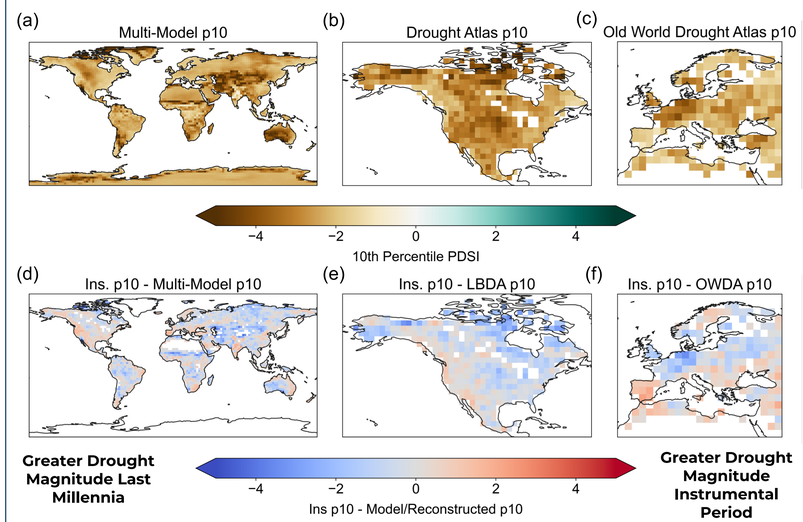


Figure 6 – The 10th percentile PDSI value averaged across CMIP6 last millennia simulations (a), and for the reconstructions of PDSI across the US and Europe respectively (b) and (c), and the absolute 10th percentile instrumental PDSI value minus the absolute model (d) and reconstructed PDSI values (e), (f).

- Where the magnitude of the reconstructions and model PDSI 10th percentile values exceeds that of instrumental period (the areas shaded blue), that region may experience soil moisture deficits outside of those observed in the instrumental period driven by natural variability alone.
- Historically, societies are adapted to the most extreme conditions experienced within living memory[12]. Areas such as the Amazon and Central Europe may therefore be particularly vulnerable to future droughts.

6. Conclusions and Future Work

- Droughts are becoming more extreme, largely on account of rising temperatures.
- Comparing instrumental PDSI to reconstructions and simulations of PDSI over the last millennia can be used to improve understanding of current and future risk.
- Regions including central Europe and the Amazon likely experienced greater magnitude drought conditions over the last millennia relative to the instrumental period – this has relevance for adaptation planning.
- Future work will attribute the roles of precipitation and temperature in generating drought conditions using CMIP6 simulations, and apply GEV statistics to understand worst-case outcomes and how their magnitude varies between the three datasets used.

References

1. Wilhite, D.A. and Glantz, M.H. (1985) "Understanding the Drought Phenomenon: The Role of Definitions," WATER INTERNATIONAL [Preprint]; 2. Wilhite, D.A. (2000) "Chapter 1 Drought as a Natural Hazard: Concepts and Definitions", 3.Dai, A. (2011) "Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008," Journal of Geophysical Research, 116(D12), p. D12115. Available at: https://doi.org/10.1029/2010JD015541; 4. Chiang, F., Mazdiyasni, O. and AghaKouchak, A. (2021) "Evidence of anthropogenic impacts on global drought frequency, duration, and intensity," Nature Communications, 12(1), p. 2754. Available at: https://doi.org/10.1038/s41467-021-22314-w; 5. King, K.E. et al. (2024) "Increasing prevalence of hot drought across western North America since the 16th century," Science Advances, 10(4), p. eadj4289. Available at: https://doi.org/10.1126/sciadv.adj4289; 6. Gebrechorkos, S.H. et al. (2025) "Warming accelerates global drought severity," Nature, 642(8068), pp. 628–635. Available at: https://doi.org/10.1038/s41586-025-09047-2; 7. Cook, E.R. et al. (2010) "Megadroughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context," Journal of Quaternary Science, 25(1), pp. 48–61. Available at: https://doi.org/10.1002/jqs.1303; 8. Ionita, M. et al. (2021) "Past megadroughts in central Europe were longer, more severe and less warm than modern droughts," Communications Earth & Environment, 2(1), p. 61. Available at: https://doi.org/10.1038/s43247-021-00130-w; 9. Coats, S. et al. (2013) "Megadroughts in Southwestern North America in ECHO-G Millennial Simulations and Their Comparison to Proxy Drought Reconstructions*," Journal of Climate, 26(19), pp. 7635–7649. Available at: https://doi.org/10.1175/JCLI-D-12-00633.1; 10. Coats, S. et al. (2015) "Are Simulated Megadroughts in the North American Southwest Forced?*," Journal of Climate, 28(11), pp. 124–142. Available at: https://doi.org/10.1175/JCLI-D-14-00071.1; 11. Taylor, K.L. et al. (2026) "Assessing the Ability of Tree-Ring Derived Aridity Records to Detect Compound Drought and Heatwave Events," Journal of Climate, p. e250472. Available at: https://doi.org/10.1175/JCLI-D-25-0472.1; 12. Thompson, V. et al. (2023) "The most at-risk regions in the world for high-impact heatwaves," Nature Communications, 14(1), p. 2152. Available at: https://doi.org/10.1038/s41467-023-37554-1

E4 DTP Edinburgh Earth, Ecology and Environment Doctoral Training Partnership

University of Maryland

The University of Edinburgh

Natural Environment Research Council

Let's connect!

If you're interested in speaking further about my work, please reach out via either of the following channels:

Email: Katherine.Taylor@ed.ac.uk

LinkedIn: https://www.linkedin.com/in/katherine-taylor-645482161/

Scan to read our recent publication '*Assessing the Ability of Tree-Ring Derived Aridity Records to Detect Compound Drought and Heatwave Events*' (Taylor et al., 2026)