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Not as Rare as Expected: Assessing Singapore's Unprecedented Droughts in a Changing Climate

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There has been growing evidence suggesting a rising frequency and/or intensity of droughts in tropical regions in a warming climate. Singapore, a water-scarce city heavily reliant on water imports, faces heightened vulnerability to extreme drought episodes. Preparing for unprecedented droughts is thus pivotal for this tropical island city to safeguard a sustainable and resilient water supply. However, the accuracy of quantifying the probability and severity of unprecedented droughts, such as those with a 1000-year return period, is hindered by observations (e.g., in situ measurements, satellite data, etc.) with limited data length, typically spanning only about 50 years. Physics-based regional climate models offer a distinct advantage in simulating extreme droughts beyond historically available data. Yet, naïve Monte Carlo simulations for rare events becomes computationally infeasible at high spatiotemporal resolutions, a scale most relevant in urban drought risk mitigation. In this study, building upon the Giardina-Kurchan-Lecomte-Tailleur algorithm, we develop a computationally efficient framework to simulate Singapore's unprecedented drought events. Our framework couples the Weather Research and Forecasting (WRF) model with a sequential importance sampling procedure, incorporating the 'Darwinian pressure' to favor trajectories conducive to extreme drought conditions. With just slightly over 100 trajectories, we can efficiently simulate very rare drought events (e.g., 1-in-10000-years and rarer) while maintaining their physical plausibility. The WRF model also enables detailed spatiotemporal dynamics of unprecedented droughts, allowing direct estimation of potential compounding extremes, such as concurrent droughts and heatwaves. Moreover, we quantify changes in the likelihood of plausible yet unprecedented droughts under various future climate change scenarios, such as Shared Socioeconomic Pathway 5-8.5 (SSP585), in comparison to the present climate. Our results reveal a robust increase in the chance of unprecedented droughts, emphasizing the importance of developing resilient water strategies for Singapore to prepare for such events in the near future.