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Global blue and green water cycles exit from pre-industrial variation – freshwater change planetary boundary exceeded?

Miina Porkka[1,2], **Vili Virkki**[1], Lan Wang-Erlandsson[3], Chinchu Mohan[4], Tom Gleeson[4], Dieter Gerten[5], and Matti Kummu[1]

[1]Water and Development Research Group, Aalto University, Espoo, Finland
[2]Global Economic Dynamics and the Biosphere, Royal Swedish Academy of Sciences, Stockholm, Sweden
[3]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden
[4]Department of Civil Engineering, University of Victoria, Victoria, British Columbia, Canada
[5]Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

Cycling of water supports a wide array of Earth system functions ranging from ecosystem provision to regulating greenhouse gas fluxes. While justifiably included in the planetary boundaries framework, the current freshwater planetary boundary fails in recognising the interplay between local and global drivers modifying the water cycle. Building on recent conceptual work and considering an extended selection of Earth system functions, we propose quantitative indicators for blue and green water to measure and monitor water cycle modifications. These indicators can capture changes at local, regional, or planetary scales, offering a robust and easily measurable way of determining alterations in the water cycle.

Our data consisted of discharge (blue water) and root-zone soil moisture (green water) simulated by state-of-the-art gridded global hydrological models in ISIMIP 2b. Initiating our analysis at the 30-arcmin grid scale, we set cell-wise dry (5th percentile) and wet (95th percentile) local bounds based on pre-industrial (1681–1860) data, separately for blue and green water. We then determined cell-wise exits from these local bounds of baseline variability and aggregated them at the global scale. This resulted in a time series of the percentage of global land area where blue or green water anomalies exit local bounds of baseline variability. The 95th percentile of these global baseline departures was then set as the safe limit of water cycle modifications. Finally, to estimate the state of the water cycle, we compared the recent past (1881–2005) blue and green water conditions to the pre-industrial conditions. First, we determined cell-wise exits from the local

bounds and then aggregated the global baseline departures to compare those with the safe limits.

We show that in all aspects - blue and green water and dry and wet anomalies - the global water cycle has undergone substantial changes and transgressed the safe limits. This is a result of a gradual change throughout the 20th century. For blue water, drying conditions dominate along the mid-latitudes, whereas for green water, large-scale wetting prevails in the Northern Hemisphere boreal regions. Major changes in both blue and green water conditions co-occur commonly around regions with the highest anthropogenic pressures. Overall, global changes especially towards drier blue water conditions and wetter green water conditions have gone far beyond the pre-industrial levels - therefore placing the water cycle in a state unknown to modern societies.

Our results underline the necessity and urgency to update the freshwater change planetary boundary. As both blue and green water cycles have entered an unprecedented state following a long and gradual change, Earth system functions upkept by the water cycle may already be or become compromised. While further studies are required to assess the status of the freshwater change planetary boundary alongside other boundaries to provide a comprehensive analysis on total Earth system resilience, our results clearly show that the global water cycle is changing towards the unknown.