• consistent, observed impact of climate change is shift towards fewer light precipitation events & more frequent heavy precipitation, pronounced in tropics.

piezometric & isotopic data: Uganda & Benin

- in humid tropics, observed groundwater-level rises and stable-isotope ratios in groundwater traced to heavy rainfall events exceeding 10 mm·day\(^{-1}\)


- heavy rainfall in the tropics is depleted with respect to the heavy isotopes of \(^{18}\)O and \(^2\)H, "*The Amount Effect*"

combined rainfall & groundwater-level monitoring
Soroti (Uganda)
piezometric evidence from semi-arid Tanzania

• recharge occurs *episodically* and *disproportionately* from extreme (>80\textsuperscript{th} percentile) seasonal rainfall generating ephemeral streamflow (*i.e.* focused recharge)

• episodic recharge results from heavy rainfall associated with *El Niño Southern Oscillation*

• confirms (1) bias in recharge to heavy rainfall; (2) episodicity of recharge in drylands and links to large-scale climate controls; and (3) importance of focused recharge in drylands
- **non-linearity** in relationship between long-term average (LTA) rainfall and recharge from systematic review of >200 studies

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*MacDonald et al. (in review) Environ. Res. Lett.*
pan-tropical evidence from stable isotopes

- isotopic composition of tropical groundwater is biased to heavy monthly rainfalls exceeding 70th percentile

evidence from GRACE satellite data

- non-linearity in trends in groundwater storage $\Delta$GWS associated with episodic nature of groundwater replenishment from extreme annual (>90th percentile, 1901–2016) precipitation

- clearest examples observed in dryland environments (e.g. California Central Valley, Great Artesian Basin)

Conclusions:

- intensification of precipitation driven by climate change amplifies groundwater recharge in many environments... yet also increases intensity/duration and frequency of floods/droughts – groundwater thus becomes a (hydro)logical source of freshwater to adapt to climate change, especially in the tropics.
- rapid transmission of extreme-heavy rainfalls through soils as recharge is inconsistent with models employing matrix-defined infiltration capacities and Richards equation – and reflects presence of structures (e.g. macropores) making groundwater more vulnerable to contamination than previously considered

- most large-scale models of recharge do not represent focused recharge, a dominant recharge pathway in drylands, undermining the validity of recharge projections