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Evidence of the dependence of groundwater resources on extreme rainfall in East Africa

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Groundwater recharge sustains the groundwater resources on which there is global dependence for drinking water and irrigated agriculture[1]. For many communities, groundwater is the only perennial source of water. Here, we present a newly compiled 55-year record of groundwater-level observations in an aquifer of central Tanzania that reveals the highly episodic occurrence of recharge resulting from anomalously intense seasonal rainfall. Episodic recharge interrupts multiannual recessions in groundwater levels, maintaining the water security of the groundwater-dependent communities in this region. This long-term record of groundwater storage changes in the semi-arid tropics demonstrates a nonlinear relationship between rainfall and recharge wherein intense seasonal rainfall associated with the El Niño Southern Oscillation and the Indian Ocean Dipole mode of climate variability[2,3] contributes disproportionately to recharge. Analysis of the Intergovernmental Panel on Climate Change AR4 and AR5 multi-model ensembles for the twenty-first century indicates that projected increases in extreme monthly rainfall, responsible for observed recharge, are of much greater magnitude than changes to mean rainfall. Increased use of groundwater may therefore prove a potentially viable adaptation to enhanced variability in surface-water resources and soil moisture resulting from climate change[4–7]. Uncertainty in the projected behaviour of the El Niño Southern Oscillation and associated teleconnections remains, however, high[8].

Groundwater is the world's largest accessible store of fresh water and supplies 36% of the world's drinking water and ~42% of the water used for irrigation[1]. Groundwater is the only reliable source of fresh water in many semi-arid and arid regions where surface waters are seasonally or perennially absent[9]. The long-term viability of groundwater resources as well as the ecosystems and livelihoods that they sustain, depends on replenishment of groundwater by recharge. Over the past 50 years, groundwater depletion has been estimated and observed in several aquifers throughout the tropics and sub-tropics[10-13]. Such depletion not only threatens ecosystem function and the livelihoods of groundwater-dependent communities in some of the world's poorest regions but is also estimated to contribute to sea-level rise[12,13]. A conceptual understanding of the relationship between rainfall and recharge is fundamental to the development of robust estimates and projections of not only groundwater recharge and depletion but of all components of the terrestrial water balance under changing climates and increasing freshwater demand.

Recharge results from effective precipitation (that is, precipitation minus losses from evapotranspiration) infiltrating the subsurface where hydraulic gradients are downward. Diffuse groundwater recharge occurs directly through the soil matrix in saturated soils and through soil macropores and fractures that bypass the soil matrix. Focused groundwater recharge takes place indirectly by way of leakage from runoff and surface-water sources including ephemeral streams and is often a critical source of recharge in semi-arid environments[14-16]. The magnitude of effective precipitation is highly sensitive to changes in precipitation and evapotranspiration, particularly in semi-arid environments where differences between these fluxes are small[16,17]. Soil-moisture balance modelling studies in the tropics[18-20] suggest a nonlinear relationship between rainfall and recharge in which recharge is biased to heavy rainfall events (>10mmd^{-1}) that temporarily exceed high rates of prevailing evapotranspiration. A key uncertainty is whether soil infiltration capacities are able to transmit, in practice, modelled increases in recharge generated by heavy rainfall. Indeed, the relationship between precipitation and groundwater recharge remains poorly resolved in many regions owing to a lack of long-term observational data.

Here we present empirical evidence of the relationship between rainfall and groundwater recharge in semi-arid tropical East Africa from a recently compiled near-continuous, 55-year (1955-2010) record of coincidental, in situ groundwater-level observations (variable time step with gaps) and monthly rainfall (Fig. 1a,b). Observations derive from the Makutapora Wellfield (38º 45’ E, 5º, 55’ S) in central Tanzania where groundwater is abstracted from an aquifer comprising deeply weathered granite overlain by alluvium. This unique time series, the longest observed record yet published for any location in the tropics, reveals the highly episodic nature of recharge events indicated by positive deflections in groundwater levels that result from anomalously intense rainfall during the austral summer monsoon (November-April). These recharge events interrupt multiannual recessions in groundwater levels. Rates of groundwater level decline have increased substantially from ~0:5 m yr^{-1} (1955-1979) to ~1:7 m yr^{-1} since 1990. This change is a response to pronounced increases in monthly groundwater abstraction from 0.1 to 0.9 million m^3 to supply potable water to the national capital, Dodoma (Fig. 1c). Intensive groundwater abstraction is sustained by natural, inter-annual groundwater storage that is replenished on a decadal timescale by episodic recharge.

The observed relationship between seasonal rainfall and groundwater recharge is nonlinear (Fig. 2a) as recharge is largely restricted to anomalously intense seasonal rainfall. The cumulative recharge distribution (Fig. 2b) shows that the top 7 (11) seasons of rainfall account for 60% (75%) of the total recharge observed over 55 years from 1955 to 2010; remaining recharge is confined to seasons that feature individual months of statistically extreme (>95th percentile) rainfall (Fig. 2a). For nearly two-thirds of the 55-year record, no recharge is observed. Indeed, the Makutapora record suggests that unless monthly rainfall exceeds 200mm (>95th percentile) or seasonal rainfall is greater than 670mm (third quartile), little or no recharge occurs. These observed thresholds reflect the requirement of intense rainfall to overcome the high rates of potential evapotranspiration that prevail in the tropics, estimated locally to be 160 mm month^{-1} during the monsoon season, to generate recharge. Recharge pathways to the Makutapora Wellfield are both diffuse, through surficial sediments within the wellfield depression, and focused by way of ephemeral streams flowing over the coarse-grained soils within alluvial fans at the margins of the depression[21] (see Supplementary Information).

We examine anomalously intense seasonal rainfall that generates recharge in central Tanzania in terms of the wider regional and global climate system. Composite analysis of regional-scale rainfall anomalies associated with the seven largest episodic groundwater recharge events indicates a marked north-south dipole pattern of precipitation over tropical southeast Africa (Fig. 3a) with opposing positive (negative) precipitation anomalies north (south) of ~10 S. This dipole pattern is congruent with the most important structure of rainfall variability across southeast Africa as defined by the leading empirical orthogonal function (EOF) of monsoon season rainfall[2] (see Supplementary Information). The leading EOF is itself strongly correlated with tropical sea-surface temperature anomalies (SSTAs) indicative of both the Indian Ocean Dipole (IOD) and the El Niño Southern Oscillation (ENSO), the dominant modes of coupled ocean-atmosphere interaction in the tropical global and Indian oceans, respectively[2]. Figure 3b clearly shows the close association among the time series of the leading EOF, ENSO and groundwater recharge events. Of the seven largest recharge events, all but one are in the top eight events of the EOF time series and five coincide with El Niño events. The other groundwater recharge event (1959-1960) is associated with locally high rainfall (Fig. 1b) that does not have a strong regional expression.

The complex interaction of ENSO teleconnections and IOD variability is known to be the key driver of climate variability over southeast Africa[2,3]. Major ENSO warm (El Niño) events and the positive phase of the IOD lead to wet extremes in the East African sector and our study region. The most striking example is that the greatest recharge event (521mm) observed in the Makutapora record (Fig. 1a) resulted from the heaviest season of monsoonal rainfall (1997-1998) recorded. This event is associated not only with the strongest ENSO warm event of the past century but also a positive IOD event[22]. From the above analysis, we conclude that the infrequent and episodic groundwater recharge events at Makutapora are primarily driven by regional-scale extreme precipitation anomalies associated with major events of the dominant modes of tropical climate variability in the region. Some of the more minor recharge events are associated with more localized rainfall anomalies (see Supplementary Information). It is unclear at present whether climate change will strengthen or weaken the influence of ENSO on East African rainfall[8]. An increase in the probability of positive IOD modes associated with heavy monsoonal rainfall in East Africa has recently been suggested as a response to anthropogenic warming from a review of AR4 models[23]. At present, the complex interactions of ENSO and IOD and their teleconnections preclude, however, firm conclusions on the impact of global warming on ENSO and IOD modes of variability and their influence on heavy rainfall in central Tanzania. This uncertainty represents a key question to be investigated using new output from AR5 models.

A robust signal of projected global warming is an increase in the intensity of heavy rainfall events. This intensification is expected to be especially pronounced in tropical wet seasons as a result of the ~6:5% K^{-1} increase in atmospheric humidity defined by the Clausius-Clapeyron relation and the sensitivity of tropical convective rainfall to total moisture content[4,5,23], verified by observational studies[6]. Analysis of general circulation model (GCM) projections for the twenty-first century over the region surrounding the study site (Fig. 4) suggests an increase in mean precipitation over the study region, associated with projected increases over equatorial East Africa more widely (see Supplementary Information). This result is similar in the analysis of GCMs contributing to the Intergovernmental Panel on Climate Change AR4 and forthcoming AR5 (+9.7 and +5.2 mm d^{-1} by the end of the twenty-first century, respectively), although the uncertainty is higher in the latter case, reflecting some important regional differences (see Supplementary Information). At the broader scale, this is part of a wider quasi-global rich-get-richer pattern in which regions of moisture convergence (divergence) are expected to experience increased (decreased) precipitation[6], consistent between the AR4 and AR5 models. However, of particular importance to this study is that projected changes to extreme monthly rainfall driving groundwater recharge observed in the Makutapora record are of much greater magnitude (+22.5 and +25.4 mm $month^{-1}$ for AR4 and AR5 GCMs, respectively) than changes projected for mean monthly rainfall. These changes in the higher moments of the rainfall distribution are an important dimension to non-stationarity in future climate and, as shown here, have important implications for groundwater processes.

Anomalously intense seasonal and monthly rainfall has been associated with negative socio-economic consequences[3] that include the loss of crops and livestock, and the destruction of homes, yet the Makutapora record shows that these episodic events sustain groundwater resources on which there is often complete dependence for freshwater in tropical semi-arid environments. The observed dependence of episodic groundwater recharge on intense rainfall is consistent with evidence from semi-arid areas of Australia[24], southwestern USA[14] and West Africa[15]. The projected shift towards more intensive monthly rainfall favouring groundwater recharge suggests that greater use of groundwater may form a viable adaptation to increased variability in surface-water resources and soil moisture resulting from climate change. In light of the observed dependence of groundwater recharge on ENSO and IOD, the limited ability of GCMs to represent these modes of climate variability and their teleconnections remains a key impediment to understanding climate-change impacts on freshwater supplies in East Africa and regional climate change scenarios more widely.

METHOD SUMMARY

The near-continuous time series of groundwater-level measurements drawn from 6 monitoring wells over a variable time step (daily to monthly) and monthly pumping volumes from the Makutapora Wellfield was constructed from observations collected by the Ministry of Water and Irrigation and the Dodoma Urban Water Supply and Sanitation Agency. Data were assembled from computer files, hardcopy plots, and notebooks stored in Wamaruvu Basin Office of the Ministry of Water and Irrigation. Monthly rainfall at the Makutapora Wellfield (35°45'E, 5°55'S) was monitored by the Tanzanian Meteorological Agency; daily records are unavailable. Groundwater recharge (q) was estimated from changes in groundwater levels (∂h) through time (∂t) assuming changes in groundwater storage are controlled by the balance of recharge and net groundwater drainage (D) from a monitoring well where specific yield (S_y) is the storage co-efficient through the equation[25]: $q = S_y(\partial h/\partial t)+D$. The Makutapora Wellfield resides within the large, local depression wherein recharge occurs both directly, through the direct infiltration of rainfall and indirectly through ephemeral streams (see Supplementary Information). D occurs both as a result of intensive groundwater abstraction for the city of Dodoma (Fig. 1c) and natural discharges. *D* was estimated from recessionary trends in groundwater levels during extended periods of absent recharge ($q = 0$). S_y was estimated from the statistically significant ($r^2 = 0.94$, $p = 0.001$) correlation that was observed (see Supplementary Information) between cumulative wellfield abstraction (-*Q*) and groundwater-level recession ($-\delta h/\delta t$) within the wellfield (A = 59 km^2) wherein $S_y = (\partial t/\text{-}\partial h)(\text{-}Q/A)$. This relationship assumes that groundwater is drawn from pore storage evenly from multiple boreholes over the wellfield area. The derived value of S_y (0.064±0.004) applies to groundwater-level fluctuations over a depth interval (1046 to 1058 m above mean sea level) comprising in situ weathered granite[26] and is consistent with that recently estimated from tracing experiments in weathered crystalline rock in Uganda[27]. Estimates of recharge during two gaps in the Makutapora Record (1960-1965, 1980-1984) were imputed empirically from the statistically significant ($R^2 = 0.82$, $p < 10^{-4}$) relationship between heavy (>580 mm) seasonal rainfall and observed recharge; aggregate values imputed for each period were validated against the observed gap in the record ($\partial h/\partial t$) and estimated *D* (see Supplementary Information).

Analysis of historical climate over the wider region employed: (i) gridded monthly precipitation at 0.5° resolution from the Global Precipitation Climatology Centre (GPCC) product from 1955 to 2009[28]; and (ii) gridded global sea surface temperature anomalies (SSTAs) on a 1.0° global grid from the Hadley Centre Sea Ice and Sea Surface Temperature data set[29]. In both cases our results are insensitive to the choice of other available observed gridded data products (see Supplementary Information). We apply the following statistical analyses: (i) composite analysis of gridded rainfall (Fig. 3a) and SSTA fields (see Supplementary Information) based on sample years of major groundwater recharge events; (ii) Empirical Orthogonal Function analysis of monthly rainfall over the region to determine objectively the space/time structures of rainfall variability (see Supplementary Information); (iii) time-correlation of the resulting Empirical Orthogonal Function time series with SSTA gridded fields to determine the association with global and regional modes of climate variability (see Supplementary Information). Climate change projections were obtained from the multi-model ensemble (MME) compiled under the 3rd (CMIP3) and 5th (CMIP5) Coupled Model Intercomparison Projects contributing to the Intergovernmental Panel on Climate Change (IPCC) 4th and (forthcoming) 5th Assessment Reports, AR4 and AR5, respectively. In total, the MME contained data from 23 GCMs for the CMIP3 data and 21 GCMs for currently incomplete CMIP5 archive, of which 8 are Earth System Models (see Supplementary Information). We use data from a single greenhouse gas emission scenario (SRES A1B) from the CMIP3 collection, and two emission scenarios from the CMIP5 collection (RCP45 and RCP85). Changes in climate were calculated over a 10° box centred on the study site for three future epochs representing the early (2021-2050), mid (2035-2065) and late (2070-2099) twenty-first century. Here, we present only results from analysis RCP8.5 scenario, as this is the trajectory closest to recent greenhouse gas emissions, and for the late 21st century alone (Fig 4). The basic structure, if not the magnitude, of the projected changes to mean and the 90th percentiles of monthly rainfall is essentially insensitive to both the epoch and choice of RCP (see Supplementary Information).

References

1. Döll, P. et al. Impact of water withdrawals from groundwater and surface water on continental water storage variations. J. Geodyn. **59-60**, 143-156 (2012).
2. Goddard, L. & Graham, N. E. The importance of the Indian Ocean for simulating precipitation anomalies over eastern and southern Africa. J. Geophys. Res. **104**, 19099-19116 (1999).
3. Conway, D. in The East African Great Lakes: Limnology, Palaeolimnology and Biodiversity (eds Odada, E. O. & Olago, D. O.) 62-92 (Kluwer, 2002).
4. Allen, M. R. & Ingram, W. J. Constraints on future changes in climate and the hydrologic cycle. Nature **419**, 224-232 (2002).
5. Trenberth, K. et al. The changing character of precipitation. Bull. Am. Meteorol. Soc. **84**, 1205-17 (2003).
6. Allan, R. P. & Soden, B. J. Atmospheric warming and the amplification of precipitation extremes. Science **321**, 1481-1484 (2008).
7. IPCC Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (eds Field, C. B. et al.) (Cambridge Univ. Press, 2012); available at http://ipcc-wg2.gov/SREX/.
8. Latif, M. & Keenlyside, N. S. El Niño/Southern Oscillation response to global warming. Proc. Natl Acad. Sci. USA **106**, 20578-20583 (2009).
9. MacDonald, A. et al. Quantitative maps of groundwater resources in Africa. Environ. Res. Lett. **7**, 024009 (2012).
10. Rodell, M. et al. Satellite-based estimates of groundwater depletion in India. Nature **460**, 999-1002 (2009).
11. Shamsudduha, M., Taylor, R. G. & Longuevergne, L. Monitoring groundwater storage changes in the Bengal Basin: Validation of GRACE measurements. Wat. Resour. Res. **48**, W02508 (2012).
12. Konikow, L. Contribution of global groundwater depletion since 1900 to sea-level rise. Geophys. Res. Lett. **38**, L17401 (2011).
13. Wada, Y. et al. Past and future contribution of global groundwater depletion to sea-level rise. Geophys. Res. Lett. **39**, L09402 (2012).
14. Pool, D. R. Variations in climate and ephemeral channel recharge in southeastern Arizona, United States. Wat. Resour. Res. **41**, W11403 (2005).
15. Favreau, G. et al. Land clearing, climate variability, and water resources increase in semiarid southwest Niger: A review. Wat. Resour. Res. **45**, W00A16 (2009).
16. Scanlon, B. R. et al. Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol. Proc. **20**, 3335-3370 (2006).
17. deWit, M. & Stankiewicz, J. Changes in surface water supply across Africa with predicted climate change. Science **311**, 1917-1921 (2006).
18. Taylor, R. G. & Howard, K. W. F. Groundwater recharge in the Victoria Nile basin of East Africa: Support for the soil-moisture balance method using stable isotope and flow modelling studies. J. Hydrol. **180**, 31-53 (1996).
19. Eilers, V. H., Carter, R. C. & Rushton, K. R. A single layer soil water balance model for estimating deep drainage (potential recharge): An application to cropped land in semi-arid North-east Nigeria. Geoderma **140**, 119-131 (2007).

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Author contributions

The Makutapora record was compiled by L.K., E.N., R.G.T., L.M. and H.S. Recharge analyses were conducted by R.G.T., M.C.T., A.M.M. and L.M. M.C.T. performed the analysis of climate data and model projections. R.G.T., M.C.T. and L.M. conceived the paper and R.G.T. and M.C.T. wrote the paper with feedback from all other authors.

FIGURES

Figure 1: 55-year observational record of groundwater levels, rainfall and groundwater abstraction from central Tanzania. **a**–**c**, Time series of groundwater-level observations from 6 monitoring wells (**a**), monthly rainfall (**b**) and monthly groundwater abstraction (**c**) at the Makutapora Wellfield from 1955 to 2010. The vertical solid arrows in **a** denote the seven greatest recharge events considered in the composite analyses. Monthly rainfall data for 2010 are missing in **b**. Records of monthly abstraction in **c** are unavailable for September 1993 and from May 1994 to September 1995 mamsl, metres above mean sea level.

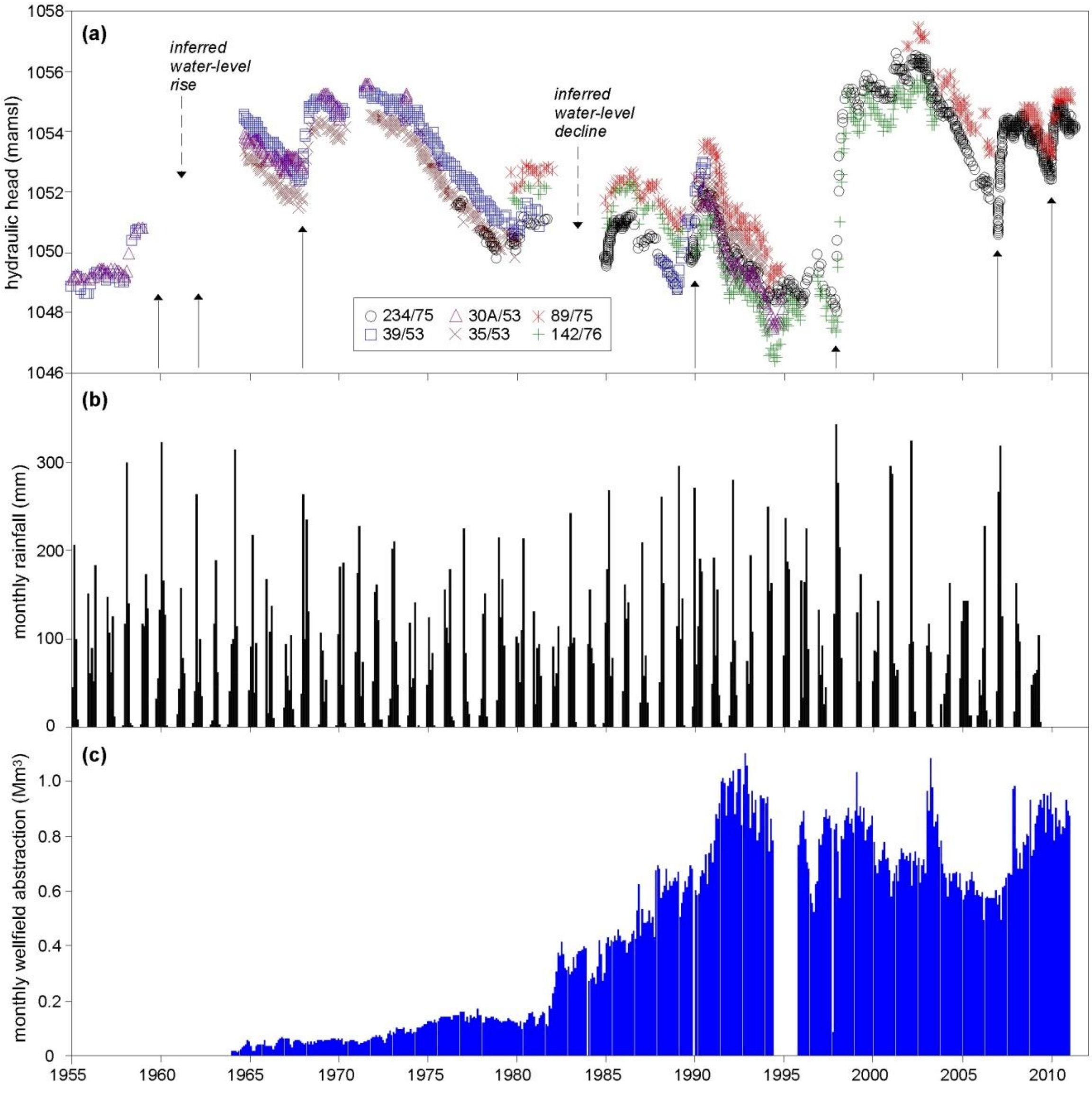

Figure 2: Analysis of the relationship between groundwater recharge and rainfall. **(a):** Cross plot of observed recharge from groundwater-level fluctuations versus rainy season (November to April) rainfall. **(b):** Cumulative contribution of annual recharge to the total recharge received at the Makutapora Wellfield from 1955 to 2010. The shaded region in a indicates seasons featuring a month of statistically extreme (>95th percentile) rainfall, the solid vertical line in a indicates the median (50th percentile), and the dashed line indicates the third quartile (75th percentile) rainy season rainfall.

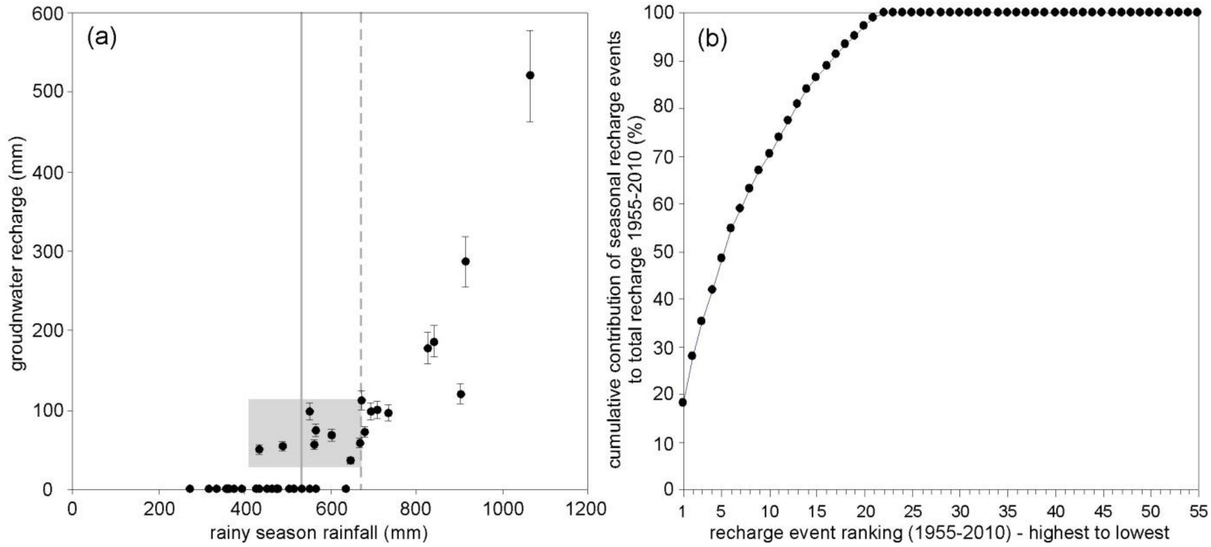

Figure 3 Analysis of climate variability associated with major groundwater recharge events. **(a):** Composite precipitation anomalies (colour scale) of the peak monsoon season (December–February) for the sample years coincident with the seven largest recharge events. Grid cells where composite mean anomalies are significant at the 0.05 level are indicated by the white dashed contour. The location of the Makutapora study site is indicated by the black dot. **(b):** Time series of the leading EOF of regional monsoon season precipitation (November–March, Global Precipitation Climatology Centre (GPCC) data) over the domain 25º,S-5ºN, 10º-45ºE. Note, the EOF aggregates over calendar years (for example 1997–1998 El Niño is plotted as 1998); and the value for 2010 is based on projection of the EOF onto data from the GPCC monitoring product. The seven largest groundwater recharge events are indicated with arrows.

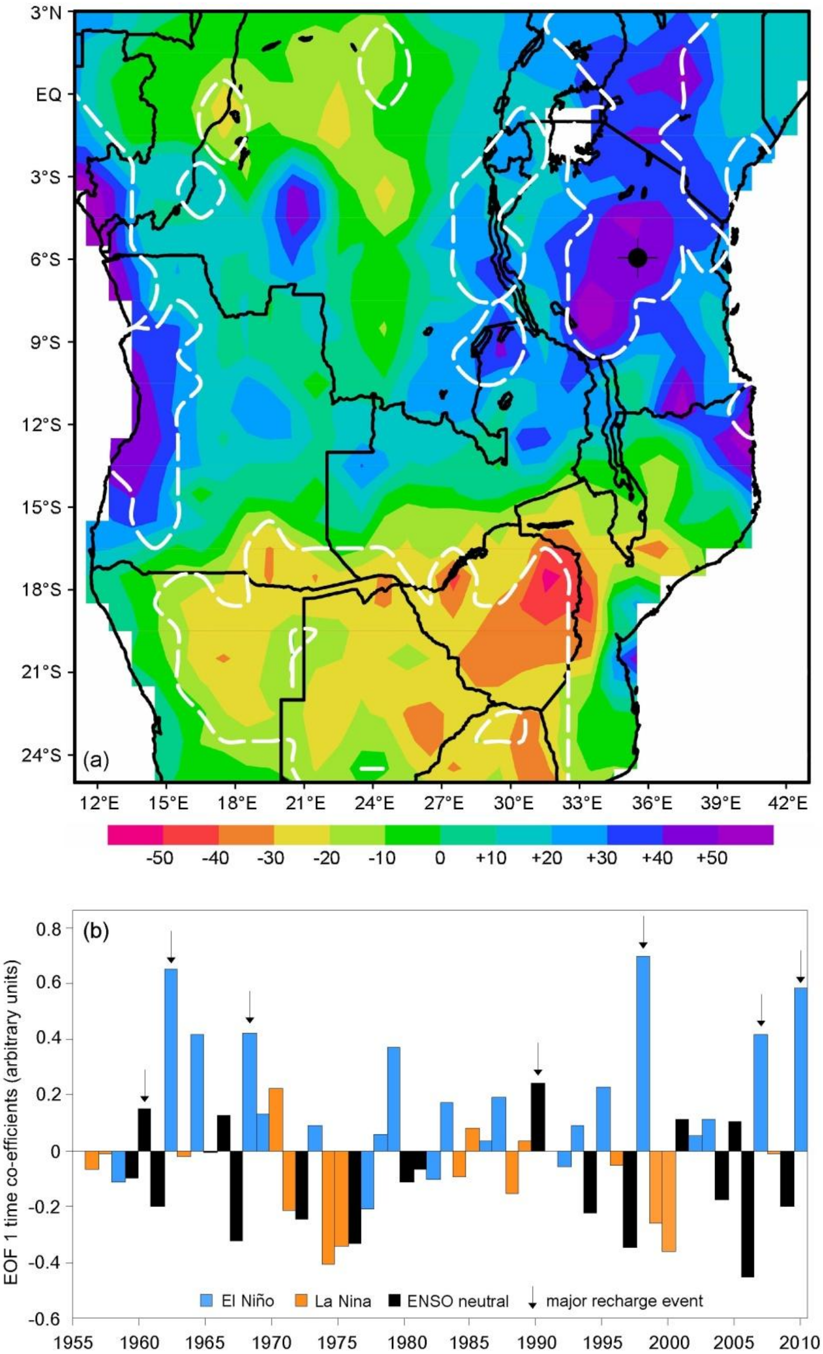

Figure 4 Projected changes in mean and extreme monthly rainfall in central Tanzania. Projected changes in precipitation over the period 2070–2099 relative to 1961–1990 for a 10º box centred on the Makutapora Wellfield in central, semi-arid Tanzania from multi-model ensembles of CMIP3 (AR4) under the A1B emissions scenario (23GCMs) **(a)** and CMIP5 (AR5) under the RCP8.5 scenario (21GCMs) **(b)** Box plots are of changes in monthly precipitation for each model in the MME. Dots indicate individual models within the MME sample, boxes show the inter-quartile range and median and circles show the mean of the MME sample.