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Short communication

Detecting climate changes of concern in highly variable environments: Quantile regressions reveal that droughts worsen in Hwange National Park, Zimbabwe

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Abstract

Rapid climate change is happening worldwide and is affecting ecosystems processes as well as plant and animal abundances and distribution. However, the large climate variability observed in arid and semi-arid regions often impairs the statistical detection of long-term trends using standard statistical methods, especially if one is primarily interested in specific components of the climate changes. Here we highlight how quantile regression overcomes some of the confounding effects of large climate variability in long-term rainfall data. For instance, we show how quantile regressions revealed that droughts worsened in Hwange National Park (Zimbabwe) during the course of the 20th century, a change that would not have been detected using simple linear regression. We briefly discuss the implications of our findings for the management of the park.

Keywords: Africa; Climate variability; Management; Methodology; Rainfall; Trends

1. Introduction

Climatic changes have recently been demonstrated in many locations and have been shown to have dramatic impacts on a wide range of ecosystems (Walther et al., 2002). Locally, scientists are now pressed to identify, characterize and investigate climatic changes and their potential effects (Sparks and Tryjanowski, 2005). However, the high natural variability observed in climatic variables in arid and semi-arid regions often prevents the detection of long-term trends using standard regression procedures, as standard errors of estimated parameters are often wide and do not allow one to reject the null hypothesis of an absence of trend.

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This confounding effect of variability appears even more important when long-term changes differ along the range of values taken by the variable of interest, a common feature of climatic changes. For instance, the long-term evolution of temperature often differs between minimum, average and maximum values (Karl et al., 1993). The severity of drought and flood events has also changed in many places, but not simultaneously (Dai et al., 1998). Moreover, although a full understanding of the patterns of climate changes is needed, in most cases only some specific changes will be sources of concern at the local scale. For instance, wildlife managers in Africa deal with biodiversity conservation and are concerned by droughts that cause major die-offs of large herbivores (Young, 1994), while acknowledging that increased rainfall would be of less concern.

Here we show how one can investigate trends in only a specific range of the rainfall distribution by using quantile regression (Cade and Noon, 2003; Koenker, 2005), and therefore obtain a detailed picture of the patterns of climate change when some of these patterns could have gone undetected using more traditional statistical analyses. We apply this technique to rainfall data collected in Hwange National Park (hereafter Hwange NP), Zimbabwe, and show that although no significant trends in rainfall were detected using standard linear regressions, droughts have actually worsened over the study period.

2. Materials and methods

2.1. Study area

Hwange NP is located on the north-west border of Zimbabwe (19°00′S, 26°30′E) and covers ca. 15,000 km^2 of semi-arid dystrophic savanna. Long-term mean annual rainfall is ca. 606 mm (1928–2005) with an average 98% of the rains falling between October and April. The interannual coefficient of variability for annual rainfall is 25% (Chamaillé-Jammes et al., 2006).

2.2. Rainfall data

We analysed data collected daily between 1928 and 2005 at three stations (Robins: 18°37′S, 25°58′E; Sinamatella: 18°35′S, 26°19′E; Main Camp: 18°43′S, 26°57′E) inside Hwange NP. Data were provided by the Scientific Services of the Zimbabwe Parks and Wildlife Management Authority and were then quality-controlled through visual inspection. Annual rainfall in year t was calculated as the sum of rainfall from October in year $t-1$ to September in year t. Annual rainfall was also averaged over the three stations to express general changes for the park. No data were collected in 2004 and 2005 at the Robins station, and these data were predicted from the regression of the Robins data against the data averaged over the two other stations ($r^2 = 0.48, p < 0.0001$) when needed for calculations over the whole park. Although quantile regression did not require normality of the response variable (Koenker, 2005), data have been $\log_e$ transformed to fulfil the normality assumption of the linear regression and allow for the comparison of the two methods.

2.3. Quantile regression

Simple linear regression estimates the rate of change in the *mean* of the response variable as a function of (i.e. conditional to, given) one or several predictor variables (see Sokal and Rohlf, 1995). Quantile regression extends this estimation to any part of the response distribution, i.e. to any selected quantile, with the τth one-sample quantile estimate defined as the value having a proportion τ of the sample observations less than or equal to the estimate (e.g. the median is the 0.5th quantile and has 50% of the observations above its value, and 50% below its value). Therefore, quantile regression allows one to simultaneously study changes in specific portions of the distribution of the response variable, independently of the change and variability experienced by the rest of the distribution. In particular, its ability to detect opposite trends in statistical extremes (upper and lower) hidden in non-significant mean effects, or to detect changes in median conditions even in extreme stochastic environments, makes it perfectly designed for climate analysis, although it has still been rarely used in such context (see Koenker and Schorfheide, 1994; Sankarasubramanian and Upmanu, 2003). Further details on quantile regression accessible to non-specialists can be found in Cade and Noon (2003) and Koenker (2005).

2.4. Statistical analyses

We compared results obtained from simple linear regression with results produced by quantile regressions. We estimated regression parameters for the 0.1, 0.2, …, 0.9th quantiles. Standard errors for the quantile regression parameters were estimated using the bootstrap method with 500 replications (Koenker, 2005). All analyses were conducted using the R *quantreg* package (http://www.econ.uiuc.edu/~roger/research/rq/rq.html).

3. Results and discussion

There was no significant long-term trend in mean annual rainfall when data were averaged over the three stations ($F_{1,76} = 3.172$, $p = 0.079$), although a p-value <0.1, however, suggested some potential long-term changes. Trends in mean annual rainfall were not significant in Main Camp and Sinamatella (respectively $F_{1,76} = 0.452$, $p = 0.504$, and $F_{1,76} = 2.127$, $p = 0.149$). Mean annual rainfall decreased in Robins ($F_{1,74} = 6.294$, $p = 0.014$), although the predictive power of that relationship was very low ($r^2 = 0.078$) due to the strong inter-annual variability. However such results masked important patterns in the rainfall changes. The quantile regression analyses revealed that the lowest part of the rainfall distribution, i.e. dry years, experienced negative trends over the study period in two out of the three stations (Table 1). This pattern was still significant when data were averaged over the three stations as rainfall in the 0.1th quantile decreased significantly during the study period whereas there were no evidences of changes in higher parts of the rainfall distribution (Table 1). Our results indicate that although no changes in mean rainfall were statistically detectable in two out of the three stations, as well as on data averaged over the three stations, dry years became even drier during the study period. Fitting trend lines estimated for selected quantile clearly showed the differences in changes across the rainfall distribution (Fig. 1). Dry years (0.1th quantile) became between 20% and 50% drier during the study period (Fig. 2). Consistently with quantile regression results, 7 out of the 10 major droughts occurred during the last 25 years, and noticeably the last year of the time-series, i.e. 2005, was the worst drought experienced by the park, with less than 300 mm recorded for the first time ever.

Recent reviews on climate change in Africa have suggested that southern Africa has been experiencing a moderate drying during the course of the 20th century (Hulme et al., 2001; Nicholson, 2001; New et al., 2001), although most negative trends reported have not been significant statistically. Our results support these observations, but highlight that these changes may not have been uniform across the rainfall distribution, happening mainly through a dramatic increase of the severity of droughts. Indeed, major drought events, associated with El Niño events (Richard et al. (2001); but see also Goddard and Graham (1999), for the effect of the Indian Ocean warming), struck southern Africa in the 1980s and 1990s, and the severity of these droughts was higher than expected from previous records of the association between ENSO and local rainfall

Table 1
Slope estimates (× 1000) for the selected quantiles ($\log_e$ transformed data) and their significance level for the three stations and the whole park, expressed as the average of the three stations

Quantile	Main camp		Sinamatella		Robins		Park	
	Slope	p	Slope	p	Slope	P	Slope	p
0.1	−3.24±2.24	0.153	**−9.05±3.42**	**0.010**	**−5.50±2.36**	**0.022**	**−6.84±2.30**	**0.004**
0.2	0.27±0.29	0.927	−5.35±3.14	0.093	**−6.52±2.02**	**0.002**	−3.67±2.56	0.155
0.3	0.32±2.60	0.901	−3.71±2.38	0.123	−3.62±2.34	0.126	−1.78±2.21	0.423
0.4	−0.50±2.38	0.835	−1.15±2.24	0.609	−1.52±2.18	0.488	−1.14±2.58	0.659
0.5	−2.47±2.31	0.289	1.02±2.10	0.628	−1.07±2.59	0.680	−0.35±2.68	0.898
0.6	−1.20±1.90	0.527	0.13±1.87	0.943	−3.16±3.14	0.318	−0.56±2.55	0.828
0.7	−0.41±1.65	0.802	0.63±2.36	0.789	−4.73±2.94	0.112	−0.97±1.76	0.583
0.8	0.34±2.36	0.885	1.43±2.64	0.589	−2.71±2.19	0.219	−0.15±1.36	0.911
0.9	0.44±2.14	0.837	−1.15±2.27	0.615	−3.14±2.84	0.274	−0.93±2.06	0.651

Information in bold identify quantiles for which trends are significant ($p<0.05$).

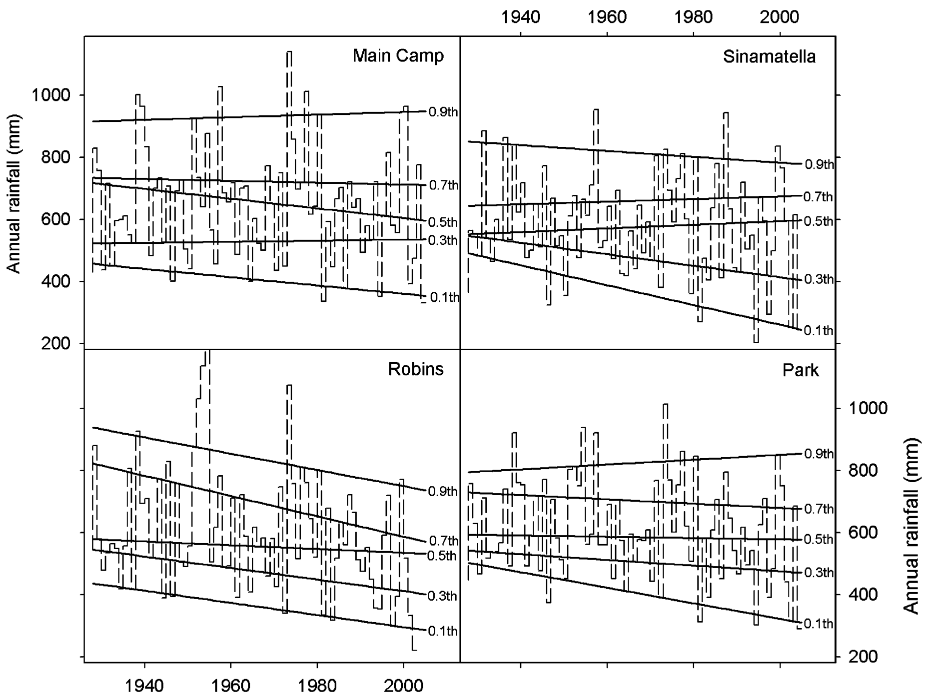

Fig. 1. Evolution of annual rainfall (dotted lines) for the three stations and the whole park, expressed as the average of the three stations. Solid lines show the 0.1th, 0.3th, 0.5th, 0.7th and 0.9th quantile regression fits.

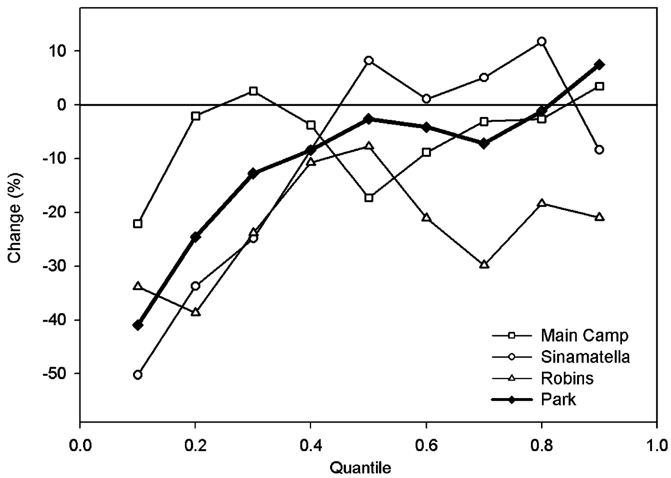

Fig. 2. Long-term changes in rainfall (%) over the study period (1928–2005), estimated by quantile regression for the selected quantiles, for the three stations and the whole park, expressed as the average of the three stations.

data (Dai et al., 1998), suggesting profound changes in climate determinants. Analyses at the intra-annual time scale also revealed that the general drying of southern Africa hides complex changes in rainfall behaviour, with extreme wet days becoming wetter, while the length of the dry season tending to extend (New et al., 2006). Moreover, as dry years became drier in Hwange NP while wet years did not experience such changes, our results support previous observations suggesting a general increase in local precipitation variance associated with global climate change (Dore, 2005). Clearly, average-based statistics are unlikely to reveal the full picture of climate changes.

Our findings have strong implications for the management of Hwange NP, as droughts strongly decrease both forage (Chamaillé-Jammes et al., 2006) and surface-water availability (Chamaillé-Jammes et al., 2007), two key resources for large herbivores. Indeed, surface water during the dry season is mainly provided through artificial pumping of ground water, maintaining year-round water levels of pans naturally filled up by rainfall during the rainy season. More pumped water will be needed to compensate for the lack of rainfall, and as drought worsen some waterholes are likely to become dry during the dry season, increasing animal attendance and consumption at the remaining ones (for description of a similar system in Kruger NP, South Africa, see Redfern et al., 2003). In Hwange NP the proportion of waterholes retaining water during the dry season decreased during dry years (Chamaillé-Jammes et al., 2007), and, for instance, elephant concentrations at waterholes increased simultaneously (Chamaillé-Jammes et al., 2007). Large herbivore concentration at waterholes is likely to have negative effects on the neighbouring vegetation, especially at times when vegetation itself is under great physiological stress (for elephants see de Beer et al., 2006). This habitat degradation could then feedback on herbivore population dynamics. Overall the observed climate change is likely to threaten the conservation status of Hwange NP, challenging the present management practices of this protected area, particularly the artificial water supply.

4. Conclusion

Quantile regressions showed that drought severity increased in Hwange NP in the course of the 20th century and the successful detection of these specific patterns of change will allow managers to set up strategies in order to mitigate the adverse consequences of such changes. Asymmetric trends appear to be a common feature of the recent climate changes, and since not all changes will be of the same importance in all places, we suggest that quantile regressions should be considered more often as a valuable tool to investigate climatic changes in arid and semi-arid regions.

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References

Cade, B.S., Noon, B.R., 2003. A gentle introduction to quantile regression for ecologists. Frontiers in Ecology and Environment 1, 412–420.

Chamaillé-Jammes, S., Fritz, H., Murindagomo, F., 2006. Spatial patterns of the rainfall—NDVI relationship at the seasonal and interannual time-scales in an African savanna. International Journal of Remote Sensing 27, 5185–5200.

Chamaillé-Jammes, S., Valeix, M., Fritz, H., 2007. Managing heterogeneity in elephant distribution: interactions between elephant population density and surface-water availability. Journal of Applied Ecology 44, 625–633.

Dai, A., Trenberth, K.E., Karl, T.R., 1998. Global variations in droughts and wet spells: 1900–1995. Geophysical Research Letters 25, 3367–3370.

De Beer, Y., Kilian, W., Versfeld, W., van Aarde, R., 2006. Elephants and low rainfall alter woody vegetation in Etosha National Park, Namibia. Journal of Arid Environments 64, 412–421.

Dore, M.H.I., 2005. Climate change and changes in global precipitation patterns: what do we know? Environment International 31, 1167–1181.

Goddard, L., Graham, N., 1999. Importance of the Indian Ocean for simulating rainfall anomalies over eastern and southern Africa. Journal of Geophysical Research 104, 19099–19116.

Hulme, M., Doherty, R., Ngara, T., New, M., Lister, D., 2001. African climate change: 1900–2100. Climate Research 17, 145–168.

Karl, T.R., Knight, R.W., Gallo, K.P., Peterson, T.C., Jones, P.D., Kukla, G., Plummer, N., Razuvayev, V., Lindseay, J., Charlson, R.J., 1993. A new perspective on recent global warming: asymmetric trends of daily maximum and minimum temperature. Bulletin of the American Meteorological Society 74, 1007–1024.

Koenker, R., 2005. Quantile Regression. Cambridge University Press, Cambridge.

Koenker, R., Schorfheide, F., 1994. Quantile spline models for global temperature change. Climatic Change 28, 395–404.

New, M., Todd, M., Hulme, M., Jones, P., 2001. Precipitation measurements and trends in the twentieth century. International Journal of Climatology 21, 1899–1922.

New, M., Hewitson, B., Stephenson, D.B., Tsiga, A., Kruger, A., et al., 2006. Evidence of trends in daily climate extremes over Southern and West Africa. Journal of Geophysical Research 111, 1–11.

Nicholson, S.E., 2001. Climatic and environmental change in Africa during the last two centuries. Climate Research 17, 123–144.

Redfern, J.V., Grant, R., Biggs, H., Getz, W.M., 2003. Surface water constraints on herbivore foraging in the Kruger National Park, South Africa. Ecology 84, 2092–2107.

Richard, Y., Fauchereau, N., Poccard, I., Rouault, M., Trzaska, S., 2001. 20th century droughts in southern Africa: spatial and temporal variability, teleconnections with oceanic and atmospheric conditions. International Journal of Climatology 21, 873–885.

Sankarasubramanian, A., Upmanu, L., 2003. Flood quantiles in a changing climate: seasonal forecasts and causal relations. Water Resources Research 39, 1134–1146.

Sokal, R.R., Rohlf, F.J., 1995. Biometry: The Principles and Practice of Statistics in Biological Research, third ed. W.H. Freeman, New York.

Sparks, T.H., Tryjanowski, P., 2005. The detection of climate impacts: some methodological considerations. International Journal of Climatology 25, 271–277.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.-M., Hoegh-Gulberg, O., Bairlen, F., 2002. Ecological responses to recent climate change. Nature 416, 389–395.

Young, T.P., 1994. Natural die-offs of large mammals: implication for conservation. Conservation Biology 8, 410–418.