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# Scale-dependence of persistence in precipitation records

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**Long-term persistence or Hurst–Kolmogorov behaviour has been identified in many hydroclimatic records[1]. Such time series are intriguing because they are the hallmark of multi-scale dynamical processes that govern the system from which they arise[2]. They are also highly relevant for water resource managers because these systems exhibit persistent, for example, multi-decadal, mean shifts or extremes clustering that must be included into any long-term drought management strategy. During recent years the growing number of palaeoclimatic reconstructions has allowed further investigation of the long-term statistical properties of climate[3,4] and an understanding of their implications for the observed change[5]. Recently, the consistency of the proxy data for precipitation was strongly doubted, when their persistence property was compared to the corresponding estimates of instrumental records and model results[6,7]. The latter suggest that droughts or extremely wet periods occur less frequently than depicted in the palaeoclimatic reconstructions. Here, we show how this could be the outcome of a varying scaling law and present some evidence supporting that proxy records can be reliable descriptors of the long-term precipitation variability.**

Earlier studies have already highlighted that annual precipitation records seem to exhibit no or short-term persistence when the timescale is small[8–10], whereas in longer time periods Hurst–Kolmogorov (HK) behaviour emerges[11–13]. It seems that rainfall variability could be affected by different physical mechanisms, which develop to two different auto-correlation structures; one structure for one to ten years (small scales) and another structure for multi-decadal intervals and beyond (large scales). An example of such behaviour is the temperature variation in a two-layer thin film system studied by Van Vliet[14] and suggested also by Pelletier[15] as a possible description of the global air temperature variability behaviour, which also encompasses the role of the oceans to atmospheric long-term fluctuations. Following the same idea, we investigated the hypothesis of white noise or Markov-type behaviour of precipitation below the decadal time resolution and HK behaviour at longer timescales.

Although the HK behaviour has a strong physical basis, as the outcome of entropy production maximization[16], it has been shown that a small sample size might mask the HK behaviour[3]. Thus, to reliably estimate moderate values of $H$ (0.7–0.8) the sample size should be at least 100 (see Supplementary Methods and Supplementary Figs 1 and 2). Some of the aforementioned studies[6,10] used time series with record lengths close to this number, and they could be prone to $H$ underestimation, especially when studies of longer instrumental records show that $H$ can rise above 0.7 (refs 17,18). Therefore, we examined all available rainfall records over Europe with lengths above 200 years, as well as the CRU gridded data (Supplementary Fig. 3), and found a mean for the $H$ coefficient close to 0.6, suggesting very weak long-term persistence.

The sensitivity of the $H$ estimation to the record length of instrumental data can also be illustrated by the following experiment: if we divide the very same observed time series into smaller subsets of equal size and redetermine $H$ we see that the series tends to appear as white noise as the record length decreases (Supplementary Table 3). In many cases the subsets of the same records showed two completely different profiles. For example, rainfall at Prague (Praha) station could be described as long-term persistent during the nineteenth century or as white noise if it was estimated only for the twentieth century (Supplementary Table 4). Could sample size bias affect the $H$ determination so much that the high proxy data values (0.8–0.9; ref. 6) would be masked? The repetition of the above experiment with synthetic data derived from a theoretical HK process showed that a sample effect alone cannot explain such a reduction of $H$ (Supplementary Table 5). A pure HK process would give high values of $H$ even in relatively short record lengths. In addition, both white noise and HK models fail to describe the strong differences in $H$ during the past two centuries, such as the one described for Prague.

A direct comparison over the same time period between the long instrumental records of central Europe and a precipitation reconstruction at an adjacent region (Bü11; ref. 19) suggests a similar behaviour on even longer timescales (Fig. 1). Both the mean value of $H$ in instrumental data and proxy data is close to 0.65 (Supplementary Table 1; stations from Klangefurt to Lille) for the period 1800–2000. However, if $H$ is estimated for the complete proxy record (2,400 years) then it rises to 0.8, which agrees with previous studies[6]. This can also be illustrated by determining $H$ over a sliding window and then examining its distribution for different observation periods (Fig. 1a). It becomes evident that as sample size increases the empirical distribution of the coefficient converges to a smaller set of values (mean = 0.80), whereas for a record length of 100 years the estimation could result in anything between white noise and a highly long-term persistent process (Fig. 1b). Again, we see a departure both from white noise and pure HK behaviour.

Previous efforts attributed this to non-climatic (or non-precipitation) noise and, as they were focused mainly[7] or solely[6] on tree-ring proxies, they linked it to their dependence on soil water availability and/or temperature. However, non-tree-ring reconstructions from different locations over the planet exhibit long-term persistence as well (Figs 2 and 3). Interestingly, the above findings imply that if HK behaviour is really a non-precipitation artefact, then this should somehow affect all different types of proxies. The most probable variable linked with this kind of bias could be temperature, as it is both connected to lake sediments via evaporation, to speleothems by $\delta^{18}O$ regulation and

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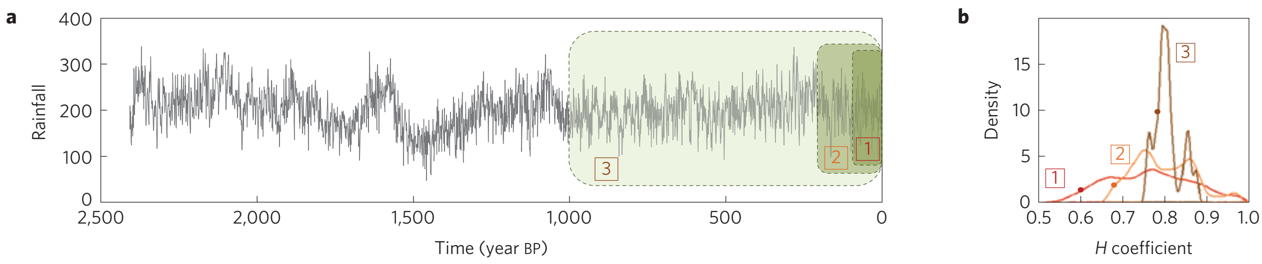

**Figure 1 | Scale-dependence of *H* estimation. a**, Reconstructed precipitation record of central Europe (Bü11) and different observation periods of 100 (**1**), 200 (**2**) and 1,000 years (**3**) **b**, Corresponding empirical distributions of $H$, if the observation periods span the whole record length as moving windows. The dots at each distribution represent the value of $H$ for the respective observation periods presented in **a**, and are 0.6 for AD 1900–2000, 0.68 for AD 1800–2000 and 0.78 for AD 1000–2000. The value of $H$ for the whole record is 0.82 (Supplementary Table 2).

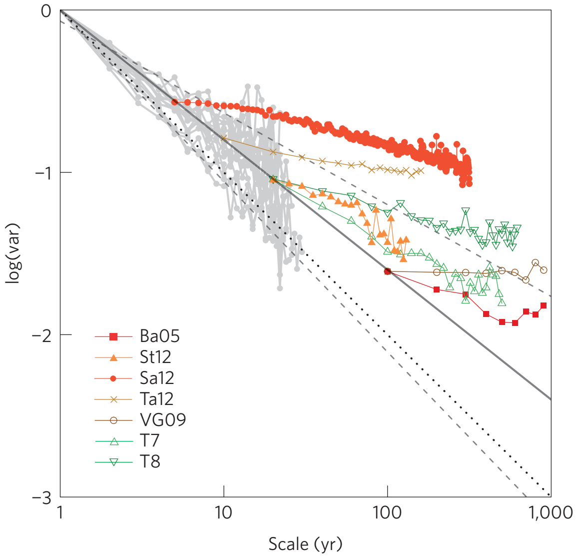

**Figure 2 | Explanatory figure showing the difference between short-term (instrumental data) and long-term (palaeoclimatic data) change.** The climacograms (see Supplementary Methods) of the 17 instrumental time series (grey round pointed lines) and seven non-tree-rings reconstructed records (legend; see Supplementary Table 2) are presented. The instrumental data mean slope is the solid grey line, the white noise slope is the dotted black line and the minimum/maximum slopes of the instrumental data are the dashed grey lines. The proxy types used for these reconstructions consisted of lake sediments (Ba05 (ref. 24), St12 (ref. 25), Sa12 (ref. 26)), speleothems (T7 (ref. 27), T8 (ref. 27)), pollen (VG09 (ref. 28)) and a combination of speleothems and historical (Ta12 (ref. 29)).

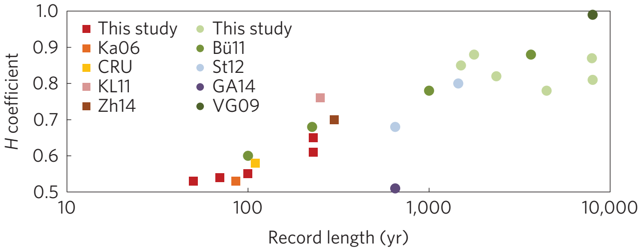

**Figure 3 | Synthesis of *H* estimation results (*squares*: instrumental; *circles*: reconstructions).** Ka06 (ref. 10), KL11 (ref. 18) and Zh14 (ref. 17) refer to earlier studies and CRU to the CRU data set used in this study. The mean $H$ of the instrumental data is estimated in different record lengths of 50, 70, 100 and 230 years (Supplementary Table 5). Two different values for 230 years represent all the records ($H = 0.61$) and the central European stations ($H = 0.65$). Different record lengths have also been used for Bü11 and St12 reconstructions (see text). The GA14 and the VG09 reconstructions are highlighted as cases of $H$ under- and overestimation.

to tree rings and pollen data through plant growth. To test this hypothetical link, the cross-correlation between the precipitation reconstructions and temperature reconstructions was examined and the results showed that the two climatic variables were uncorrelated (Supplementary Fig. 4).

Another possible non-precipitation source of long-term persistence could be found in the aggregation of the proxy records. As precipitation is averaged over time, sometimes there is no strong distinction between consecutive values for large segments of the reconstructed time series. In some cases the uncertainty of the aggregation is given, which allowed us to estimate the bias to a range of 2.5 to 10% (see Supplementary Methods). This kind of bias is usually found in low-resolution reconstructions, such as Ba05 and VG09, which may seem to have $H$ values above 0.9 and sometimes close to 1. A possible way to remedy this issue is to use the annual instrumental records to increase both the resolution and record length (see Supplementary Methods). The results of the application of four different versions of this method to Ba05 and VG09, also preserved the changing persistence scheme according to the observation period (Supplementary Fig. 5).

On the other hand there are some non-climate biases that can mask HK behaviour. A common occasion is that long-term persistence could be misinterpreted as inhomogeneity in data, especially when there are no adjacent stations. As $H$ grows, it becomes more probable to falsely identify a rainfall record as inhomogeneous (Supplementary Table 6). It is indicative that for the modest value of $H = 0.7$, almost half of the time series fail to pass a simple Student $t$-test. In addition, some techniques used in the creation of the reconstructed time series may also conceal the true persistence structure. Such are the cases of de-trending and pre-whitening, which have been widely used in tree rings and remove any low-frequency variability[20]. A useful example can be found in a recent tree-ring reconstruction of blue oak trees (GA14), which have been shown to be particularly sensitive to precipitation variability[21]. This record was de-trended and pre-whitened to be fitted to the instrumental data, and hence suggested white noise behaviour for rainfall, whereas the nearby St12 record exhibited weak persistence for the same period of the past 700 years. However, it must be noted again that if the whole St12 record is used (AD 500–AD 2000) a stronger HK pattern emerges.

We conclude that instrumental records are too short to be used for inferring long-term properties of the rainfall variability. On the other hand, although biases in proxy data usually lead to the underestimation of the persistence structure regardless of proxy type, the opposite could also happen—that is, overestimation due to low resolution. Thus, it is also not very safe to make assumptions for the short-term behaviour of rainfall based solely on proxy data, especially if the sample size is small. This discrepancy might have its cause in a relative stable short-term rainfall regime affected by

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either slower large-scale fluctuations or by abrupt changes that shift the mean significantly, which is close to the variations observed in the past—for example, the historic mega-droughts at northern America[22] or the changes in Asian monsoon during the Holocene[23]. Finally, there is evidence that rainfall variability can be described by a varying scaling behaviour scheme, asymptotically tending to a high value as timescales increase, rather than a unique scaling law for all timescales (Fig. 3).

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## Author contributions

Y.M. conceived the idea, collected and analysed the data, and wrote the manuscript; D.K. supervised the work, provided conceptual and technical advice, and edited the manuscript.

## Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to Y.M.

## Competing financial interests

The authors declare no competing financial interests.

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