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Magnitude correlations in global seismicity

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By employing natural time analysis, we analyze the worldwide seismicity and study the existence of correlations between earthquake magnitudes. We find that global seismicity exhibits nontrivial magnitude correlations for earthquake magnitudes greater than $M_w6.5$.

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Recently, a new time domain, called natural time χ, has been proposed [1] which has been shown [2] to be optimal for enhancing the signals' localization. This result has been obtained by studying the Tsallis entropy [3] for $q = 2$ of the Wigner function in time-frequency space and reflects that natural time reduces uncertainty and extracts signal information as much as possible. Natural time analysis (see below) has been applied to diverse fields like high T_c superconductivity [4], cardiology [5], statistical physics (e.g., an on-off intermittency model [6], multiplicative cascades [7], and an $1/f$ model [8]), biological physics [1], as well as for the case of earthquakes [6,7,9–14] (for a review see Ref. [15]). For the latter case of earthquakes, the study of their complex correlations in time, space, and magnitude (m) has been the object of several recent studies (e.g., see [16–22]).

In a time series consisting of N earthquakes with magnitudes m_k, $k = 1,2,\ldots,N$, the *natural time* $\chi_k = k/N$ serves as an index [1] for the occurrence of the kth earthquke. It is, therefore, smaller than, or equal to, unity. For the analysis of seismicity, the evolution of the pair (χ_k, E_k) is considered [9,15], where E_k denotes the seismic energy released during the kth event. The latter is related [23] to the magnitude m_k by $E_k = E_0 10^{1.5m_k}$, where E_0 is a constant related to the energy units used. On the basis of the pair (χ_k, E_k), the normalized power spectrum $\Pi(\omega) = |\frac{\sum_{k=1}^{N} E_k \exp(i\omega\chi_k)}{\sum_{n=1}^{N} E_n}|^2 = |\sum_{k=1}^{N} p_k \exp(i\omega \frac{k}{N})|^2$, where $p_k = E_k/\sum_{n=1}^{N} E_n$ and ω is the natural cyclic frequency, was introduced [1]. $\Pi(\omega)$ is a kind [1,15] of *characteristic function* for the probability distribution p_k in the context of probability theory. According to the probability theory, the moments of a distribution and hence the distribution itself can be approximately determined once the behavior of the characteristic function of the distribution is known around zero. For $\omega \to 0$, a Taylor expansion of $\Pi(\omega)$ leads to [1,9] $\Pi(\omega) \approx 1 - \kappa_1\omega^2$, where

$$\kappa_1 = \sum_{k=1}^{N} \chi_k^2 p_k - \left(\sum_{k=1}^{N} \chi_k p_k\right)^2 \tag{1}$$

is the variance of natural time. For *critical* dynamics, for example, the seismicity before the occurrence of a main shock and after the initiation of the seismic electric signal [15,24], the relation $\kappa_1 = 0.070$ holds [6,7,10,14].

The quantity $\Pi(\omega)$ for $\omega \to 0$ (or κ_1) can be considered [9] an *order parameter* for seismicity since its value changes abruptly when a main shock occurs. In a seismic catalog comprising of W earthquakes, the following procedure is followed (e.g., see Refs. [9,11,13]): Starting from the first earthquake, we calculate the κ_1 values using $N = 6$ to 40 consecutive events (including the first one). We next turn to the second earthquake and repeat the calculation of κ_1. After sliding event by event through the whole earthquake catalog, this procedure can be followed for $n(=W - 39)$ times, amounting to $n_1(=35n)$ calculated κ_1 values. The latter values enable the construction of the probability density function (pdf) $p(\kappa_1)$ as well as the estimation of the average value $\mathrm{E}(\kappa_1)$ and the standard deviation σ. For example, upon using the Southern California Earthquake Catalog comprising of $W = 85\,862$ earthquakes with $m \geqslant 2$ which occurred during the period 1981–2003 within the area $N_{32}^{37}W_{114}^{122}$ (hereafter called SCEC), we obtain the pdf $p(\kappa_1)$ depicted with red plus symbols in Fig. 1. In Ref. [9] the statistical properties of κ_1 (i.e., the order parameter of seismicity in natural time) have been studied by means of the scaled [25] distribution $\sigma p\{[\mathrm{E}(\kappa_1) - \kappa_1]/\sigma\}$ [e.g., see the red plus symbols in Fig. 1(b) for SCEC]. It has been found [9] that the scaled distributions for different seismic regions collapse on the same curve, which interestingly exhibits, over four orders of magnitude, an exponential "tail" similar to that obtained when studying [25–28] the order parameters of several equilibrium critical phenomena as well as in nonequilibrium systems. Such a behavior is strikingly reminiscent of the one found earlier in the analysis of nonstationary biological signals including heart rate [29], locomotor activity [30], etc, where pdf curves obtained for different scales of observation fall onto a single master curve. The study of fluctuations of the order parameter of seismicity (i.e., κ_1) in excerpts of regional seismic catalogs before and after significant main shocks recently revealed [12] the presence of a pronounced bimodal feature in $p(\kappa_1)$ *only* before main shocks. Moreover, it has been shown [13] that in order for the whole feature of $p(\kappa_1)$ to be reproduced [e.g., see Fig. 1(a) for SCEC] both the distribution of earthquake magnitudes as well as long-range temporal correlations between the magnitudes of successive earthquakes should be taken into account.

Natural time analysis enables the identification [7,11] and quantification of magnitude correlations in real seismicity time series by comparing the value of $\mathrm{E}(\kappa_1)$ of the original catalog with the distribution obtained for $\mathrm{E}(\kappa_{1,\mathrm{shuf}})$ when studying

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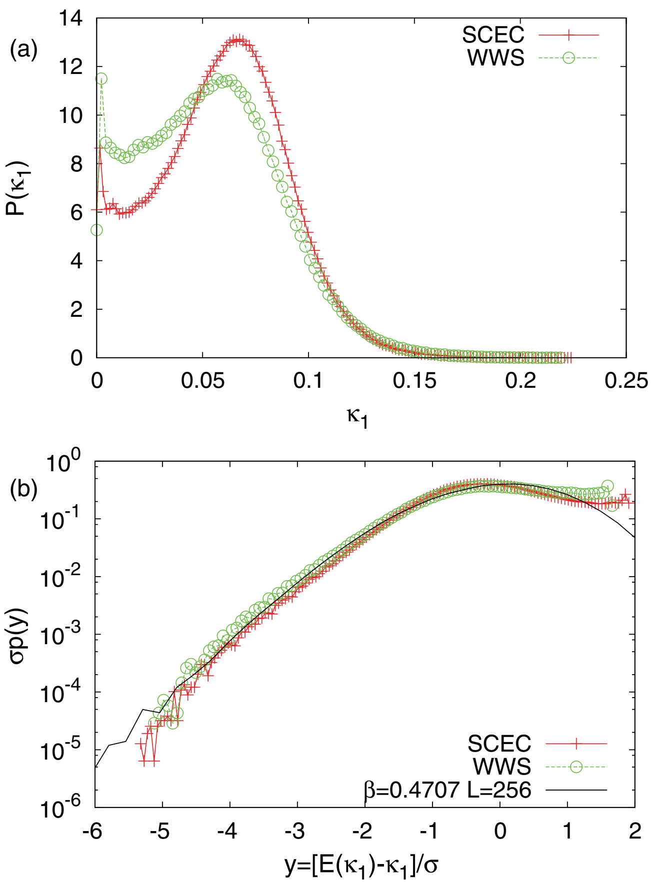

FIG. 1. (Color online) (a) The pdf $p(\kappa_1)$ vs κ_1 for SCEC and WWS. (b) The scaled distribution $\sigma p(y)$ vs $y=[\mathrm{E}(\kappa_1)-\kappa_1]/\sigma$, where σ stands for the standard deviation of κ_1. The black solid line corresponds to the scaled distribution of the order parameter for the 2D Ising model of linear dimension $L=256$ at (inverse temperature parameter) $\beta=0.4707$ and has been drawn as a guide to the eye (for more details, see Ref. [9]).

many *randomly* shuffled copies of the original catalog. This is so because it can be shown [7] that when considering a moving window of N consecutive events

$$\mathrm{E}(\kappa_1)=\kappa_{1,\mathbb{M}}+\sum_{j=1}^{N-1}\sum_{m=j+1}^{N}\frac{(j-m)^2}{N^2}\mathrm{Cov}(p_j,p_m), \quad (2)$$

where $\kappa_{1,\mathbb{M}}$ is the value of κ_1 corresponding to the time series of the averages $\mu_j\equiv\mathrm{E}(p_j)$ of p_j, that is, $\kappa_{1,\mathbb{M}}=\sum_{j=1}^{N}(j/N)^2\mu_j-(\sum_{j=1}^{N}\mu_j j/N)^2$, and $\mathrm{Cov}(p_j,p_m)$ stands for the covariance of p_j and p_m defined as $\mathrm{Cov}(p_j,p_m)\equiv\mathrm{E}[(p_j-\mu_j)(p_m-\mu_m)]$, whereas if we shuffle *randomly* the seismicity time series μ_j becomes equal to $1/N$ and the average value of $\kappa_{1,\mathrm{shuf}}$ amounts [7] to

$$\mathrm{E}(\kappa_{1,\mathrm{shuf}})=\kappa_u\left(1-\frac{1}{N^2}\right)-\kappa_u(N+1)\mathrm{Var}(p), \quad (3)$$

where $\kappa_u=1/12$ and $\mathrm{Var}(p)=\mathrm{Var}(p_j)=\mathrm{E}[(p_j-1/N)^2]$ independent of j. When studying long-term seismic catalogs by a sliding window of N earthquakes, it is improbable to obtain a trend in μ_j, that is, $\mu_j\approx 1/N$, and hence $\kappa_{1,\mathbb{M}}\approx\kappa_u(1-1/N^2)$ in Eq. (2), leading to

$$\mathrm{E}(\kappa_1)-\mathrm{E}(\kappa_{1,\mathrm{shuf}})\approx\kappa_u(N+1)\mathrm{Var}(p)+\sum_{j=1}^{N-1}\sum_{m=j+1}^{N}\frac{(j-m)^2}{N^2}\mathrm{Cov}(p_j,p_m). \quad (4)$$

Thus, the difference between the actual value of $\mathrm{E}(\kappa_1)$ for a seismic catalog from the distribution of $\mathrm{E}(\kappa_{1,\mathrm{shuf}})$ obtained by randomly shuffling the same catalog mainly results from the (second order) correlations between earthquakes in natural time. For the case of SCEC, it has been found [11] that the magnitude correlations depend on the magnitude threshold M_{thres} used for the construction of the seismic catalog. For each M_{thres}, the catalog was randomly shuffled and the distribution of $\mathrm{E}(\kappa_{1,\mathrm{shuf}})$ was determined. It turned out that for the M_{thres} considered (see Fig. 2), the distribution of $\mathrm{E}(\kappa_{1,\mathrm{shuf}})$ was a Gaussian distribution $N[\mu(M_{\mathrm{thres}}),\sigma(M_{\mathrm{thres}})]$ for which both the average value $\mu(M_{\mathrm{thres}})$ and the standard deviation $\sigma(M_{\mathrm{thres}})$ depended on M_{thres}. Since $\mathrm{E}(\kappa_{1,\mathrm{shuf}})$ was a Gaussian random variable, the presence of temporal correlations could be quantified by finding the probability that the value $\mathrm{E}(\kappa_1)$ of the original catalog results from $N[\mu(M_{\mathrm{thres}}),\sigma(M_{\mathrm{thres}})]$. Equivalently, by finding the z score

$$z=\frac{\mathrm{E}(\kappa_1)-\mu(M_{\mathrm{thres}})}{\sigma(M_{\mathrm{thres}})}, \quad (5)$$

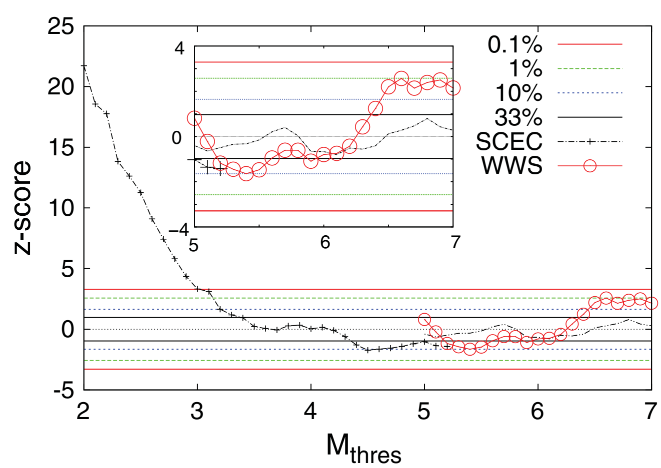

FIG. 2. (Color online) The z score of $\mathrm{E}(\kappa_1)$ of the worldwide seismicity (WWS red circles) together with that corresponding to the SCEC data (cyan plus), discussed in Ref. [11], as a function of the magnitude threshold M_{thres}. Both z scores are calculated with respect to the Gaussian distribution $N[\mu(M_{\mathrm{thres}}),\sigma(M_{\mathrm{thres}})]$ obtained from the analysis of $\mathrm{E}(\kappa_{1,\mathrm{shuf}})$ that results from randomly shuffled copies of the original earthquake catalogs. The intervals corresponding to the probability $\mathcal{P}$ to observe the correlation present in the original sequence of events by chance are bounded by the horizontal lines for $\mathcal{P}=10^{-3}$, 10^{-2}, 10^{-1}, and 0.33. The black solid-dotted line corresponds the z scores obtained when a *randomly* shuffled copy of WWS is studied by the same procedure. For the reader's convenience, the inset depicts the results in the range $M_{\mathrm{thres}}=5$ to 7 in an expanded scale.

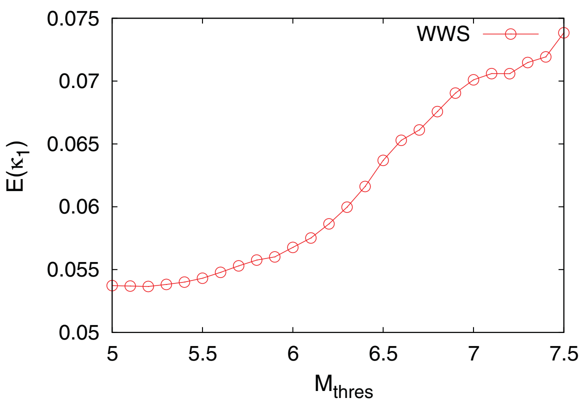

FIG. 3. (Color online) The average value $\text{E}(\kappa_1)$ for the worldwide seismicity (WWS circles) vs the magnitude threshold M_{thres}.

if the z score differs markedly from zero, this indicates the presence of temporal correlations. The results, which are reproduced here by the cyan plus symbols in Fig. 2, showed that magnitude correlations do exist in SCEC but tend to decrease with increasing M_{thres}. Moreover, for $M_{\text{thres}} > 3.1$ *no definite* results about the existence of correlations could be statistically inferred [11].

The results mentioned so far refer to regional earthquake catalogs. In order to investigate the existence of magnitude correlations on a global scale, we analyzed in natural time the worldwide seismicity from the Harvard Global Centroid Moment Tensor Catalog as reported by the United States Geological Survey (to be called WWS hereafter). A minimum magnitude threshold $M_{\text{thres}} = 5.0$ was used and resulted in $W = 29\,223$ earthquakes during the period 1 January 1977 to 30 September 2009. For the global seismicity the pdf $p(\kappa_1)$ is depicted with green circles in Fig. 1(a) and certainly differs from that of SCEC (cf. recall that in Ref. [9] the regional seismicities of Japan and SCEC have been found to coincide, see also below). Albeit, the scaled distribution $\sigma p\,\{[\text{E}(\kappa_1) - \kappa_1]/\sigma\}$ depicted in Fig. 1(b) exhibits features similar to that of SCEC, that is, it collapses more or less on the black line, which was drawn on the basis of the 2D Ising model as a guide to the eye.

We now investigate the presence of (temporal) magnitude correlations in WWS by considering various $M_{\text{thres}} = 5.0$ to 7.5 (cf. for $M_{\text{thres}} = 7.5$ there are only 127 earthquakes in the catalog). The values of $\text{E}(\kappa_1)$ versus the M_{thres} are shown in Fig. 3. For each M_{thres}, $n_2 = 10^3$ randomly shuffled copies of the catalog were studied in natural time and the distribution of $\text{E}(\kappa_{1,\text{shuf}})$ was found (by means of the Kolmogorov-Smirnov-Lilliefors test) to be a Gaussian distribution $N[\mu(M_{\text{thres}}),\sigma(M_{\text{thres}})]$ up to $M_{\text{thres}} = 7.0$. As in the case of SCEC, the average value $\mu(M_{\text{thres}})$ and the standard deviation $\sigma(M_{\text{thres}})$ are both M_{thres} dependent. They are given together with the number W of earthquakes for each M_{thres} in Ref. [31]. The standard error $\delta\mu(M_{\text{thres}})(\equiv\sigma(M_{\text{thres}})/\sqrt{n_2})$ of the mean $\mu(M_{\text{thres}})$ and the standard error $\delta\sigma(M_{\text{thres}})$ of the standard deviation $\sigma(M_{\text{thres}})$ are also inserted in Ref. [31], we note that for normally distributed data [32]: $\delta\sigma(M_{\text{thres}}) = \sigma(M_{\text{thres}})/\sqrt{2(n_2-1)}$ (see also Refs. [33,34]). An inspection of these values shows that the maximum relative error for both parameters does not exceed 5%. Following the procedure described above for SCEC, the z scores for WWS are depicted in Fig. 2 with red circles. We observe that for $M_{\text{thres}} \geqslant 6.5$, the probability to obtain the observed value of $\text{E}(\kappa_1)$ by chance from a randomly shuffled copy of the same catalog falls below 10% and may reach values close to 1%, for example, for $M_{\text{thres}} = 6.9$. As an additional check of the method, we followed exactly the same procedure for a randomly shuffled copy of WWS and the calculated z scores are also shown (with the black solid-dotted line) in Fig. 2. They fall within the 33% margin and no significant fluctuations are present even for the large ($M_{\text{thres}} \geqslant 6.5$) magnitude thresholds. All the above results indicate the presence of statistically significant correlations in the global seismicity. In order to exclude the possibility that this phenomenon is due to aftershocks, we examined the pairs of consecutive earthquakes that occurred within 10 deg difference in latitude (δx) and longitude (δy), that is, $|\delta x| + |\delta y| < 10^\circ$, for which the Båth law (stating that the difference in magnitude Δm between a main shock and its largest detected aftershock is approximately a constant *independent* of the main shock magnitude, typically [35] $\Delta m \approx 1.2$) was valid. We found only three pairs out of the 529 earthquakes in the catalog corresponding to $M_{\text{thres}} = 6.9$. Moreover, we note that in this catalog only 16 earthquakes had magnitudes larger than or equal to $M_{\text{thres}} + \Delta m = 8.1$ and thus could produce strong aftershocks to be included in the catalog. Interestingly, the values of $\text{E}(\kappa_1)$ that correspond to the range of $M_{\text{thres}} = 6.5$ to 7.0 lie from 0.064 to 0.070 (see Fig. 3).

Finally, let us comment on the fact that although the scaled distributions of SCEC and WWS exhibit a similar exponential tail [see Fig. 1(b)], their $p(\kappa_1)$ differ as shown in Fig. 1(a). This can be understood in the following sense: Fig. 2 shows that the results for SCEC—which were obtained for $M_{\text{thres}} = 2$—exhibit significant temporal correlations (see also Ref. [13]), whereas those of WWS for $M_{\text{thres}} = 5$ do not. Thus, $p(\kappa_1)$ in Fig. 1(a) differ because, as mentioned, both the distribution and the temporal correlations between magnitudes have to be taken into account [13] to reproduce exactly the same pdf. The exponential tail of the scaled distribution, on the other hand, has been shown to remain unchanged even when *randomly* shuffling the earthquake catalogs, see Fig. 4 of Ref. [9]. An additional point that corroborates the above explanation is the following: whereas the most probable value $\kappa_{1,p}(\approx 0.066)$ of κ_1 for SCEC differs [11] from that of a randomly shuffled copy of the catalog, the value of $\kappa_{1,p}(\approx 0.058)$ for WWS [see Fig. 1(a)] practically coincides with the value proposed [11] for randomly shuffled earthquake data, that is $2^{1.5/b}/[3(1+2^{1.5/b})^2]$ see their Eq. (3), when substituting the maximum likelihood estimate [36] of the b value in the Gutenberg-Richter law for the WWS data.

In summary, upon employing natural time analysis in the worldwide seismicity we found statistically significant temporal correlations between earthquake magnitudes when considering magnitude thresholds $M_{\text{thres}} = 6.5$ to 7.0.

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