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Discussions

Brief Communication: Correlation of global earthquake rates with temperature and sunspot cycle

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Abstract

We studied the complex and non-stationary records of global earthquake employing the robust statistical and spectral techniques to understand the patterns, processes and periodicity. Singular Spectral Analysis (SSA) and correlation methods are used to quantify the nature of principle dynamical processes of global annual earthquake rates. The SSA decomposes the principle component of earthquake rates (first mode), which suggests that there is a linear increase in the yearly earthquake number from 1975 to 2005 accounting for 93 % variance and may be identified with the earth's internal dynamical processes. Superimposed on this monotonic trend, there is an 11 years cyclic variation (second and third modes) accounting for 5 % variance, which may corresponds to the well-known solar cycle. The remaining 2 % higher order fluctuating components appears to be associated with artificial recharge and natural triggering forces (reservoir, tidal triggering etc.). The correlation study indicates that there is strong positive and negative correlation among the global earthquake rates with surface air temperature and sunspot numbers respectively. Interesting coupling mechanisms do exist, in which atmospheric circulations perturbed by the abrupt temperature variability might change the torques/momentum of inertia (earth's angular momentum) of the earth and thereby may offer the required inputs to trigger earthquake activities at the "critical phases".

1 Introduction

Earthquake recurrences, regional seismicity patterns and artificially/induced and triggered seismic events have provided significant clues on the dynamical behavior of the earth. Such studies have also provided useful constraints for modeling the earthquake generating process. From the classical point of view, the occurrence of earthquakes is mainly due to the plate motions. However, there are several other natural and artificial triggering agents, which may be associated or triggered with some other exogenic forces and create cyclic nature in their earthquake occurrence (Kasahara, 2002). The predictability analyses of earthquake process using K2 entropy, predictive correlation analysis and phase space projection (Tiwari et al., 2003; Tiwari and Srilakshmi, 2005) on regional scale have shown evidence of low dimensionality and quasi-periodic nature of earthquake dynamics associated with seasonality bias. The impulsive and quasi-periodic external forcing (Reservoir, Tidal etc.) on earthquake is a know phenomena for the past few decades (Carder, 1945; Souriau et al., 1982; Heaton, 1982; Gupta, 1983, 2002; Wilcock, 2001; Tanaka et al., 2002; Cochran et al., 2004; Tanaka, 2010).

The periodic nature of earthquakes recurrences is also a known phenomenon for more than a century (Schuster, 1897; Knopoff, 1964). Many researchers have reported the possible correlation and periodic forcing of solar and lunar tides on earthquakes processes (Cochran et al., 2004; Cadicheanu et al., 2007; Métivier et al., 2009; Tanaka, 2010; Chao-Di et al., 2013). According to Kasahara (2002), small variations in periodic tidal forcing could trigger the volcanic earthquakes by creating shear stresses and accelerating the fault movement in a suitable direction.

Another periodic forcing on earthquake processes is due to the solar activities. The periodic solar forcing of earthquake process as regional and global phenomenon has been reported by many other researchers (Jusoh and Yumonto, 2011; Odintsov et al., 2007; Tavares and Azevedo, 2011; Zhang, 1998). There are numerous studies, which have shown anti-correlation between seismicity and solar activity (Simpson, 1967). Simpson (1967) analyzed nearly 13 year long global earthquake rates, compared to the Zurich sunspot numbers, and suggested that there was a negative correlation between seismicity and sunspot numbers. He has also summarized two possible methodologies to explain the coupling between the solar activity and terrestrial seismicity. However, the solar forcing may mainly affect the earth processes through the variation in the solar radiation (solar input) to the earth. Thus, the correlation of solar indices with seismic activity shown by Simpson (1967) is acceptable. Recently, Shestopalov and Kharin (2014) have shown positive and negative correlation between sunspot numbers and earthquakes. In addition, Shestopalov and Kharin (2014) have shown the centennial scale solar activity effect through a systematic analysis of global seismicity from 1680–

2012. In a recent study, Fourel et al. (2013) have shown the effect of unstable cool lower lithosphere as a common driving mechanism that is intrinsic to continental plate rifting. Fourel et al. (2013) supports the plausible link between solar activity and terrestrial seismicity.

Here in this paper, we examine the relationship more rigorously by quantify the forcing in terms of their contribution. We have analyzed the global annual earthquake rates in terms of eigen contribution of different periodic principal components using Singular Spectral Analysis (SSA). The correlation analysis employed here to unveil the correlation among global annual earthquake occurrence rate, surface air temperature and sunspot numbers. This analysis completely deviates from the earlier work, in a sense that we have started the data analysis by examining appropriately its completeness followed by applications of new techniques. This provides full confidence to us to discuss firmly the physical mechanism through the concept of coupling of solar cycle, temperature variations and earthquake occurrences.

2 Data

The earthquake data used for the present study is obtained from USGS global catalogue for the magnitudes 4 and above for the period of 1975 to 2005. The global temperature and sunspot number data used in the present study is downloaded from NOAA and SIDC websites respectively for the same period. The magnitude completeness of the earthquake catalogue estimated as 4.7 through Gutenberg–Richter relationship plot shown in Fig. 1.

3 Methods of data analyses

The application of singular spectral analysis (SSA) is well known since more than three decades (Broomhead and King, 1986a, b; Fraedrich, 1986) as an efficient time series

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analysis tool to analyze the dynamics of the underlying systems that generated the series (Ghil et al., 2002). It is very popular for principle component analysis (Serita et al., 2005) of different types of atmospheric and geophysical signals and useful for filtering the geophysical fields (Rajesh et al., 2014) and astronomical images (Zotov, 2012) to identify significant dynamical components. In the present work we have adopted SSA algorithm to decompose the annual earthquake number data to identify the principle component. The SSA has been performed following the steps (Golyandina et al., 2001).

Trajectory matrix $\mathbf{T}_{(L\times K)}$ *formulation.* The time series $\boldsymbol{X(t)} = \{x_1, x_2, \ldots, x_N\}$ of length N will be projected into phase space of dimensions L called window length ($2 < L \leq N/2$, and $K = N - L + 1$) to get trajectory matrix $\mathbf{T}_{L\times K} = [\boldsymbol{X}_1 : \ldots : \boldsymbol{X}_K]$. Where $\boldsymbol{X}_i = \{x_{i+1}, x_{i+2}, \ldots, x_{i+L}\}$ is a vector of length L and i takes values from 1 to K.

Singular value decomposition. Eigen vectors ($\boldsymbol{U}_i, \boldsymbol{V}_i$) and values ($\sqrt{\boldsymbol{\lambda}_i}$) of the trajectory matrix are obtained through the Singular Value Decomposition.

$$\mathbf{T} = \sum_{i=1}^{\mathrm{d}} \sqrt{\boldsymbol{\lambda}_i} \boldsymbol{U}_i \boldsymbol{V}_i^T \quad (1)$$

The group ($\sqrt{\boldsymbol{\lambda}_i}, \boldsymbol{U}_i, \boldsymbol{V}_i$) is called the ith eigen triplet.

Grouping and reconstruction. From the identified eigen triplets we will reconstruct the trajectory matrix ($\mathbf{T}_\mathrm{r}$) using $\mathbf{T}_\mathrm{r} = \sum_i \sqrt{\boldsymbol{\lambda}_i} \boldsymbol{U}_i \boldsymbol{V}_i^T$, where i represent the a group of Eigen triplets.

$$\mathbf{T}_\mathrm{r} = \begin{bmatrix} \boldsymbol{y}_{(1,1)} & \cdots & \boldsymbol{y}_{(1,K)} \\ \vdots & \ddots & \vdots \\ \boldsymbol{y}_{(L,1)} & \cdots & \boldsymbol{y}_{(L,K)} \end{bmatrix} \quad (2)$$

Diagonal averaging. The reconstructed series $X_\mathrm{r} = \{g_1, g_2, \ldots, g_k, \ldots, g_N\}$ can be obtained through diagonalization or Hankelization of reconstructed trajectory matrix

shown in Eq. (2).

$$g_k = \begin{cases} \frac{1}{k+1} \sum_{m=1}^{k+1} y_{m,k-m+2} & \text{for } 1 \leq k < L \\ \frac{1}{L} \sum_{m=1}^{L} y_{m,k-m+2} & \text{for } L \leq k < K \\ \frac{1}{N-k} \sum_{m=k-K\mp 2}^{N-K+1} y_{m,k-m+2} & \text{for } K \leq k \leq N \end{cases} \quad (3)$$

4 Result

The consideration of earth as a closed and/or an isolated system for studying its various processes may not be appropriate, since the modern concept of earth system science suggest the coupling of endogenic and exogenic forcing to drive the earth's dynamical processes. Here, we study the occurrences of the global earthquake to understand the dynamics and driving forces by means of the contributions of their principle components and eigenvalues on global scales. As a first step of our analysis, we have filtered the entire data with a cutoff magnitude ($M \geq 4.7$) (Fig. 1) and then the annual earthquake rates are normalized and compared with the normalized surface air temperature data. The trends of earthquake data are clearly matching with the temperature data (Fig. 2). We find a strong correlation with correlation coefficient +0.77 among normalized earthquake numbers and normalized temperature.

The strong correlation between temperature and global earthquake rates infers that the major dynamical processes driving the global temperature and earthquake process are of the same kind. The global surface air temperature contains an increasing trend along with oscillatory pattern during the period of analysis. As a whole the global temperature is the representative of solar activity as well as energy receiving from earth (in the form of radiation). The radiation from the earth is possible, as the earth undergoing cooling from the day one of its origin. As we do not have a blackbody as sensor

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to observe all the radiation bands emanating from earth, we are missing some crucial information in the measurements of heat flow. Nevertheless, atmosphere is a strong absorber containing large variety of chemical species, which are sensitive to specific bands of radiation. Therefore, the radiations that are missing in our measurements could also be captured by the atmosphere and thus retaining in the form of trends in the atmospheric parametric measurements. Researchers inferred the centennial to millennial scale solar induce oscillations in the temperature data set (Tiwari et al., 2013). The comparison of solar activity with temperature data also supports the effect of higher order solar cycles (centennial scale) on the seismic activity reported by Shestopalov and Kharin (2006).

The earthquake rate data was further subjected to SSA using the appropriate window length 15. The window length was chosen appropriately keeping in view the length of the data size. The first three principle components were found significant with 98 % variance and the remaining principal components contributes only 2 %. The first principle component alone shows 93 % variance with a linear increasing trend starting from 1975 to 2005. The second and third principle components superimposed on the main trend shows apparently 11 years periodic component with variance 5 %. The rest of the components contribute 2 % , which may be attributed to artificial and natural triggering forces (reservoir and tidal triggering etc.). Thus, our analysis quantified the contribution of ~ 11 year solar cycle effect on global seismic activity in terms of Eigen value percentages (5 %). We have reconstructed the data using principle components 2 and 3 to compare with the sunspot number data. The normalized reconstructed data of earthquake rates along with the normalized annual sunspot number data are shown in Fig. 3. One can clearly see that there is peak-to-peak out of phase match between the sunspot numbers and reconstructed annual earthquake rates (Fig. 3). Thus, the normalized global earthquake numbers reconstructed from the periodic components of 11 years periodicity has shown a significant negative correlation (-0.4) with the sunspot number. The earlier researchers (Simpson, 1967; Shestopalov and Kharin,

2014) have also reported the negative correlation between sunspot number 11 year cycle and earthquake occurrence.

Statistical correlation and/or evidence of matching periodicity among the two or more phenomena cannot guarantee their physical link. Hence, at this stage, we can only surmise a probable physical mechanism among the solar activity, temperature variations and earthquakes occurrences. Keeping in view of only 5 % contribution of 11 year oscillatory component superimposed on the main monotonic earthquake data trend, the link between earthquakes and solar cycle may not be the direct one. Hence, the solar cycle apparently visible in the global earthquake record could be considered as a triggering agent only. We, however, note that the surface activity of the Sun produces variations in its electromagnetic and corpuscular emissions, which consist of both continuous (photospheric) and sporadic (flare) components (Stothers, 1989; Roberts, 2013). Accordingly, the variable part of this solar radiation produces small incremental reversals of heating or cooling of the earth's atmosphere. This is clearly seen in various records of earth's global and regional temperature, pressure, precipitation and zonal wind pattern in the form of 11 year solar cycle (Kelly, 1977; Labitzke, 1987; Labitzke and van Loon,1989; Stothers, 1989). A direct implication of this perturbation on circulation patterns of the earth's air masses may lead a slight alteration of the earth's angular momentum (Stothers, 1989). For sustainability and stability of earth's dynamics, the solar induced changes in angular momentum attuned through a change in its rotational speed, which are apparently reflected in the length of the day (LOD) variations. In a recent study, Michelis et al. (2013) verified and reconfirmed the periodic variations in LOD (Curries, 1981). According to Lambeck and Cazanev (1976), the change in the length of the day is due to the impact of seasonally changing solar insolation. The observed 11 year solar induced cyclic variation in the LOD is one of the evidences for such periodic forcing (Challinor, 1971; Curries, 1981). The other slower cycles reported by them are also confirmed in a recent work (Michelis et al., 2013) and probably also observed after very large individual solar flare (Danjon, 1962a, b; Gribbin and Plagemann, 1973; Stothers, 1989). It appears, therefore, that atmospheric disturbances/perturbations might some way or other is involved in catalyzing the small abrupt/instantaneous changes in the earth's rate of rotation. Associated torques in the solid earth might then trigger a host of minor and major earthquake (Anderson, 1974) depending upon the intensity of nonlinear coupling among these phenomena. Integrating the above results, the change in the earth's angular momentum by the solar activity may drive seismic activities with a common periodicity.

Further to the above mechanism, one could also hypothesize the global atmospheric perturbation, which might influence earthquake activities through changes in annual/seasonal precipitation. It has been suggested (Stothers, 1989; Tiwari and Rao, 2001) that increase in rain fall around the year of solar minima must lead to temporally larger reservoir's of ground water in and near rift and shear zones, volcanic magmas, (earthquakes prone regions). The increase in the precipitation near the earthquake prone site (epicenter) at the times of "earthquake criticality" has been reported from Indian earthquakes (Goswami et al., 2014). There is well known relation between the Indian precipitation records and solar activities (Reddy et al., 1989). Tiwari and Rao (2001) analyzed the power law distribution of earthquake occurrence from Northeast, India and inferred a possible seasonal and solar cyclic pattern in earthquake record. Hence, there is possible explanation for the indirect link between seismicity and temperature/solar activity.

5 Conclusions

We have applied SSA to separate the dynamical principal components from the global earthquake record spanning over the period of 1975 to 2005, which are involved in generating the earthquake activities. Based on SSA of a complete earthquake data set, we have quantified the 11 year solar cyclic pattern, with 5 % variance in terms of eigen value, which is superimposed on a linear monotonic trend. The observed monotonic trend in the earthquake data alone contributing to 93 % variance, which appears to be linked with the earth's internal dynamical processes. The negative correlation

(correlation coefficient −0.4) between the SSA reconstructed data of the 11 year periodic components and Sunspot numbers agree well with the earlier results carried out by other researchers on regional and global scale. Even though the possible evidence of periodicities in the earthquake process is a somewhat debated issue in earth science community, the 11 year cyclic variation in the earthquake occurrence was verified and reconfirmed through the comparison of the reconstructed earthquake rates with sunspot data. Evidence of periodicities implies predictably and therefore, if such cycles indeed exist they would add a significant dimension to improve predictions of the future earthquakes.

The correlation analysis between the annual global earthquake rates and global temperature revealed that there is a good correlation (coefficient +0.77) between the two phenomena, rendering an impression that both dynamical processes are coupled some way or other. The present study provide an interesting example of coupled multiple physical processes, which require more rigorous data analyses using the longer earthquake record for quantifying and confirming the contribution of such cyclic forcing.

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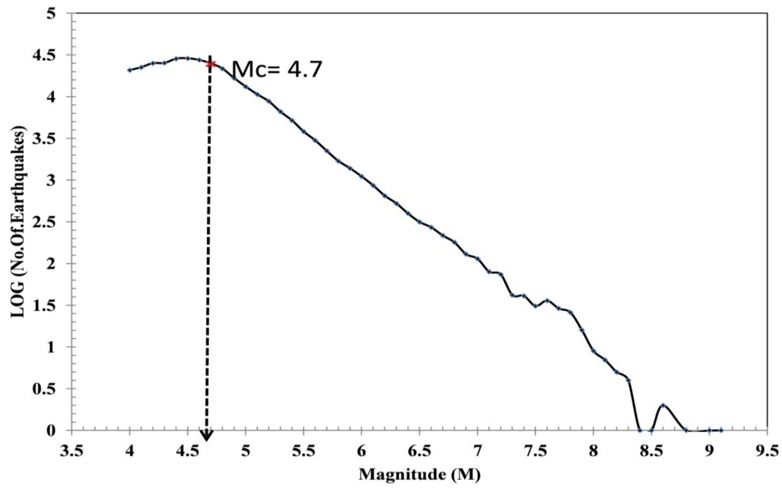

Fig. 1. Gutenberg–Richter plot of Global earthquake data from 1975 to 2005.

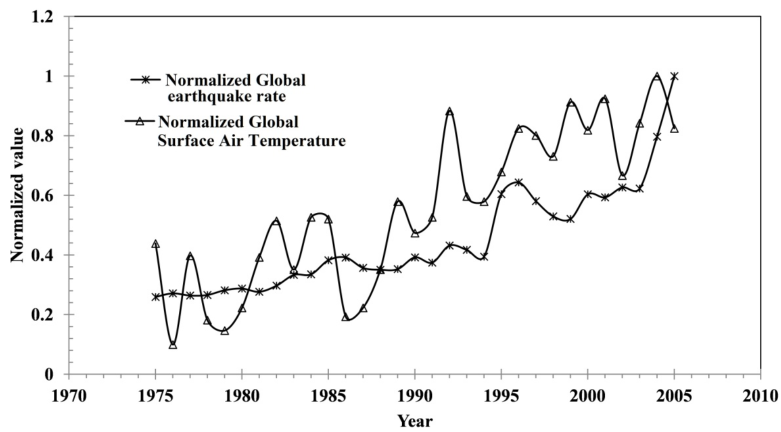

Fig. 2. Normalized yearly global earthquake rates and normalized global surface air temperature from 1975 to 2005.

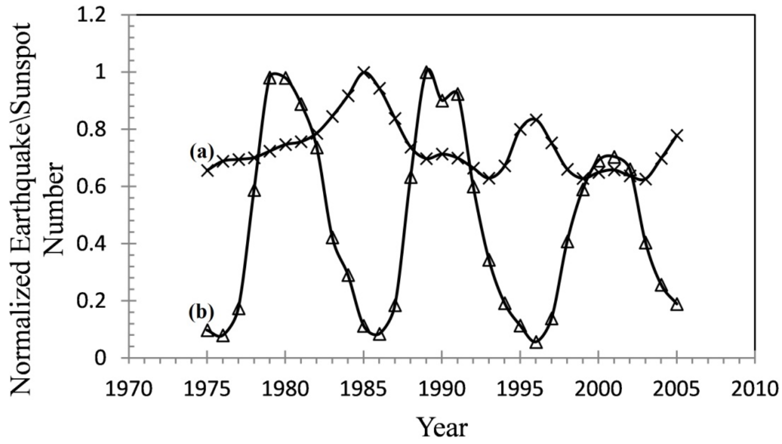

Fig. 3. SSA reconstructed normalized yearly global earthquake rates from principle components 2 and 3 **(a)** and normalized Sunspot numbers from 1975 to 2005 **(b)**.