THE NEUTRON MONITOR TIME SERIES STATISTICS ANALYSIS AND EARTHQUAKES PREDICTION

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We have considered several methods for time series analysis applied to the neutron monitor counting rate and earthquake data set to find a possible correlation between the neutron counting rate at Tien-Shan mountain station and simultaneously registered earthquakes in 2000 km range from the target city of Almaty, Kazakhstan. This correlation has a complex form defined by the spatially and temporally ordered set of events and used to estimate the probability of an earthquake based on the readings of the station's detectors located 50 km up in the mountains from the city.

Introduction

The great number of publications on tectonics and geomorphology of the region have being produced in countries bordering the Tien-Shan mountains reflecting the changing seismic activity, increasing number of monitoring stations producing new data and introduction of the new methods of analysis [1, 2]. Reach data statistics and complex nature of the registered events, both seismic and in ionosphere, are also contributing to the production of new publications and results.

Tien-Shan high elevation research station has the well established reputation in scientific community and hosts the multiple facilities to study a wide range of ionosphere phenomena. Its data are included in international databases and used for monitoring solar, near and far space events with high precision and accuracy [3, 4]. Multiple studies have being done on the possible connection between seismic or/and atmospheric events with neutron counting rate (further referred as ***NCR***) registered with the surface and underground neutron monitors located at Tien-Shan station (3340 m above sea level) and at similar facilities down at the intermediate level (1750 m a.s.l.) and at the Kazakh National University (850 m a.s.l) [5, 6].

Different neutron monitors and detectors hosting facilities around the world have being addressing this connection with some success. For example, M.A. Despotashvili et al. [7] and V. F. Ostapenko et al. [8] had studied the hard component of the cosmic rays and its standard deviation, while B. M. Kuzhevskij et al. [9] and N.N. Volodichev et al. [10] studied the thermal neutron flux variation strongly dependent on the surface and Sthe Earth's crust properties of the region. Exemplary studies on ***NCR*** vs. earthquakes earthquake's magnitude (further referred as $\boldsymbol{em_t}$) correlation including in-depth physics or nature of the connection analysis may be found in [10]. Certain statistics of positive correlation has been presented in each work.

For our purposes we choose scatterplot approach which is excessively used in broad range of data analysis and produces great visualization and statistics info. Previously Goltz et al. [11] employed the iterated functions system clumpiness test when searching for the nonlinear earthquakes precursors in radon concentration time series. These series possess the same periodic nature as ***NCR*** and radon flux is one of the major contributors to it at the ground level [12] Nevertheless, the results after removing the daily periodic component are found to be uncorrelated noise rather than low-dimensional nonlinear process. Similar nonlinearity only in cloud formation affected by galactic cosmic rays was studied by Harrison et al. [13]. As expected, the scatterplot data show statistically insignificant nonlinear cosmic ray effect but claimed to have a larger cumulative effect on a longer timescale (e.g. centennial) climate variations. This loose and complex relationships between variables in the earth sciences, their complex geographical and frequency distribution demand the proper treatment by the time series statistical methods of analysis [14].

Experimental results

The same data set which has being analyzed by us from the point of view of having complex, nonlinear structure of intermittent periodicity [6] has been divided into blocks characterized by the different distance from a target city. It should be mentioned that the set of neutron detectors at Tien-Shan station and Almaty city are separated by somewhat significant distance of 50 km. The chosen two time series are represented by the neutron monitor data through September 2007 and by corresponding set of seismic event registered through the same month. The range of the seismic events taken into consideration is determined by the network of monitoring facilities, MKAR, ABKAR, KKAR, BVAR and KURK (IRIS), available to the National Nuclear Center of the Republic of Kazakhstan [16]. The ***NCR*** data was acquired with a 1-minute temporal resolution by the neutron monitors at Tien-Shan Mountain Station (3340 m above sea level) and could be found for download and analysis at [17].

The following single smooth generalized regression model was considered.

$$\log(\mu_t) = f(em_t), \quad t = 1,\ldots,n. \tag{1}$$

where $f(em_t)$ is a smooth unknown function of the earthquake magnitude em_t at time $E(\boldsymbol{NCR}_t) = \mu_t$ and $\boldsymbol{NCR_t}$ follows Poisson distribution with mean $\exp(f(em_t))$. Low index $\boldsymbol{t}$ stands for the time dependence. Different approaches to fitting such a model have been developed. Here we used the penalized regression smoothing spline approach [18]. The smooth function $f(em_t)$ was represented by penalized cubic regression splines with the basis dimension 10. Smoothing parameter was selected by minimizing the unbiased risk estimator [18, 19]. For implementation of this approach R package *mgcv* has been used. R is a free programming language and environment standard for practical statistical analysis [20].

Four types of data sets have been analyzed. Each set is selected to be within the certain distance range from the city of Almaty. That is within 0 to 500 km, 500 to 1000 km, 1000 to 1500 km and from 1500 to 2000 km. The distance between the registered earthquake and Almaty city has been calculated along the great-circle connecting these two points using the haversine formula.

Fig. 1 shows the estimated fitted curves for all four data sets. Considerably non-linear with possible time lag effect of the earthquake magnitude on neutron counting rate resulted in a significant result at level α=0.1 only for the first data location.

Four checking plots for the first data set are given in Fig. 2. Taking into account that there were only 78 data available, the diagnostic plots suggest that the model assumptions are not obviously wrong. Similar plots were obtained for the others data sets but not shown.

Discussion

All regression curves plotted are found to be characterized by a low (α=0.1) or none statistical significance. Nonlinear nature of dependence is expected to be of a high complexity and has not been targeted for complete analysis. Thus diurnal and lower frequency variations in data have being kept and served for the purpose of additional data quality analysis. These variations are hidden in the density of scatterplot changing along the Y axis. The data resolution is limited by the earthquakes magnitude range of M_w=0.09-5.13 and these are left unsorted with respect to aftershocks or their belonging to one specific event or point of origin. Originally minute neutron monitor resolution data has being additionally averaged over 18 working channels and then underwent moving average on 1 hour basis.

The transient difference between the upper left plot (range from 0 to 500 km) and bottom right one (range from 1500 to 2000 km) is mainly caused by the structure of our data favoring the events happening within the Kazakhstan Republic, close to Almaty city.

Of certain interest is the fact that the neutron detectors are located within 50 kilometers from the center of the city in the mountains. That may be of the low significance geographically and from the vastness and extent of ionosphere point of view but of certain interest if the task of earthquake prediction will have a reliable solution and these results will be later used for a seismological zoning of the region.

The plots densities, magnitude wise, remain quite uniform which is confirmed by statistical analysis.

All calculations, data analysis and graphs were done using Matlab (Mathworks, Natick, MA, United States) and R language and environment for statistical computing and graphics.

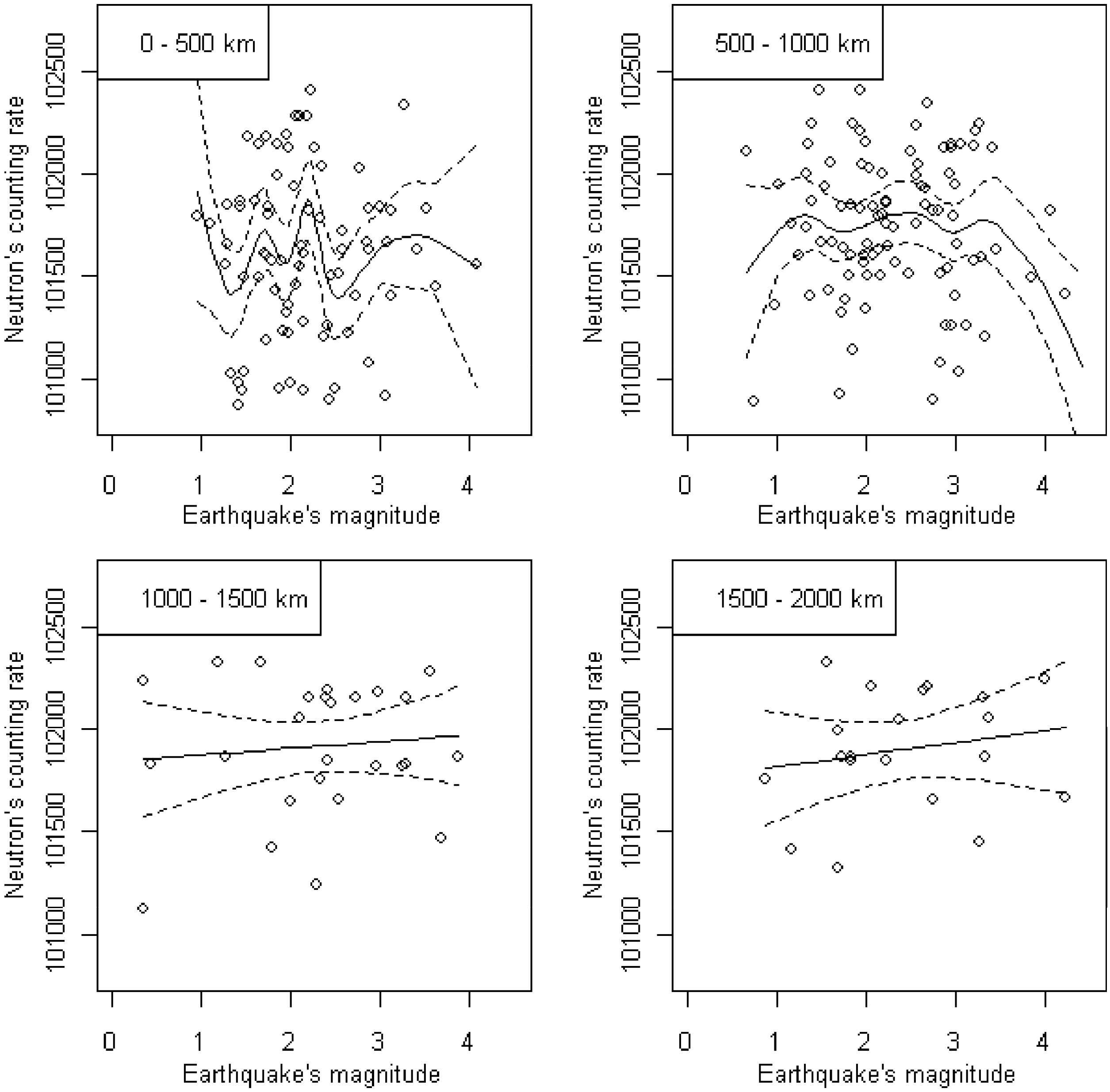

Fig.1. ***NCR*** vs. *em* dependence plotted for 4 data sets. From top to bottom and from left to the right, the earthquakes are registered within 0 to 500 km, 500 to 1000 km, 1000 to 1500 km and 1500 to 2000 km. Two σ confidence interval is marked by the dotted lines on each plot

Conclusions

As we can see if the comparatively reach data statistics is available (like for the data points in 0 to 500 km range) the certain conclusions could be made about possible correlation between earthquakes and ***NCR***. As expected this correlation is fading away as we move farther from the city, that is away from the central monitored regions of Kazakhstan and specifically away from Tien-Shan mountains. Despite the luck of desired prediction power this correlation contains potentially rich information on seismic events distribution throughout Republic, that is reflecting tectonic properties of our country projected onto Tien-Shan mountains and coupled to them ionosphere phenomena.

Due to the complex nature of the subject under study the results obtained are of trial and error nature but it does diminish their value in the search of reliable tools for prediction of catastrophic events like the earthquakes. The possible future studies are expected to target statistical properties of earthqukes vs. ***NCR*** data for the different regions and timescales.

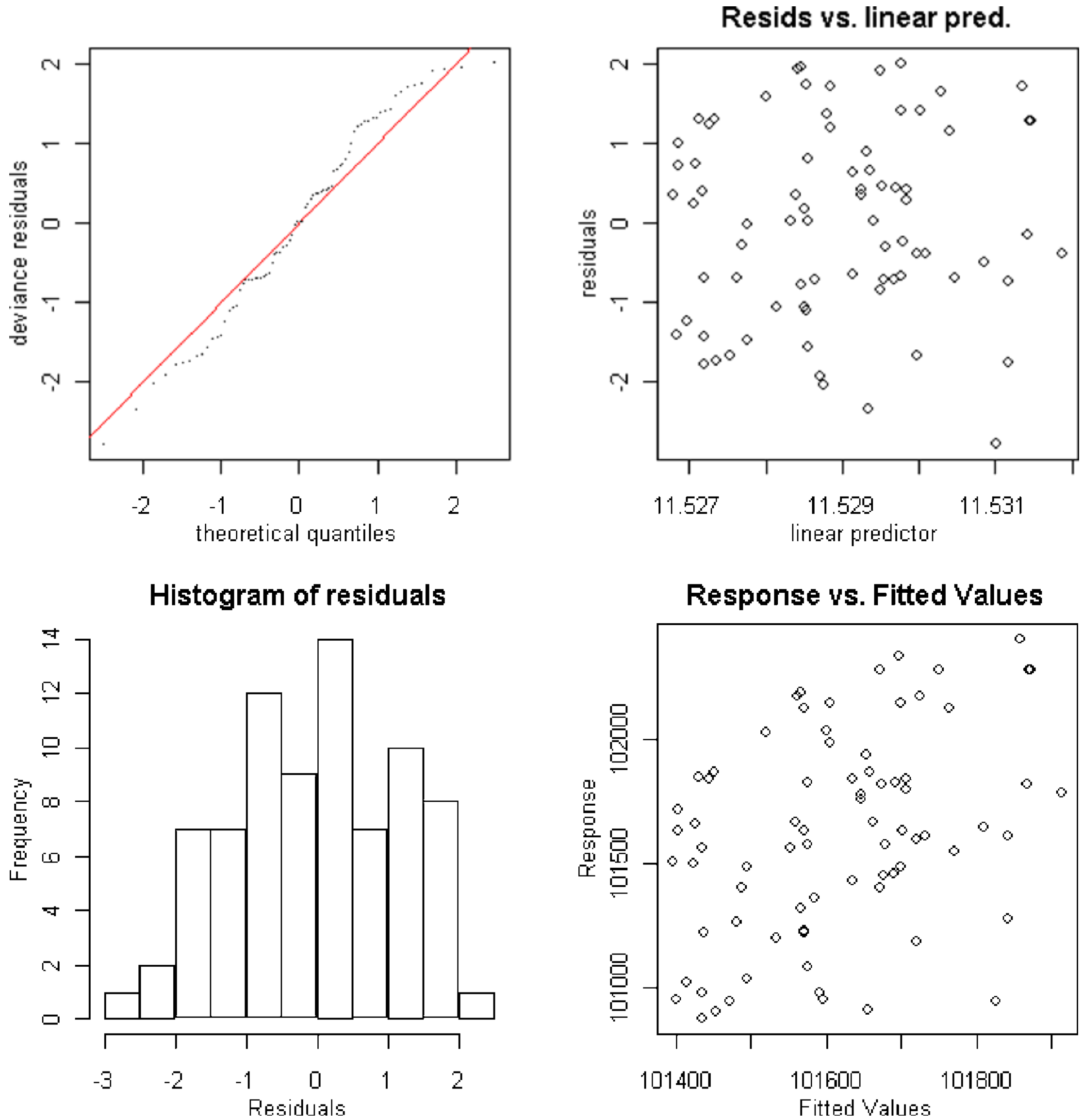

Fig.2. Diagnostic plots of residuals for the data located within 0-500 km distance range from the city of Almaty, Republic of Kazakhstan generated by *gam.check* function from *mgcv* package

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НЕЙТРОН МОНИТОРДЫҢ УАҚЫТ ҚАТАРЫНЫҢ СТАТИСТИКАЛЫҚ ТАЛДАУЫ ЖӘНЕ ЖЕР СІЛКІНУІН БОЛЖАУ

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Бұл жұмыста биіктегі Тянь-Шань станциясындағы нейтрон мониторлардың санау жылдамдығы мен Алматы қаласынан 2 000 км-ге дейін арақашықтықта тіркелген жер сілкіну арасындағы корреляцияның бар болуын анықтау мақсатында нейтрон мониторының берілгендеріне және Қазақстандағы жер сілкінісінің берілгендер базасына қатысты уақыт қатарларын талдауға арналған статистикалық әдістер қарастырылған. Байқалатын корреляция кеңістік-уақыттық реттелген оқиғалармен күрделі функционалдық байланыста және қаладан 50 км қашықтықта тауда орналасқан нейтрон мониторларының көрсеткіштері бойынша жер сілкінісінің болуын анықтауға мүмкіндік береді.

СТАТИСТИЧЕСКИЙ АНАЛИЗ ВРЕМЕННЫХ РЯДОВ НЕЙТРОННОГО МОНИТОРА И ПРЕДСКАЗАНИЕ ЗЕМЛЕТРЯСЕНИЙ

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В данной работе рассмотрены методы статистического анализа временных рядов применительно к данным нейтронных мониторов и базе данных землетрясений по Республике Казахстан с целью нахождения возможной корреляции между скоростью счета нейтронных мониторов Тянь-Шаньской высокогорной станции и одновременно регистрируемых в диапазоне до 2000 км от города Алматы землетрясений. Наблюдаемая корреляция имеет сложную функциональную связь с пространственно-временным упорядоченным рядом событий и используется для оценки вероятности землетрясений по показаниям нейтронных детекторов расположенных в горах на удалении 50 км от города.