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Abstract — This paper presents a preliminary analysis of observations on ultra-low frequency ground electric signals from stations operated by the China Seismological Bureau over the last 20 years. A brief description of the instrumentation, operating procedures and data processing procedures is given. The data analysed consists of estimates of the total strengths (cumulated amplitudes) of the electric signals during 24 hour periods. The thresholds are set low enough so that on most days a zero observation is returned. Non-zero observations are related to electric and magnetic storms, occasional man-made electrical effects, and, apparently, some pre-, co-, or post-seismic signals. The main purpose of the analysis is to investigate the extent that the electric signals can be considered as pre-seismic in character. For this purpose the electric signals from each of five stations are jointly analyzed with the catalogue of local earthquakes within circular regions around the selected stations. A version of Ogata's Lin-Lin algorithm is used to estimate and test the existence of a pre-seismic signal. This model allows the effect of the electric signals to be tested, even after allowing for the effects of earthquake clustering. It is found that, although the largest single effect influencing earthquake occurrence is the clustering tendency, there remains a significant preseismic component from the electrical signals. Additional tests show that the apparent effect is not post-seismic in character, and persists even under variations of the model and the time periods used in the analysis. Samples of the data are presented, and the full data sets have been made available on local websites.

Key words: Ultra-Low frequency electric signal, earthquake risk, Hawkes' self-exciting and mutually exciting model, Beijing

1 Introduction

Systematic studies on the ground electric field as a source of possible earthquake precursors were started in China following reports of substantial electric anomalies before the $M_S 7.8$ Tangshan earthquake in 1976. Since that time more than 100 stations have been built in China for observing the ground electric field. Initially, observations were made over the whole frequency band. Experience showed that observations on specific frequency bands, particularly the frequencies from 0.1 to 20 Hz, were most effective and best able to avoid contamination by industrial noise. In 1981, construction began on an ultra-low-frequency (ULF) observational network in the Beijing region, using a frequency band of 0.1-10 Hz. The first stations from this network started operation in 1982, while others were added during the ensuing decade. The main purpose of this paper is to provide a preliminary statistical analysis of accumulated data from the stations in this network.

Earlier studies of the electric signals data, of a more informal character and involving stations from the whole of China, were made by Chen and Xu (1994), and Guan et al. (1995, 1996, 1999, 2000). They suggested that anomalous fluctuations of the ultra-low frequency electric field may occur up to twenty days before a relatively large earthquake in a neighborhood of the future focal region, and that the characteristics of the anomalies may be related to the distance of the recording station from the epicenter, and the magnitude of the coming earthquake. This paper concentrates on data from five selected stations in the Beijing network, and uses a statistical model to try to quantify the correlations between the occurrence of anomalous fluctuations in the electric field, and the occurrence of local earthquakes. The earthquake data

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used in this study are listed at the end of the paper, and were extracted from the China National Catalogue. A sample of the electric field data used in this study is also listed at the end of the paper; the full set, together with the earthquake data, is available from website http://www.ism.ac.jp/∼ogata/RM916/Data.

In the following sections, we first give a brief account of the observational equipment and operating procedures used by stations in the network (Section 2). This is followed in Section 3 by an outline of the procedures used to obtain the earthquake and electric signals data in the form used in the analysis. Section 4 describes the main statistical model used, which is applied in Sections 5 and 6 to data from the five selected stations. The model is used to check the presence of both pre- and post-seismic effects, and allows for the effects of earthquake clustering. Section 6 also outlines some supplementary analyses designed to check internal consistency and other features. The final section sets out the main conclusions of the paper.

2 Observation Network and Equipment

The electric signals observation network, from which the data for the present study was taken, is located in a broad region around Beijing: see Fig 1. It was started in 1981 with the aim of monitoring fluctuations in the electro-magnetic radiations at frequencies in the 0.1–10 Hz (ULF) frequency band. The station locations were chosen to avoid, as far as possible, man-made sources of interference from electric railways, highways, underground metal pipes, power transformer substations, high-voltage power lines, areas of high energy consumption, radio stations and power lines with ground connections. At the same time they were selected to be close to known seismic belts or active faults. 8 stations are currently operating in this network, from which the 5 stations with the longest and highest quality records were selected for the present study. The locations of the selected stations, namely Langfang, Sanhe, Qingxian, Huailai and Changli, are also shown in Figure 1. Langfang, Sanhe, and Qingxian stations were set up in 1981–1982, Huailai in 1987, and Changli in 1990.

The equipment and observation systems are similar at all the above stations. They use the E-EM system designed by the Provincial Seismological Bureau of Hebei. We provide only a brief description here, referring to Chen and Xu (1994), Chen et al. (1998). for more detailed illustrations and technical parameters of the operating systems.

The basic structure of the E-EM system is shown in Figure 2(a). It uses HBEMD-3 type sensors (see Chen et al, 1998) to detect the electric signals. To reduce the effects of polarization potential, the electrodes of the sensor are made of high-quality stainless steel (Cr18Ni9C), and are cylinder shaped with a height of 300mm and a radius of 4 mm; see Figure 2(b). In addition, 1000μFarad capacitors are connected in series into the system at each station, to eliminate direct currents.

At each station, two pairs of electrodes are installed along perpendicular axes. The electrodes are buried from 6 meters to 12 meters deep, and some 40 meters apart. The electric signals detected by the sensor are transmitted to the pre-processor for preliminary noise reduction, and then to the recorder. All wires used for signal transmission are screened by high quality metal nets, covered by water-proof pipes, and buried 0.6–0.8 meters below the surface. They go directly to the laboratory from underground, and it is checked that no power supply wires, communication cables or metal blocks are present nearby before operation commences.

The pre-processor includes an impedance matching unit and filter. Its main functions are to prevent any 50 Hz noise produced by industrial power supplies from coming into the amplifier, and to prevent the polarization potential from changing the working point of the amplifier.

The signals are then fed to the amplifier to activate the recorder pen. The recorders used (shown in Figure 2(c)) are a modification of the DJ-1 recorder, originally designed for recording the medium-long period components (0–10 HZ) of ground movement with the DK-1 seismometer. These recorders and seismometers are widely used in Chinese seismological stations. The recording method is by automatic continuous pen record.

In order to improve the power supply quality, a stabilization plant is used for the electricity supply instead of the usual commercial power supply. Power from automatically recharged batteries is used when the power from the stabilization plant is cut off. In addition, dual T bandpass filters, together with impedance matching methods, are used to filter out any 50 Hz signals deriving from local power supplies or other sources.

The resulting record sensitivity is 0.5 mV/mm, with a noise level of less than 0.15 mV. The frequency response function of the system is shown in Figure 3. It confirms that the main frequency band is 1-10 Hz.

Noise reduction is a crucial feature of the operational system. Considerable care is needed in selecting the site of the station, and adjusting the sensitivity so that the smaller anomalous signals lie just above the noise threshold. Other design features which help in noise reduction include the choice of the observational frequency band, the depths to which the electrodes and transmission cables are buried, the use of high-quality electrodes to reduce the effects of polarization potential, use of a high input resistance, screening of all transmission cables, filtering out of 50 Hz noise, and power-supply stabilization. Even despite these efforts, the existing stations differ considerably in their ability to pick up or distinguish the anomalous signals.

3 Data

3.1 Electric Signals Data

The data used for the present analysis is the list of signal strengths, as reported each day from each of the electric signals stations to the Centre for Analysis and Prediction in Beijing. As already mentioned, the five stations for the present study, chosen on the basis of the quality and completeness of their records, are Huailai, Changli, Sanhe, Qingxian and Langfang. Because the stations were set up at different times, and operated continuously over different periods, the observation time intervals for these stations are different and are set out in detail in Table 1.

The signal strengths are determined on a daily basis according to the following protocol, which was established at the beginning of the observation period, and is observed in the same manner at each station. Each day, the drum record for each pair of electrodes is examined for the presence of anomalies. The threshold of the observing system is set low enough so that on most days the recording is close to a horizontal line (zero). Typically, the anomalous signals do not occur continuously throughout the day, but in episodes. A given episode may assume a variety of forms, but most commonly appears on the drum record as a signal of roughly sinusoidal character with irregular amplitude and frequency (see Fig 4).

The measure adopted to quantify the daily signal strength is a rough estimate of the total cumulative amplitude (duration times mean amplitude), computed as set out below.

First, for each episode in each of the two measurement directions (N-S and E-W), an average amplitude is estimated from the drum record by taking half the maximum throw on the chart plus half an approximate mean square value. The average amplitude of the episode is then converted to an average electric field strength by multiplying by an instrument scaling factor (mV/mm) and dividing by the distance between the electrodes.

Next, the average field strength for each episode is multiplied by the duration of the episode (in seconds, also taken from the drum record) to produce a measure A of the total strength of that particular episode. If N episodes occur during the day, with associated total strengths $(A_1, \ldots, A_N)$, the total cumulated daily strength is determined as

$$A_{total} = A_1 + A_2 + \cdots + A_N.$$

This procedure is used for each of the two measurement directions (N-S and E-W), and yields the two components A_{NS}, A_{EW} of the strengths which are reported each day to CAP in Beijing.

A sample of the records of the daily strengths from one of the stations is shown in Table 2. From these it can be seen that the signal strengths vary greatly from day to day. Zero values indicate the days on which no anomalous activity could be detected; non-zero values vary from one to around one thousand. The full set of daily strengths from the five stations is too lengthy to be listed in the paper, but is available from the ISM Website http://bemlar.ism.ac.jp/Data/.

For the purpose of the present analysis only, detailed variation of the daily strengths was ignored, and the days were crudely classified as either possessing (1) or not possessing (0) anomalous signals, according as to whether or not the the daily strengths satisfied the criterion

$$A = A_{NS} + A_{EW} \geq 200$$

In this way, the signal data was transformed into a set of daily $0-1$ values which were conventionally regarded as occurring at 0.00 hours on the day following the signal readings. This series was then used as one of the components in the later correlation studies. Table 1 lists for each station the numbers of days on which earthquake events were recorded, the numbers of days on which signal events (1's) were recorded, and the ratio between these numbers. The last column is included as a possible indicator of the noisiness of the site, in terms of the number of electric signal days not directly associated with earthquakes. The occurrences are displayed in Figure 5, together with the earthquake data for each station.

3.2 Recognition of interference signals

Experience has shown that low-sky or sky-to-ground lightning, power lines that leak electricity to the ground near the station, and local domestic or industrial activities may influence electric field observations made using the buried electrode method. Some such sources of noise can be distinguished easily from the anomalous signals described earlier by the differences in character of the recorded waveforms. As an example, Figure 6 shows both waveforms typical of the anomalous signals, and a single large pulse typical of an interference signal. Figure 6 shows the interference signals from low-sky lightning and power lines leakages near the station.

When clearly distinguishable features of the latter kind are observed, they are excluded from the calculation of the daily strengths. In all other cases, irrespective of their supposed source, fluctuations above the noise level are assumed to form part of the anomalous signal, and are included in the calculation of the daily strengths.

3.3 Earthquake Data

For each station, a special sub-catalogue was prepared, consisting of events for which either

(a) the epicentral distance from the station was less than 200 km, and the local magnitude was 4.0 or greater, or

(b) the epicentral distance from the station was less than 300 km, and the local magnitude was 5.0 or greater.

The data for these subcatalogues was extracted from the main China catalogue prepared by CAP; copies of this catalogue, if required for research purposes, can be obtained from the weblink http://www-wdcds.seis.ac.cn (contact Professor Ma Li in case of difficulties, as the Website is currently in Chinese only).

An epicentral plot of earthquakes with local magnitudes 4 and greater occurring within an approximately 800 km square region around Beijing is shown in Figure 1. Earthquakes falling into at least one of the five sub-catalogues are shown with dark circles; other earthquakes are shown with light circles. Time-magnitude plots of the earthquakes from the subcatalogues for each of the five selected stations are shown in Figure 5.

The five sub-catalogues are also condensed and summarized in Table 3. The table lists origin times, epicentres and local magnitudes for each event, and indicates the stations for which the given event fell within one or other of the two specified circles. For each station, the earthquake events satisfying the prescribed criteria were coded as a sequence of occurrence times, ignoring magnitudes and other coordinates. The two series for each station, one series for the electric signals and the other for the earthquakes, formed the inputs for the analyses described below.

None of the subcatalogues has been declustered prior to the analysis; rather, the clustering effect is itself modelled through the self-exciting term in the models discussed in the next section. Indeed, a secondary aim of the paper is to check the extent to which clustering can affect the apparent significance of the electric signals terms (cf Michael, 1997). With the exception of Huailai station, for which the 300km observation region includes the aftershock regions of both the Datong and Zhangbei events, the number of direct aftershocks entering the subcatalogues is rather small, as can be verified from Figure 5.

3.4 Some features of the data

From the preceding tables and plots, several important features can be seen which may be useful to bear in mind for the subsequent analysis.

1. Much of the earthquake activity during the study period is associated with three major earthquake groups. The first represents continuing low-level activity in an extended region around the epicentre of the 1976 M_S=7.8 Tangshan earthquake. This activity continued into the early 1990's. The other two major groups are mainly aftershocks of the two $M = 6.4$ Datong earthquakes of 1991/1992, and of the 1998 $M = 6.2$ Zhangbei earthquake. The whole region was quiet between these two events.

2. The clustering effect is particularly pronounced for the Huailai station, the study region for which encompassed both the Datong and Zhangbei clusters, as well as partially extending into the region of the Tangshan events. By contrast, the Changli station entered the study only in 1990, and lies too far to the East to contain the smaller ($4 \leq M < 5$) aftershocks from either the Datong or the Zhangbei sequences. Its subcatalogue shows the least clustering of all five stations.

3. The electric signals are also very highly clustered, even on some occasions when there appear to be no associated earthquakes. This feature is particularly pronounced for Langfang and Huailai stations, both of which show substantially increased electric signals activity in the later part of the record. These two stations, especially Langfang, were affected by urbanization of their immediate environment during the study period. Urbanization has not occurred to the same extent at the other stations. The increased activity observed at the first two stations may therefore give some indication of the sort of interference effects to be expected from man-made sources.

4 Self-exciting and mutually exciting models

In this section we describe the model used for the major part of the analysis. The self-exciting and mutually exciting earthquake model was developed by Ogata and Utsu (see Ogata et al. 1982; Ogata, 1983; Utsu and Ogata, 1997) from the Hawkes process (Hawkes, 1971). It is most easily described through its conditional intensity function,

$$\lambda(t)dt = E[N(dt)|\mathcal{H}_t], \tag{1}$$

where $\mathcal{H}_t = \{\text{Observation history up to time } t\}$. In essence, the conditional intensity function represents the target process as a time-varying Poisson process with rate $\lambda(t)$ conditioned by the past history. The conditional intensity function of the combined self-exciting and mutually-exciting model (referred to as the combined model in the rest of the paper) can be written as

$$\lambda(t) = \mu + \lambda_S(t) + \lambda_E(t), \tag{2}$$

where μ represents the constant background rate, λ_S is the self-exciting term, which models clustering among the target events, and λ_E is the external excitation term, which models the contribution to the rate from the external process. The self-exciting term is taken in the form

$$\lambda_S(t) = \sum_{t_i<t} g(t - t_i), \tag{3}$$

with the summation extended to all the events occurring before time t in the target process $\{t_i : i = 1, 2, \cdots, n_1\}$, $g(t)$ being a sum of Laguerre polynomials

$$g(t) = e^{-\alpha t} \sum_{k=0}^{N_S} p_k t^k. \tag{4}$$

Similarly, the external excitation term is written as

$$\lambda_E(t) = \sum_{u_i<t} h(t - u_i), \tag{5}$$

with the summation taken over all the events occurring before time t in the process of precursor events (here the electric signals) $\{u_i : i = 1, 2, \cdots, n_2\}$, $h(t)$ again being a sum of Laguerre polynomials,

$$h(t) = e^{-\beta t} \sum_{k=0}^{N_E} q_k t^k. \tag{6}$$

The Laguerre polynomials are used here as a convenient family of orthogonal functions which in principle can be used to model the response functions to any required degree of accuracy; more detailed discussions of the model are given in Vere-Jones and Ozaki (1982), Ogata et al (1982), Ma and Vere-Jones (1997), or the IASPEI manual, Utsu and Ogata (1997). The model was used in the earlier studies mainly to investigate possible triggering effects between different kinds of seismicity.

In practice the number of terms included in the sum has to be balanced between concerns of sensitivity and over-fitting, and is the main target of the model-selection procedures described later. With limited data, as in the present situation, and little prior knowledge as to the likely form of the response functions, the fitted response functions can be interpreted only as crude approximations to any underlying physical processes.

Usually, the excitation effect in the fitted model reaches its maximum immediately or shortly after an event occurs, then decays quickly with time and becomes negligeable after sufficient time.

If we drop out λ_E, the model becomes a self-exciting model; if we drop out λ_S, the model becomes an externally excited model; if both λ_S and λ_E are neglected, the model reduces to a Poisson model. All of these types of models will be used in our analysis.

We shall keep the notation $\{t_i : \ i = 1, 2, \cdots, n_1\}$ for the main or target process, and $\{u_i : \ i = 1, 2, \cdots, n_2\}$ for the external exciting process or secondary process.

In our analysis, we first take the earthquake events as the target process and the anomalous electric signals as the external process, to see whether the electric signals have explanatory power in relation to the occurrence times of earthquakes. Then we reverse the roles of the two processes, take the anomaly events as the main process and earthquakes as the external process, to see whether the electric signals might be triggered by some mechanism following the occurrence of an earthquake.

Given a set of observation data, the parameters of the model can be estimated by maximizing the likelihood function, which for a conditional intensity model has the standard form (analagous to that for a Poisson process)

$$\log L(\boldsymbol{\theta}) = \sum_{i:0 \le t_i \le T} \log \lambda(t_i; \boldsymbol{\theta}) - \int_0^T \lambda(t; \boldsymbol{\theta}) du, \tag{7}$$

where t_i denotes the occurrence time of the ith event, $[0, T]$ is the observation time interval, and Θ is the vector of parameters (see, for example, Daley and Vere-Jones, 2002, Chapter 7).

The parameters for the combined model can be written as

$$\boldsymbol{\theta} = (\mu; \, \alpha, \, p_1, \, p_2, \, \cdots \, p_{N_S}; \, \beta, \, q_1, q_2, \cdots, \, q_{N_E}).$$

Model selection, particularly the determination of the numbers of parameters N_S and N_E in the Laguerre expansions, was carried out using the Akaike Information Criterion (AIC, see Akaike, 1974). The statistic

$$AIC = -2 \max_{\boldsymbol{\theta}} \log L(\boldsymbol{\theta}) + 2k_p \tag{8}$$

is computed for each of the models fitted to the data, where k_p is the total number of fitted parameters. In comparing models with different numbers of parameters, addition of the quantity $2k_p$ roughly compensates for the additional flexibility which the extra parameters provide. The model with the lowest AIC value is taken as giving the optimal choice for forward prediction purposes.

Insofar as it depends on the likelihood ratio, the AIC can also be used as a rough guide to model testing. As a rule of thumb, in testing a model with $k + d$ parameters against a null model with just k parameters, we take a difference of 2 in AIC values as a rough estimate of significance at the 5% level. If standard asymptotics were applied, such a difference would correspond to a significance level of 4.6% when $d = 1$, 5% when d = 2, 4.6% when d=3, and 3.5% when d=5. Such figures give a rough guide to significance levels, but should be used conservatively, because of the relatively small sample sizes and other approximations.

One of the main advantages of the combined model in the present context is that it allows the effect of the electric signals terms to be examined even in the presence of clustering (modelled by self-excitation) in the earthquakes themselves.

5 Main Analysis

In the main analysis, we use the model format available within the Lin-Lin programme (Utsu and Ogata, 1997). This requires all coefficients in the trend and polynomial expansions to be non-negative, thus ensuring positivity of the conditional intensity, at the expense of some flexibility in the functional forms available.

The combined model is fitted separately to data from the five selected stations in the Beijing region, namely Huailai, Changli, Sanhe, Qingxian and Langfang. Because of data availability, the observation time intervals for those stations are different, as summarized in Table 1.

Taking the earthquakes as the target events, we consider the following models to examine the relationship between the electric signals and the earthquakes:

1. Poisson process with polynomial trend (restricted to second order);
2. self-exciting model, without external excitation;
3. externally excited model without self-excitation;
4. combined model of both self-exciting and external excitation terms.

In Section 6, to test whether the electric signal might be a post-seismic effect, we interchange the roles of the electric signals and the earthquakes.

5.1 Self-exciting versus Poisson models.

The purpose of this step is to determine the size and significance of the clustering effect among the earthquakes before using the self-exciting model as a base model to determine the contribution of the electric signals in fitting the earthquake data. This step was accomplished by fitting the self-exciting model to the earthquake data, and comparing it to the Poisson model with polynomial trend. The first and second row blocks in Table 4 list the outputs from this analysis for each of the five selected stations.

From this table we can see that the clustering effect plays an important role in the process of the earthquake occurrences. For each station except Changli the reduction in AIC is very substantial, well above what would be required to establish significance at around the 5% level. The effect is particularly pronounced for Huailai, as we might expect from the clusters contained within the Huailai record. The changes in seismicity rate for Huailai were mainly caused by these clusters, so here and elsewhere we have restricted the trend to a second degree polynomial with non-negative coefficients. The Changli station, by contrast, shows a relatively small degree of clustering, large enough for the self-exciting model to be preferred to the Poisson model, but barely large enought to establish the significance of the clustering effect.

We conclude that clustering should be taken into account for all five stations, and that it is a particularly important feature for the stations closest to the source regions of the Datong and Zhangbei clusters.

5.2 Externally excited versus Poisson models

We next compare the Poisson model to the externally excited models for the five data sets (see the third row block in Table 4. We see that the electric signals reduce the Poisson AIC values by amounts which are less than the reductions due to the self-exciting terms for Huailai and Langfang stations, but comparable to or greater than those reductions for Sanhe, Changli and Qingxian stations. These large differences suggest that the external signals have considerable explanatory power. However, we shall see that these values are somewhat inflated, being based in part on the fact that both earthquakes and signals are clustered, so that to a degree the electric signals can act as a surrogate for the self-exciting terms.

5.3 Combined versus self-exciting models.

Finally, we compare the fits of the self-exciting and combined models. The final row block of Table 4 shows that addition of the external excitation terms to the self-exciting terms contributes further reductions of the AIC values for all five stations. All five reductions are substantial, even though smaller than those obtained by testing the electric signals models directly against the Poisson model. Note that the differences in AIC values between the combined model and the Poisson model are much larger than the differences between the externally excited model and the Poisson. Both effects show that the explanatory power of the electric signals is considerably exaggerated unless the clustering terms are taken into account, as forewarned by Michael (1997). The important conclusion, however, is that the electric signals retain a significant explanatory power even after the clustering has been taken into account by the self-exciting terms.

Additional insight can be obtained by examining the information gains per event. This quantity - here just the difference in log-likelihoods normalized by the number of events - is a measure of the improvement in predictability in passing from the base model to the test model (see e.g. Vere-Jones

(1988) or Harte and Vere-Jones (2004) for further discussion; the idea goes back to early papers by Kagan (eg Kagan and Knopoff, 1977). The gains per earthquake event for each station are shown in Table 5, together with the gains per signal event in passing from the self-exciting to the combined model. It is interesting that the stations showing the smallest degree of clustering show the largest gains/event. The low gains per electric signal for Huailai and Langfang suggest that these stations may be more subject to interference from noisy signals than the other stations, although the low gains may also represent just a further nuisance effect of the clustering.

5.4 Fitted conditional intensity and impulse response functions

An example of the conditional intensity function of the combined model, and the associated impulse response functions, is shown in Figure 7 for Sanhe station. The response functions are only crudely fitted because of the rather small amount of earthquake data. The shapes of the impulse response functions $g(t)$ and $h(t)$ suggest that the relative risk of earthquakes is high during the first few days after the occurrence of an earthquake or an electric signal event, then decays rapidly with time. Note, however, the differences in scales for the self-exciting and electric signals terms. The latter is much more diffuse, although the apparent rate of decay for both response functions may be exaggerated by the choice of Laguerre functions, associated with exponential decay, as the function basis (see further discussion in Section 6). The differences between the maximum absolute values of two functions $g(t)$ and $h(t)$ is an indication that, for this station at least, the immediate increase in risk due to the occurrence of an earthquake is larger than the immediate increase in risk from an electric signal event.

Another way of examining the relative contribution of the self-exciting and the external excitation terms is to compare the contributions of the three terms μ, $(1/T)\int_0^T \lambda_S(t)dt$ and $(1/T)\int_0^T \lambda_E(t)dt$ to the overall mean rate $(1/T)\int_0^T \lambda(t) = N_E/T$. The results are shown in Table 6. There is substantial variation in the estimates of the background rates and percentages between the different stations. Some of this is probability due to model instability, but the entries broadly reflect features we have already identified, such as the extensive clustering in the Huailai records.

Overall, both the self-exciting and the electric signal terms make significant contributions to the to risk, with the signals term contributing typically about one-third of the total risk.

6 Supplementary Analyses

The present section describes three additional analyses, all of which were undertaken to investigate aspects of the stability or interpretation of the previous results. The most important of these, described first, investigates the possibility that the electric signals are not pre-seismic but post-seismic in character. This is achieved by reversing the roles of the electric signals and the earthquakes. Then we examine the robustness of the signals effect by allowing a slight over-fitting of the clustering effect in the earthquakes, and only then testing the effect of adding in the signals as an external term. Finally, we break the period after the time of the Datong sequences, use the initial period to fit the model, and the later period to test it.

6.1 Analysis of electric signals using earthquakes as explanatory variables

In this analysis we take the same modelling framework as the preceding section, but reverse the roles of earthquakes and the earthquakes. That is to say, we consider Poisson and self-exciting models for electric signal events, and then examine the effect of adding in the earthquakes as a possible external exciting term. The results are summarized in Table 7, which has the same structure and interpretation as Table 4, so that we restrict our remarks to a few key points of interest.

The comparison between the Poisson and self-exciting models shows that the electric signal events are even more highly clustered than the earthquakes. The large reductions in AIC values shown in the second row block of the table correspond to information gains per event varying from 0.71 for Huailai to 1.37 for Changli.

By contrast, addition of the earthquakes as externally exciting events causes almost no improvement of fit, whether or not the self-exciting terms are included. The third block in Table 7 shows that, even despite the clustering in both sets of events, for three of the stations AIC selected the Poisson model in preference to a model with external excitation from the earthquakes. In the final block, when both self-exciting and external terms are added, the earthquake terms add a significant effect only for Huailai.

An explanation of the anomalous behaviour of Huailai station is suggested when we plot the conditional intensity function for the electric signals, as in Figure 8(a). From this it is clear that there is an increasing trend in the frequency of electric signals at Huailai. At the same time, the response function for the external exciting term, as shown in Figure 8(c), has such a slow decay that the cumulative sum builds up over time, thus emulating the trend. In effect, therefore, the externally exciting term for Hualilai models not the direct predictive effect of an earthquake, but the increasing trend in the numbers of signals detected at the Huailai station. A similar but smaller trend exists also for Langfang station. A more typical response curve for the self-exciting term for the electric signals is shown in Figure 8(e), for Qinxian station, where the self-exciting model was selected by AIC.

In no case do we find convincing evidence that the earthquakes trigger the electric signals.

6.2 Testing with an Extended Model for the Self-Exciting (Clustering) Term

As one of the referees pointed out to us, in the present context one of the drawbacks of the Lin-Lin model is the rapid exponential decay of the self-exciting term, which, in association with AIC selection criterion, may limit the ability of the self-exciting term to explain subsequent events which are then picked up by the electric signals. This effect may exaggerate the effectiveness of the electric signals.

As a first step to investigate this effect, we carried out some subsidiary analyses using the ETAS model to give a better picture of the self-exciting term. The conditional intensity for the ETAS model has a similar form to (3) except that the decay function is modelled by a power-law term based on the Omori formula, rather than on the Laguerre polynomial formulation in (4) (see eg Ogata, 1989, 1999) for further details).

Table 8 shows the results of these analyses. In this table, the results from the ETAS model replace those from the self-exciting term of the Lin-Lin model, while those from the combined model are left unchanged from Table 4. Thus the fit from the combined Lin-Lin model is compared to the fit from the ETAS model. Only for Huailai station does the change affect the character of the results. For all the other stations, the electric signals still produce a significant improvement in fit.

For Huailai station, it is evident that the ETAS model fits the two large aftershock sequences very much better than the self-exciting term from the Lin-Lin model. When compared to the fit from the combined model, this improvement (which covers half of the total earthquakes in the Huailai catalogue) swamps any effect from the electric signals. Except for the relatively short period covered by these two sequences, however, the electric signals appear to precede earthquake events much as for the other stations. It therefore seems likely that a more complete analysis, which used a combination of the ETAS and electric signals terms in place of the combined Linlin model, would show that the electric signals retained some explanatory power.

6.3 Testing with Separate Learning and Evaluation Periods

In Table 9, we summarize the results of fitting the Lin-Lin and Etas models to data from Sanhe station (the one with the longest record) in two parts. The first (training) period, 1982 - end 1989 was used to fit the Poisson, self-exciting, combined, and ETAS models; the second (evaluation) period (1990 - end 1998) was used to assess the performance of the model on an independent data set. The combined model gave the lowest AIC during the training period, and was clearly selected as the best of the four models. The combined model also gave the highest log-likelihood value in the evaluation period. More than 1/3 of the earthquakes in the Sanhe catalogue (26) occurred during the evaluation period, making the information gain/earthquake (comparing combined to self-exciting, as in Table 5) about $7.5/26 \approx 0.28$, which is quite comparable to the overall gains reported in that table. The results for the Huailai station again show the dominance of the clustering term as registered by the ETAS model. When compared to the self-exciting model, there is still a modest information gain/event.

7 Discussion and conclusions

In this paper, we have used a version of the Hawkes mutually-exciting model to examine the statistical correlations between the electric signal events, which were recorded by 5 stations in the Beijing region, and the intermediate size earthquakes which occurred within a 200-300km radius of each of the stations. For each station separately, the results indicate that the signals provide weak but nonetheless non-trivial precursory information about the occurrence of magnitude 4 and larger earthquakes in the circular region around the station. In the converse direction the results are equally unequivocal; in no case do the earthquakes appear to carry significant precursory information about the occurrence of the signal events recorded at the station.

In response to concerns expressed by the referees and others who have commented on earlier drafts of this paper, we would like to make the following comments.

1. While it may be that the electric signals data analyzed in this study have been collected by relatively simple equipment, and that the initial data handling requires a degree of subjective intervention and interpretation, the data analyzed are part of a systematic, standardized process of measurement and reporting that has been carried out in the Beijing region for the better part of twenty years. From the point where they have been collected by CAP, the data used are quantitative, objective, and available for analysis. Within CAP, they form a regular and integral part of the surveillance and forecasting programme, and have done for many years.

2. During the period of the study, all five stations report very comparable effects, despite local variations in seismicity and geological and man-made environment. Even if the observation period is broken up into sections, similar effects are observed in each section, as outlined in section 6.3. The greatest deviations from the common pattern occur for Huailai station. Even here it seems likely that the discrepancies are caused by the two large aftershock sequences which enter the earthquake subcatalogue for this station, and that the discrepancies would be much reduced if the aftershock periods were either better modelled in the combined model, or removed from the analysis.

3. The statistical analysis applied to this data is also crude. Information is lost in converting the signals to 0-1 data, and only the simple Lin-Lin model has been used in the main analysis. Nevertheless it is sufficient to show that the precursory effect of the electrical signals persists even after allowance has been made for earthquake clustering, and that the electric signals are pre- and not post-seismic in character. Interpretation of the AIC values and associated significance levels is subject to some uncertainty, but in most cases there is a large margin of error. The fact that similar significance levels are recorded for all stations substantially increases the overall significance.

4. It is clear that in some cases the signals have been contaminated by the occurrence of electric storms, man-made electrical appliances, etc. Except in the most obvious cases, all such disturbances have been incorporated into the assessment of the daily strengths. In such a situation, unless the interfering signals carried predictive information similar to those of the anomalous signals themselves, one would expect them to act as noise and to decrease the apparent correlations between the signals and earthquakes. Additional studies by Guan and coworkers suggest that in fact the majority of the observed signals are not related to interference from meteorological phenomena or magnetic storms. For example, the electric signals do not appear to reflect annual fluctuations in rainfall or temperature (Guan et al, 1996), nor do the large-scale magnetic storms appear to be associated with major variations in either the electric signals or the earthquakes (ibid). As for man-made signals, the two sites most likely to be affected by these, namely Langfang and Huailai, both show increased frequency of electric signals with time, and are accompanied by rather low values of the predictive power per signal. These features suggest that, for these stations at least, the earthquake-associated signals are indeed diluted by noise signals which build up as urbanization of the area increases. At least for the observation periods in the present study, however, these effects are not so large as to destroy the correlations with the earthquakes.

5. At present, we have no answer to what may be the most serious problem associated with the present topic, namely the absence of a plausible physical process that can explain the source and precursory character of the electric signals. Our view here is that the existence of such a mechanism cannot yet be ruled out, and that in such a situation the collection and presentation of empirical data, such as outlined in the present study, is a necessary stage in the scientific process.

6. Although we are aware of the controversy which has surrounded earlier reports of links between ground electric signals and earthquake occurrence, and the many serious criticisms which have been directed towards some of these, we believe that the present data and analysis should be given the opportunity to be considered in their own right. At the least the data analyzed here summarize the results of two decades of preparatory work which is unique of its kind in scale and consistency of application.

In conclusion, we should emphasize that this is only a preliminary analysis of the data on electric signals held by the China Seismological Bureau Centre of Analysis and Prediction. Its aim was to establish that there is at least a prima facie case for taking seriously the claims that there may be a connection between electric signals and earthquakes. At this point, we cannot fully exclude the possibility that the positive results obtained in this analysis have their roots in aspects of the data handling, selection procedures, and analysis, or in some coincidental relation between earthquake occurrence and man-made or physical noise. Our belief, however, is that this is unlikely to be the case.

We should also emphasize that the present paper does not pretend to set up a quantitative forecasting scheme. It is based on a retrospective study of existing data, and leaves unresolved many issues relating to the combination of information from the different stations, and the estimation of locations and sizes of possible future earthquakes, all of which would have to be resolved before a quantitative forecasting scheme could be put into place. Some of these aspects are pursued further in the companion study by Zhuang et al (2002), which is currently available as a technical report; some part of its findings are summarized in Ogata and Zhuang (2001).

At the present time, the electric signals stations around Beijing are in the process of being converted to digital stations. When this process is completed, it should allow an unequivocal answer to be given to concerns about reliability and objectivity of the data which have been raised. Should the results confirm the findings in the present report, the existing data will be a unique source of information about the electric signals, and their protection becomes a matter of both national and international importance.

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Table 1: Observation periods and observed numberS of events at each station

Station	Location	Observation period	N_{EQ}	N_{EQ}/T	N_{ES}	N_{ES}/N_{EQ}
Huailai	$40°26', 115°31'$	'87-05-1 ∼ '98-01-31	59	5.32	239	4.05
Langfang	$39°32', 116°41'$	'82-01-1 ∼ '96-12-31	77	5.13	366	5.73
Sanhe	$39°59', 117°04'$	'82-01-1 ∼ '98-01-31	75	5.00	266	3.55
Changli	$39°48', 119°19'$	'90-01-1 ∼ '96-12-31	22	3.14	42	6.00
Qingxian	$38°35', 116°50'$	'82-01-1 ∼ '96-12-31	60	2.20	271	8.21

N_{EQ}: number of earthquakes; N_{ES}: number of electric signal events.
Rates are in events/year.

Table 2: A segment of the records of daily strength from Sanhe station

Date	A_{NS}	A_{EW}	$A_{NS} + A_{EW}$
......			
1982-04-23	0	0	0
1982-04-24	0	0	0
1982-04-25	0	0	0
1982-04-26	0	0	0
1982-04-27	0	0	0
1982-04-28	434	134	568
1982-04-29	217	19	236
1982-04-30	389	167	556
1982-05-01	401	211	612
1982-05-02	216	17	233
1982-05-03	50	0	50
1982-05-04	389	122	511
1982-05-05	322	17	339
1982-05-06	611	235	846
1982-05-07	16	1	17
1982-05-08	37	2	39
1982-05-09	0	0	0
1982-05-10	12	1	13
1982-05-11	0	0	0
1982-05-12	2	0	2
1982-05-13	1	0	1
1982-05-14	0	0	0
......			

For the purposes of the present analysis, electric signals are noted as having been present on a given day if and only if the total strength $A_{NS} + A_{EW}$ exceeds 200. In other cases the signals are noted as having been absent.

Table 3: List of the earthquakes in this analysis. The coding in the last columkn indicate the stations for which the given event lay within one or other of the observation circles: H=Huailai, L = Langfang, S = Sanhe, C = Changli, Q = Qinxian. Lower suffix (eg H_1) refers to smaller event within 200km radius. Upper suffix (^{1}) refers to larger event in outer annulus ($M > 5$ between 200 and 300km from station). Double suffix ($^1_1$) refers to a larger event within the smaller circle.

Date	Time	Latitude	Longitude	Magnitude	Remark
1982-01-20	14:54:13	37°02′	117°32′	4.2	Q_1
1982-01-26	17:47:57	37°24′	114°52′	4.8	Q_1
1982-01-27	12:30:42	39°45′	118°46′	4.4	S_1C_1
1982-02-09	17:33:37	39°38′	118°09′	4.7	$L_1S_1C_1$
1982-03-08	03:41:59	39°52′	118°40′	4.9	S_1C_1
1982-03-30	12:06:33	39°48′	118°30′	4.2	S_1C_1
1982-07-09	17:18:24	38°07′	119°23′	4.1	C_1
1982-08-09	04:07:11	38°58′	120°35′	4.0	C_1
1982-10-19	20:46:01	39°53′	118°59′	5.3	$L^1S_1C_1^1$
1982-12-10	02:16:46	40°28′	116°33′	4.9	$H_1L_1S_1$
1983-01-31	01:50:03	37°26′	115°01′	4.1	L_1Q_1
1983-02-06	08:05:47	37°31′	114°57′	4.5	L_1Q_1
1983-04-03	10:16:30	40°45′	114°47′	5.1	$H_1^1L^1$
1983-07-21	05:55:55	40°49′	114°42′	4.4	H_1
1983-08-03	14:21:15	37°38′	119°06′	4.4	C_1
1983-08-08	09:04:58	40°40′	115°23′	4.1	H_1L_1
1983-08-21	05:00:31	39°43′	118°19′	4.1	S_1C_1
1983-08-26	17:22:18	39°48′	117°13′	4.3	$H_1L_1S_1C_1$
1983-09-09	22:12:45	40°28′	116°34′	4.0	$H_1L_1S_1$
1983-09-15	12:18:35	37°31′	114°16′	4.1	Q_1
1983-10-05	00:25:17	39°51′	118°54′	4.7	S_1C_1
1984-01-07	19:18:22	39°43′	118°45′	5.2	$L^1S_1C_1^1$
1984-02-27	05:00:08	39°26′	118°01′	4.3	$L_1S_1C_1$
1984-03-11	11:24:07	39°38′	118°22′	4.0	S_1C_1
1984-03-16	11:43:54	38°28′	119°05′	4.0	S_1C_1
1984-05-17	11:08:26	38°58′	119°08′	4.2	S_1C_1
1984-11-27	09:54:20	40°30′	114°08′	4.5	H_1
1984-11-27	09:58:20	40°29′	114°16′	4.1	H_1
1984-12-13	11:20:25	39°39′	118°13′	4.1	S_1C_1
1985-01-26	20:55:53	37°22′	114°46′	4.2	Q_1
1985-04-22	11:31:33	39°45′	118°46′	5.0	$L^1S_1C_1^1$
1985-04-22	19:02:37	39°44′	118°47′	4.3	S_1C_1
1985-04-22	19:56:59	39°43′	118°46′	4.7	S_1C_1
1985-05-22	18:51:44	39°50′	118°32′	4.7	S_1C_1
1985-08-11	01:17:16	39°44′	118°45′	4.0	S_1C_1
1985-08-11	01:30:32	39°45′	118°47′	4.5	S_1C_1
1985-08-11	02:29:15	39°46′	118°46′	4.0	S_1C_1
1985-08-23	23:19:31	39°45′	118°45′	4.0	S_1C_1
1985-08-25	17:05:19	39°44′	118°30′	4.4	S_1C_1
1985-10-05	12:01:58	39°47′	118°27′	5.0	$H^1L^1S_1^1C_1^1Q^1$
1985-10-17	00:08:25	39°17′	114°39′	4.1	$H_1L_1Q_1$
1985-11-21	19:42:22	40°05′	115°50′	4.7	$H_1L_1S_1$
1985-11-23	08:47:14	38°47′	121°11′	4.5	C_1
1985-11-30	22:38:00	37°14′	114°49′	5.6	$L^1S^1Q_1^1$
1986-01-11	17:54:35	37°26′	114°54′	4.1	L_1Q_1
1986-02-05	17:18:36	39°45′	118°26′	4.0	S_1C_1
1986-02-15	07:08:47	37°45′	115°14′	4.8	L_1Q_1

Table 3: (continued)

Date	Time	Latitude	Longitude	Magnitude	Remark
1986-02-18	06:07:03	37°48′	115°11′	4.5	L_1Q_1
1986-07-02	11:56:58	38°23′	120°29′	4.6	C_1
1986-07-02	11:58:29	38°24′	120°30′	4.3	C_1
1986-11-10	16:58:05	40°03′	116°43′	4.7	$H_1L_1S_1$
1986-12-16	07:25:56	37°16′	114°45′	4.2	Q_1
1987-03-21	07:00:23	38°17′	114°15′	4.5	L_1Q_1
1987-05-22	11:50:42	40°00′	116°47′	4.0	$H_1L_1S_1$
1987-06-07	12:26:23	39°32′	118°05′	4.5	$L_1S_1C_1$
1987-07-16	02:16:28	39°47′	118°38′	4.5	S_1C_1
1987-08-08	07:35:06	39°20′	117°53′	4.7	$L_1S_1C_1$
1987-08-08	17:35:08	39°20′	117°54′	4.1	$L_1S_1C_1$
1987-11-11	21:18:39	40°17′	114°48′	4.7	H_1L_1
1988-05-09	06:22:01	39°18′	118°06′	4.2	$L_1S_1C_1$
1988-07-23	13:51:43	40°05′	114°13′	5.0	$H_1^1L_1^1S^1Q^1$
1988-07-25	01:47:39	39°31′	118°06′	4.4	$L_1S_1C_1$
1988-07-26	22:46:39	39°34′	118°06′	4.9	$L_1S_1C_1$
1988-07-30	18:44:32	39°46′	118°43′	4.3	S_1C_1
1988-08-03	17:44:11	39°36′	118°39′	4.6	S_1C_1
1988-10-26	01:29:44	39°52′	118°29′	4.3	S_1C_1
1989-06-18	14:50:59	39°40′	118°19′	4.3	S_1C_1
1989-07-23	03:15:09	37°22′	115°02′	4.3	Q_1
1989-10-05	11:55:35	39°37′	118°15′	4.2	S_1C_1
1989-10-18	22:57:23	39°57′	113°50′	5.7	$H_1^1L^1S^1Q^1$
1989-10-18	23:29:59	39°57′	113°50′	4.2	H_1
1989-10-19	00:52:55	39°57′	113°48′	4.2	H_1
1989-10-19	01:01:34	39°57′	113°49′	6.1	$H_1^1L^1S^1Q^1$
1989-10-19	01:09:43	39°54′	113°46′	4.0	H_1
1989-10-19	01:11:17	39°58′	113°49′	5.1	$H_1^1L^1S^1Q^1$
1989-10-19	01:26:26	40°00′	113°51′	4.4	H_1
1989-10-19	02:20:46	39°59′	113°52′	5.6	$H_1^1L^1S^1Q^1$
1989-10-19	05:02:03	39°55′	113°49′	4.4	H_1
1989-10-19	18:29:03	39°55′	113°44′	5.1	$H_1^1L^1S^1Q^1$
1989-10-20	01:56:48	39°56′	113°48′	4.1	H_1
1989-10-20	19:41:41	39°59′	113°54′	4.1	H_1
1989-10-23	21:19:32	39°55′	113°49′	5.2	$H_1^1L^1S^1Q^1$
1989-10-29	10:22:43	39°56′	113°49′	4.1	H_1
1989-12-09	07:04:51	39°53′	113°49′	4.2	H_1
1989-12-13	09:10:11	39°56′	113°53′	4.1	H_1
1989-12-14	12:13:01	37°36′	115°17′	4.8	L_1Q_1
1989-12-25	04:26:23	40°20′	118°57′	4.7	C_1
1989-12-31	16:24:48	39°58′	113°51′	4.0	H_1
1990-03-16	15:08:39	39°46′	118°27′	4.2	S_1C_1
1990-05-23	14:13:01	40°13′	116°28′	4.3	$H_1L_1S_1$
1990-07-21	08:41:51	40°35′	115°50′	5.0	$H_1^1L_1^1S^1Q^1$
1990-07-23	16:41:32	39°45′	118°29′	4.9	S_1C_1
1990-08-03	18:05:44	37°53′	115°02′	4.2	L_1Q_1
1990-09-22	11:02:19	40°05′	116°22′	4.5	$H_1L_1S_1$
1990-12-24	13:31:03	37°54′	115°01′	4.1	L_1Q_1
1991-01-29	06:28:04	38°28′	112°32′	5.5	H^1
1991-03-26	02:02:38	39°58′	113°51′	6.1	$H_1^1L^1S^1Q^1$
1991-03-26	02:07:27	39°59′	113°50′	4.3	H_1
1991-04-01	05:35:23	39°54′	113°49′	4.0	H_1
1991-05-07	00:25:01	39°48′	118°42′	4.3	S_1C_1
1991-05-29	19:02:10	39°43′	118°18′	5.2	$H^1L^1S_1^1C_1^1Q^1$

Table 3: (continued)

Date	Time	Latitude	Longitude	Magnitude	Remark
1991-05-30	07:06:55	39°41′	118°16′	5.6	$H^1L^1S_1^1C_1^1Q^1$
1991-07-11	19:05:05	39°41′	118°23′	4.3	S_1C_1
1991-07-27	17:54:47	39°51′	118°48′	4.4	S_1C_1
1991-08-21	05:28:28	37°20′	114°42′	4.3	Q_1
1991-08-22	06:23:37	37°28′	114°44′	4.1	Q_1
1991-09-02	04:17:42	38°49′	119°59′	4.1	C_1
1991-09-20	17:52:06	39°20′	114°05′	4.1	H_1L_1
1991-09-28	08:37:47	40°05′	117°03′	4.0	$H_1L_1S_1$
1991-09-28	18:48:06	40°04′	117°04′	4.0	$H_1L_1S_1$
1991-10-05	05:44:39	39°18′	117°57′	4.0	$L_1S_1C_1$
1991-10-07	07:25:21	37°56′	115°04′	4.1	L_1Q_1
1991-10-17	02:19:42	39°44′	118°25′	4.3	S_1C_1
1992-02-14	17:08:43	39°46′	118°26′	4.4	S_1C_1
1992-07-22	05:43:02	39°17′	117°56′	4.9	$L_1S_1C_1$
1993-06-14	03:01:00	37°25′	119°56′	4.1	C_1
1993-08-30	07:27:59	39°54′	113°49′	4.1	H_1
1993-08-30	08:13:38	39°54′	113°49′	4.0	H_1
1993-09-27	15:44:16	39°39′	118°42′	4.0	S_1C_1
1993-11-18	07:05:09	39°36′	117°27′	4.4	$L_1S_1C_1$
1994-10-04	15:54:17	39°44′	118°26′	4.0	S_1C_1
1994-12-23	13:13:40	40°28′	115°33′	4.3	H_1L_1
1995-06-27	09:39:51	38°14′	119°28′	4.0	C_1
1995-07-20	20:51:23	40°16′	115°26′	4.1	$H_1L_1S_1$
1995-10-06	06:26:53	39°40′	118°20′	5.4	$H^1L^1S_1^1C_1^1Q^1$
1995-11-13	14:33:19	39°22′	113°12′	4.5	H_1
1996-04-08	00:39:28	39°51′	118°44′	4.0	S_1C_1
1996-12-16	05:36:33	40°10′	116°30′	4.5	$H_1L_1S_1$
1996-12-16	09:52:24	40°06′	116°35′	4.0	$H_1L_1S_1$
1997-04-12	15:05:02	38°17′	120°29′	4.3	C_1
1997-05-25	14:59:08	40°42′	114°52′	4.7	H_1
1998-01-10	11:50:39	41°06′	114°18′	6.2	$H_1^1L^1$
1998-01-10	11:59:17	41°20′	114°32′	4.0	H_1
1998-01-10	12:09:58	41°06′	114°28′	4.5	H_1
1998-01-10	13:03:59	41°05′	114°30′	4.6	H_1
1998-01-10	15:38:18	41°09′	114°32′	4.2	H_1
1998-01-10	20:01:55	41°07′	114°26′	4.0	H_1
1998-01-10	21:50:32	41°11′	114°26′	4.3	H_1
1998-01-10	23:33:20	41°04′	114°25′	4.0	H_1
1998-01-11	02:37:47	41°05′	114°25′	4.6	H_1
1998-01-11	11:31:43	41°05′	114°26′	4.4	H_1
1998-01-12	02:41:54	41°08′	114°27′	4.3	H_1
1998-01-12	18:32:29	41°12′	114°28′	4.3	H_1
1998-01-14	01:17:26	41°04′	114°27′	4.2	H_1
1998-01-14	11:09:57	41°11′	114°31′	4.3	H_1
1998-01-17	10:41:18	41°06′	114°26′	4.3	H_1
1998-01-18	04:07:25	41°09′	114°22′	4.6	H_1
1998-01-18	06:17:54	41°07′	114°28′	4.3	H_1
1998-01-22	12:11:51	41°08′	114°26′	4.4	H_1
1998-01-27	07:29:07	41°02′	114°29′	4.2	H_1
1998-02-13	07:05:05	41°03′	114°27′	4.0	H_1
1998-04-14	10:47:48	39°41′	118°28′	5.0	$H^1L^1S_1^1C_1^1Q^1$
1998-04-14	10:48:06	39°41′	118°28′	4.4	S_1C_1
1998-04-16	07:13:44	41°05′	114°27′	4.0	H_1
1998-06-02	09:32:04	41°11′	114°24′	4.8	H_1

Table 4: Results from fitting models to the earthquake data

Station	N_P	N_S	N_E	k_p	$\log L$	AIC	Δk_p	$\log L/L_0$	ΔAIC
Trend model							-		
Huailai	2	-	-	2	-33.66	71.31	-	-	-
Langfang	1	-	-	1	-50.77	103.54	-	-	-
Sanhe	1	-	-	1	-56.67	115.34	-	-	-
Changli	1	-	-	1	-25.29	52.58	-	-	-
Qingxian	1	-	-	1	-54.52	111.06	-	-	-
Self-exciting model							vs. trend model		
Huailai	1	1	-	3	89.10	-170.22	1	122.76	241.53
Langfang	1	1	-	3	-22.77	51.55	2	28.00	-51.99
Sanhe	1	1	-	3	-39.98	83.96	2	16.69	-31.38
Changli	1	1	-	3	-23.11	52.22	2	2.18	-0.36
Qingxian	1	1	-	3	-42.23	90.47	2	12.28	-20.59
Externally excited model							vs. tend model		
Huailai	1	-	2	4	15.68	-23.35	2	49.34	-94.66
Langfang	1	-	2	4	-30.14	68.28	3	20.63	-35.26
Sanhe	1	-	2	4	-32.20	72.46	3	34.47	-42.88
Changli	1	-	1	3	-20.13	46.26	2	5.16	-6.32
Qingxian	1	-	2	4	-26.08	60.17	3	28.44	-50.99
Combined model							vs. Self-exciting model		
Huailai	1	1	2	6	100.86	-189.72	3	11.76	-19.50
Langfang	1	1	2	6	-8.70	29.40	3	14.07	-22.15
Sanhe	1	1	2	6	-15.83	43.66	3	24.15	-40.30
Changli	1	1	1	5	-17.67	45.34	2	5.44	-6.88
Qingxian	1	1	2	6	-22.65	57.31	3	19.58	-33.16

N_S: order of the Laguerre polynomial used for the self-exciting term; N_E: order of the Laguerre polynomial used for the external excitation term; k_p: total number of fitted parameters in the model; $\log L$: maximized log likelihood; AIC: as defined by (8); Δp: difference between the numbers of parameters in the two models for comparison; $\log L/L_0$: log likelihood ratio of the two models for comparison; ΔAIC: difference in AIC values between the two models for comparison;

Table 3: (continued)

Date	Time	Latitude	Longitude	Magnitude	Remark
1998-06-02	10:47:29	41°03′	114°30′	4.5	H_1
1998-07-14	18:16:08	41°06′	114°27′	4.4	H_1
1998-07-27	09:05:16	41°12′	114°29′	4.8	H_1
1998-07-27	09:16:56	41°06′	114°27′	5.0	$H_1^1L^1$
1998-07-27	11:17:48	41°10′	114°29′	4.7	H_1
1998-08-13	18:21:52	41°01′	114°35′	4.7	H_1
1998-08-15	18:11:22	38°38′	119°14′	4.4	S_1C_1

Table 5: Information gains per earthquake and per signal for each station

Station	Infogain/earthquake (cluster v Poisson)	Infogain/earthquake (combined v cluster)	Infogain/signal (combined v cluster)
Huailai	2.08	0.20	0.049
Langfang	0.36	0.18	0.038
Sanhe	0.22	0.28	0.091
Changli	0.10	0.25	0.130
Qingxian	0.20	0.33	0.072

The information gain means here the log-likelihood ratio, normalized by dividing by the number of earthquake events or the number of signal events.

Table 6: Comparison of intensities in the combined model.

Station	μ	Background	Clustering	Signals	$\int_0^T \lambda_E dt/N_S$
Huailai	0.3104	20.6%	50.8%	28.6%	0.071
Langfang	0.7601	57.2%	14.9%	27.9%	0.056
Sanhe	0.6814	53.4%	10.5%	36.2%	0.102
Changli	0.4143	48.1%	29.7%	22.2%	0.116
Qingxian	0.4084	37.3%	15.7%	47.1%	0.104

μ is the estimated background rate in events per 100 days; the next three columns give percentages of the total rate due to each term in the intensity; the final column is a rough indication of the number of predicted earthquakes per electric signal.

Table 7: Results from fitting models to the electric signals data

St.	N_P	N_S	N_E	k_p	$\log L$	AIC	Δp	$\log L/L_0$	ΔAIC
Poisson model							-		
Huailai	2	-	-	2	195.23	-386.46	-	-	-
Langfang	2	-	-	2	479.90	-955.79	-	-	-
Sanhe	1	-	-	1	135.76	-269.52	-	-	-
Changli	1	-	-	1	-21.12	44.25	-	-	-
Qingxian	1	-	-	1	162.32	-322.65	-	-	-
Self-exciting model							vs. Trend model		
Huailai	2	1	-	4	378.04	-748.08	2	182.81	-361.62
Langfang	2	1	-	4	741.20	-1474.40	2	261.30	-518.61
Sanhe	1	2	-	4	384.47	-760.94	3	248.71	-491.42
Changli	1	1	-	3	28.45	-50.90	2	49.57	-95.15
Qingxian	1	2	-	4	433.99	-859.98	3	271.67	-537.33
Externally excited model							vs. Trend model		
Huailai	1	-	3	5	221.16	-432.32	3	25.93	-45.86
Langfang	2	-	1	4	483.47	-958.95	2	3.57	-3.16
Sanhe	1	-	3	5	137.58	-267.16	4	1.82	2.36
Changli	1	-	1	3	-21.12	48.25	2	0.00	4.00
Qingxian	1	-	9	11	198.01	-334.01	10	35.69	-11.36
Combined model							vs. Self-exciting model		
Huailai	1	2	2	7	391.29	-768.59	3	13.25	-20.51
Langfang	2	1	1	6	741.20	-1470.40	2	0.00	4.00
Sanhe	1	2	1	6	384.65	-757.30	2	0.18	3.64
Changli	1	1	1	5	30.34	-50.68	2	1.89	0.22
Qingxian	1	2	2	7	434.56	-857.13	3	0.57	2.85

N_S: order of the Laguerre polynomial used for the clustering term; N_E: order of the Laguerre polynomial used for the external excitation term; k_p: total number of fitted parameters in the model; $\log L$: maximized logarithm likelihood; AIC: as defined by (8); Δp: difference between the numbers of parameters in the two models; $\log L/L_0$: logarithm likelihood ratio of the two models; ΔAIC: difference in AIC values between the two models.

Table 8: Fitting results from the ETAS model

Station	μ	K	c	α	p	$\log L$	AIC	AIC_l
Huailai	0.3346	0.002340	0.0001442	2.608	1.088	120.2	-230.4	-189.72
Langfang	1.008	0.006772	0.004906	1.012	1.200	-16.73	43.45	29.40
Shanhe	.8576	0.02022	0.0007426	0.3438	1.094	-35.64	81.28	43.66
Changli	0.7429	0.01807	0.01675	0.0000	1.423	-28.10	66.20	59.62
Qingxian	0.8161	0.005854	0.02902	0.2707	2.029	-42.32	94.63	57.31

AIC_l represent the AIC-values for the corresponding best combined model in Table 4.

Table 9: Training and evaluation

Sanhe			
	Training ($N_{EQ} = 49$) 1982.1.1 – 1989.12.31		Prediction ($N_{EQ} = 26$) 1990.1.1 – 1998.1.31
Model	$\log L$	AIC	$\log L$
Combined	0.87	10.26	-23.67
Self-exciting	-11.07	28.15	-31.20
ETAS	-8.99	27.98	-29.08
Poisson	-23.67	49.34	-36.01

Huailai			
	Training ($N_{EQ} = 23$) 1982.1.1 – 1990.12.31		Prediction($N_{EQ} = 36$) 1991.1.1 – 1998.1.31
Model	$\log L$	AIC	$\log L$
Combined	43.18	-74.35	48.18
Self-exciting	38.16	-70.32	48.54
ETAS	56.90	-103.80	60.37
Poisson	-10.59	23.18	-24.95

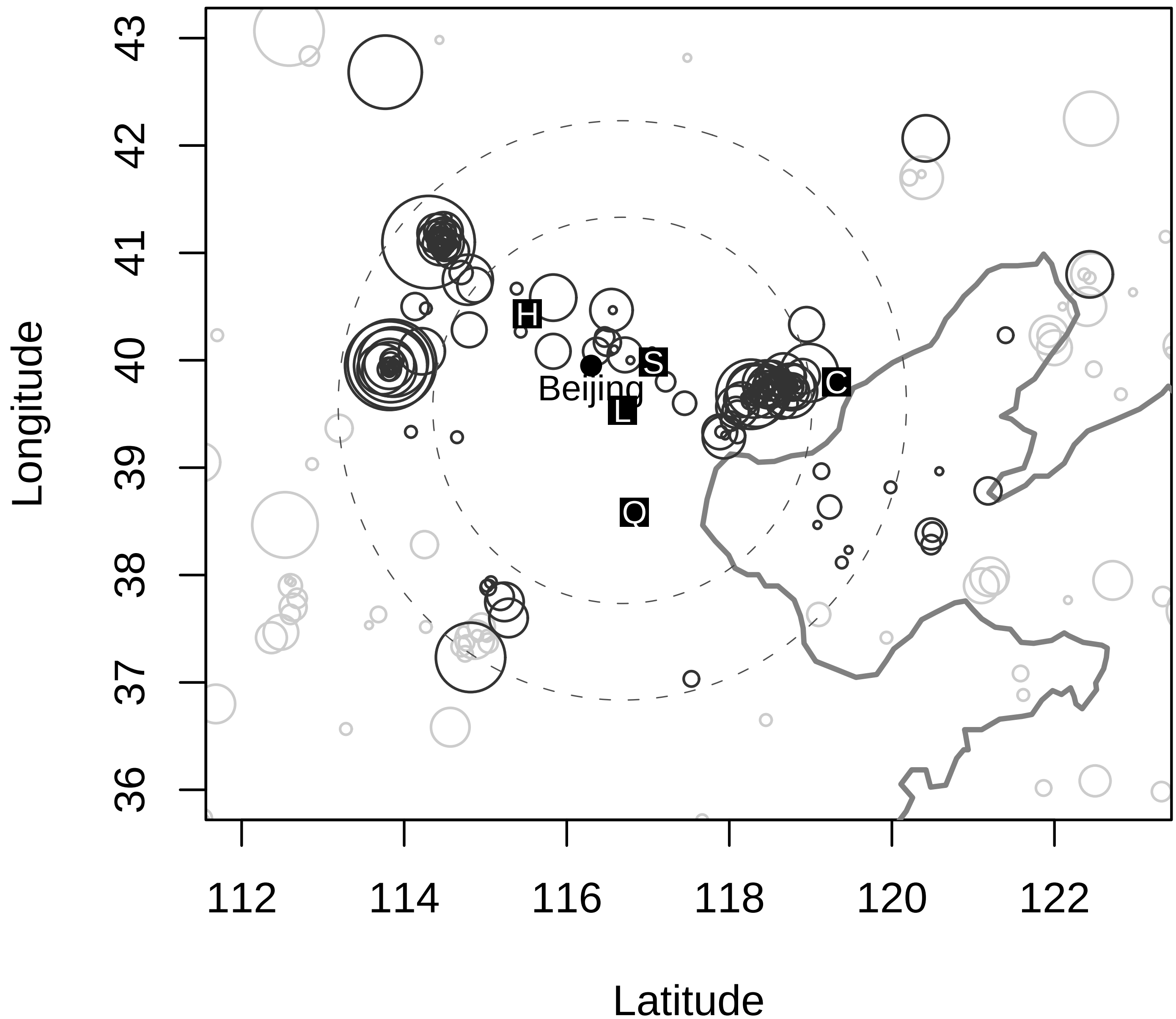
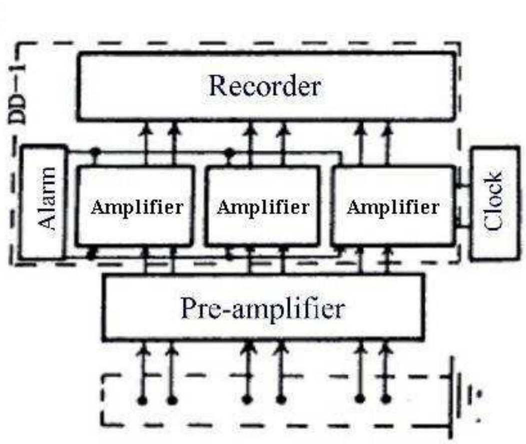


Figure 1: Distribution of earthquakes and electric signals observation stations around Beijing. Observation stations are denoted by black squares, with station initial inside. The two circles represent 200- and 300km circles around Lanfang station. Earthquakes are represented by small circles. The diameter corresponds to size of event, from $M_L = 4$ for smallest to $M_L = 6.7$ for largest. Dark circles denote events which fell within the observation region for at least one station; light circles denote other events with similar magnitudes. The Tangshan area is to the East, adjacent to the Changli station. The Datong and Zhangbei aftershock sequences are the clusters to the S.W and N.W. of Huailai station, respectively.

(a)



(b)

(c)

Figure 2: (a) A general circuit diagram for the observation equipment; (b) A photograph of the electrodes and the DJ-1 recorder. The body of the sensor of the electrodes is made of high quality Cr18Ni9C stainless steel. The water-proof pipe (white) will cover the whole screened transmission cables (black) when the electrodes are installed; (c) The DJ-1 recorder.

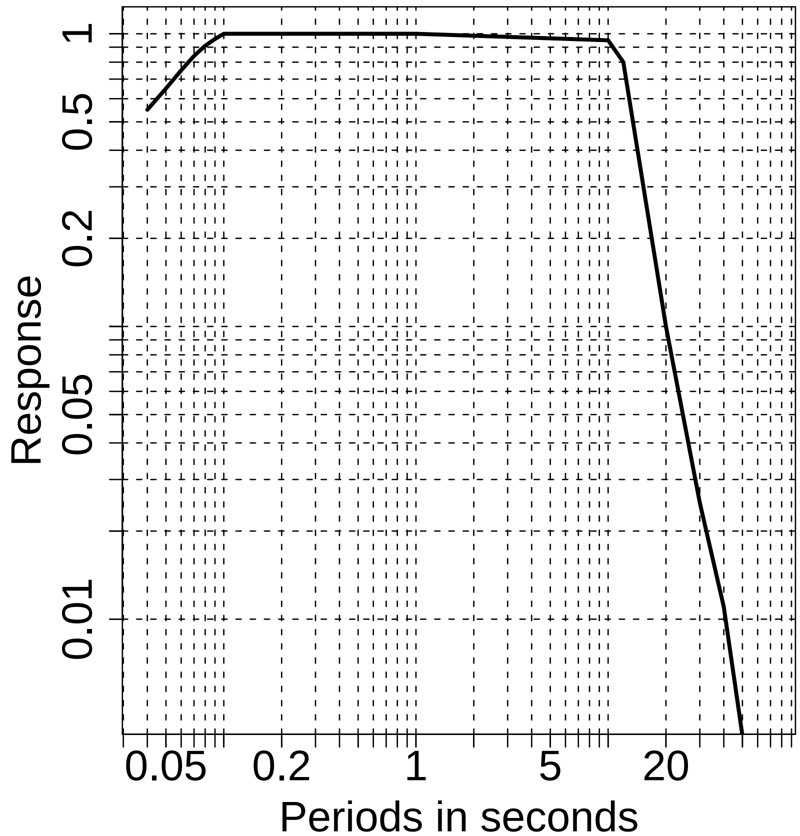


Figure 3: The observation system response function.

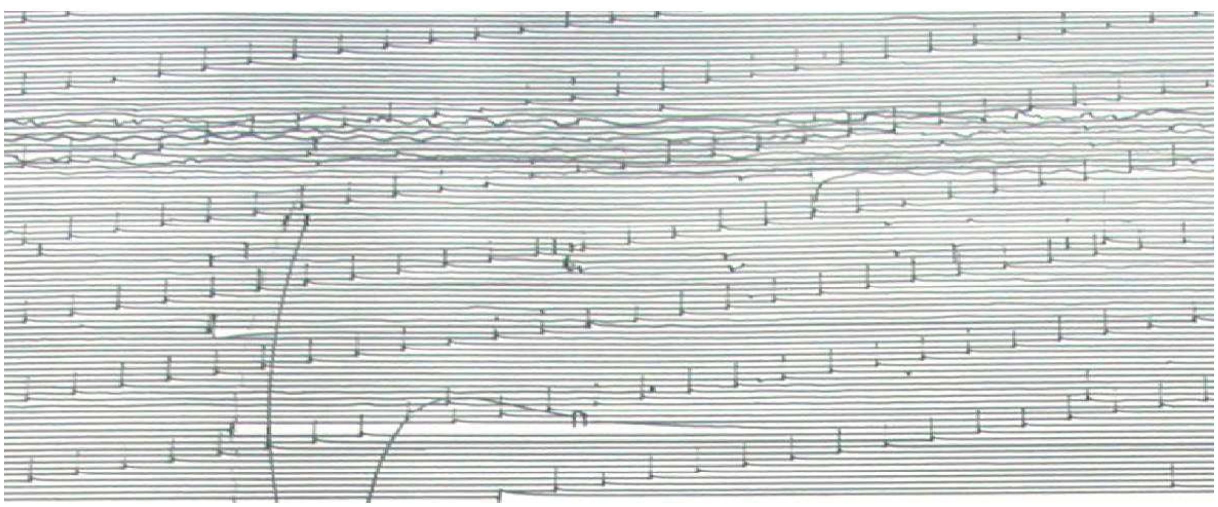


Figure 4: A photocopy of an original record. The fluctuations in the upper part of the chart are typical of the observed anomalous signals. The large pulse in the lower half of the chart is an example of a clearly distinguishable interference pulse, not included in the computation of the daily signal strength.

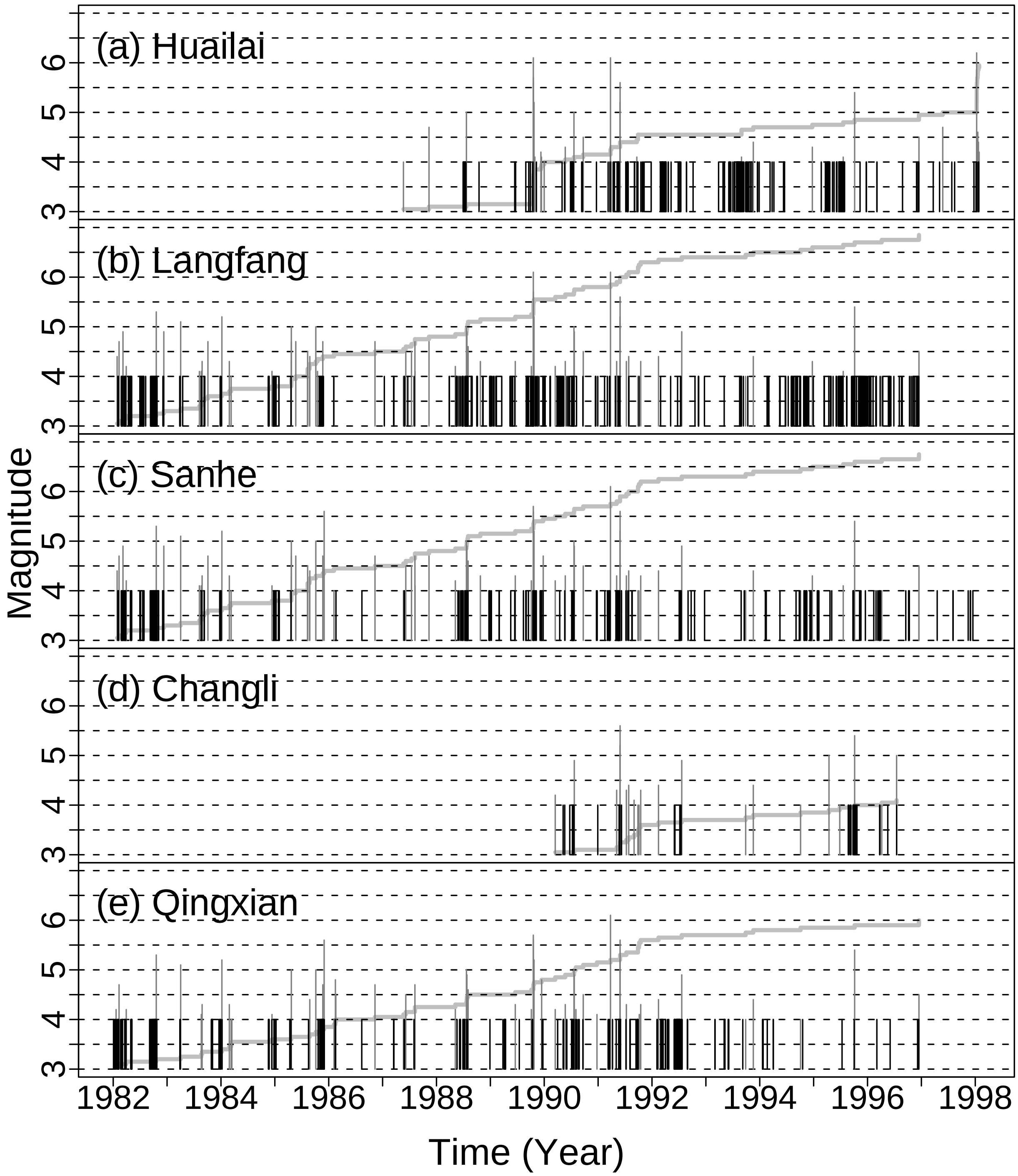


Figure 5: Electric signal data and earthquake data used in this analysis. Electric signals (ie days where 1 is recorded) are represented by heavy vertical lines reaching to M=4. Earthquakes are represented by thin vertical lines, the height corresponding to M_L on the left hand scale. Cumulative numbers of earthquakes are represented by the thick grey lines, scaled by the dashed horizontal lines from 0 to 80. Periods with no events recorded correspond to periods for which the stations were not operational.

(a)

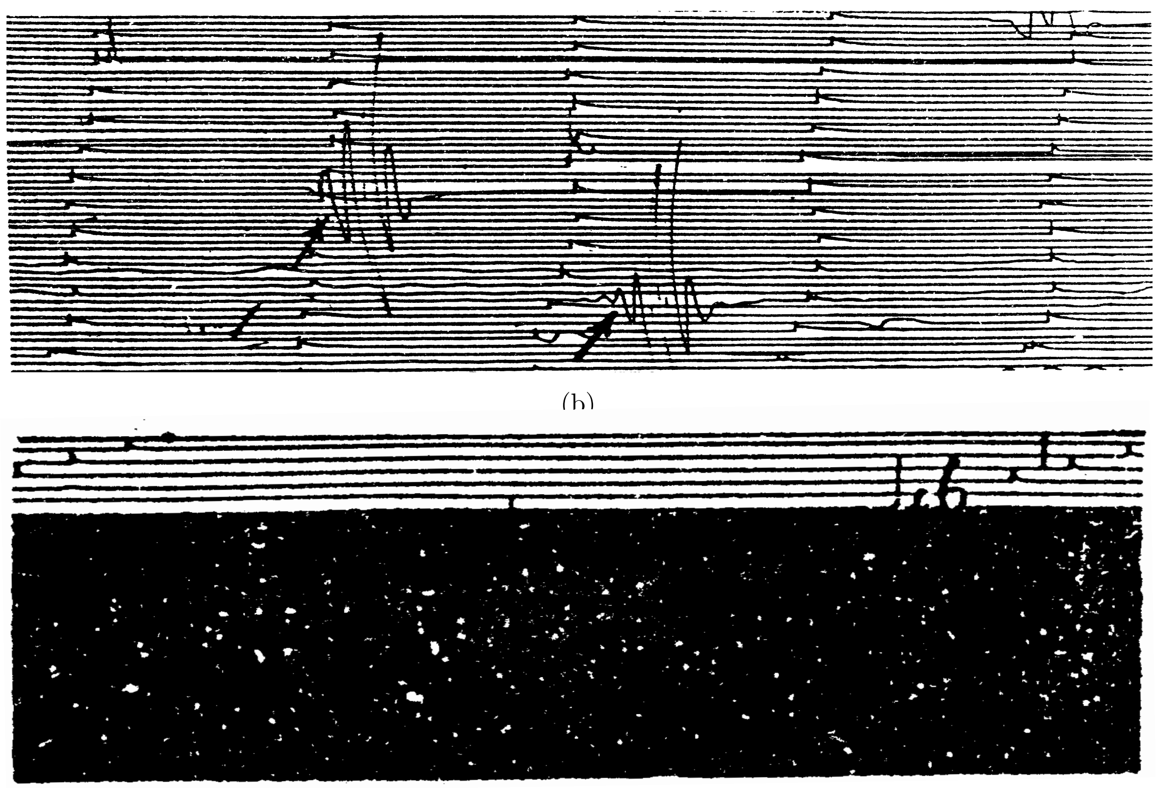


Figure 6: A photocopy of a record with noises (the upper panel) from ground strong lightnings and (the bottom panel) from electricity leaked by power lines. In the upper panel, the short vertical bars, which form up a line intersecting the horizontal line, are the timing marks at every minute, and irregular pulses caused by strong ground lightnings are marked by arrows. In bottom, the part in black represent the period of power leakage.

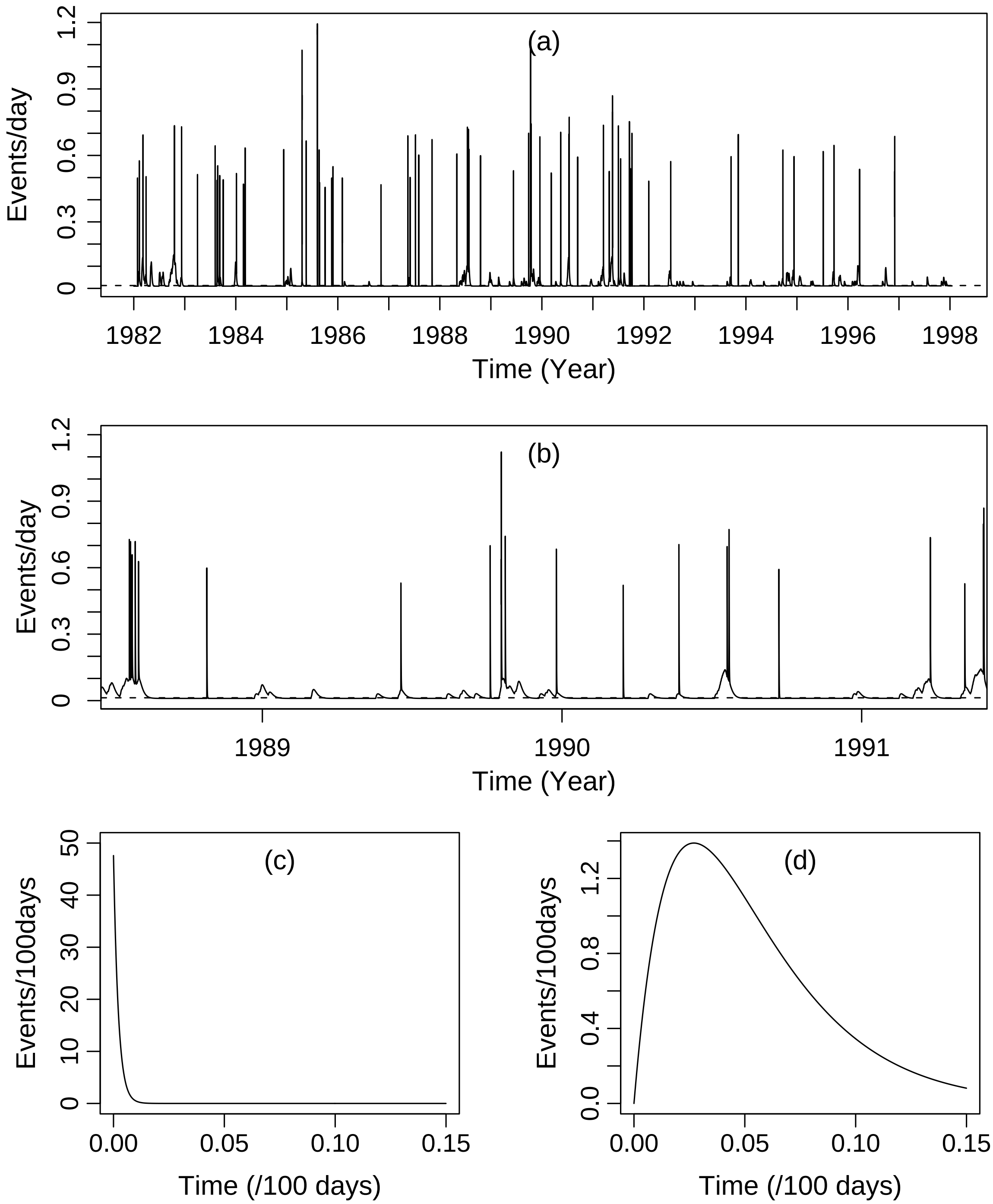


Figure 7: Fitting results for the earthquake data around the Sanhe station using the ULF electric signal events as explanatory factors. Top: Conditional intensity function throughout the whole time period; Middle: Conditional in a short period; Bottom left: impulse response from self excitation; Bottom right: impulse response from mutual excitation.

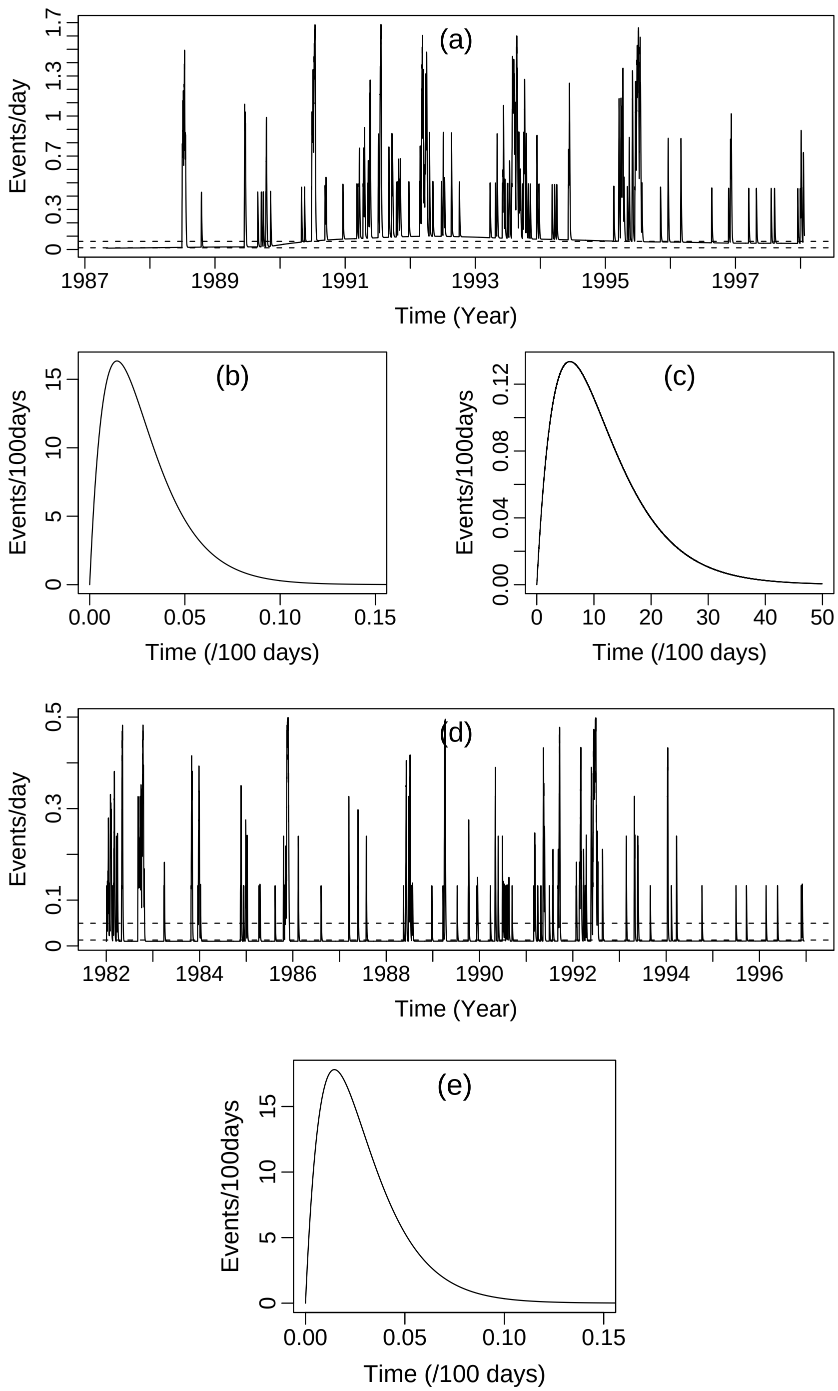


Figure 8: Fitting results for the ULF electric signal events from the Huailai and Qianxian station using the earthquake data as explanatory factors. (a) Conditional intensity function at Huailai station; (b) impulse response from self excitation at Huailai station; (c) impulse response from external excitation at Huailai station; (d) conditional intensity function at Qinxian station; (e) impulse response from self excitation at Huailai station (no response from external excitation because the model with only self-exciting terms is selected).

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Title:

Preliminary Analysis of Observations on the Ultra-Low Frequency Electric Field in a Region around Beijing

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ultra-low frequency electric signal; earthquake; precursor; self-exciting and mutually exciting model

Abstract:

This paper presents a preliminary analysis of observations on ultra-low frequency ground electric signals from stations operated by the China Seismological Bureau over the last 20 years. A brief description of the instrumentation, operating procedures and data processing procedures is given. The data analysed consists of estimates of the total strengths (cumulated amplitudes) of the electric signals during 24 hour periods. The thresholds are set low enough so that on most days a zero observation is returned. Non-zero observations are related to electric and magnetic storms, occasional man-made electrical effects, and, apparently, some pre-, co-, or post-seismic signals. The main

— *to be continued* —

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purpose of the analysis is to investigate the extent that the electric signals can be considered as pre-seismic in character. For this purpose the electric signals from each of five stations are jointly analyzed with the catalogue of local earthquakes within circular regions around the selected stations. A version of Ogata's Lin-Lin algorithm is used to estimate and test the existence of a pre-seismic signal. This model allows the effect of the electric signals to be tested, even after allowing for the effects of earthquake clustering. It is found that, although the largest single effect influencing earthquake occurrence is the clustering tendency, there remains a significant preseismic component from the electrical signals. Additional tests show that the apparent effect is not post-seismic in character, and persists even under variations of the model and the time periods used in the analysis. Samples of the data are presented, and the full data sets have been made available on local websites.