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Statistical Seismology: Physical and Stochastic Modelling of Earthquake Occurrence and Forecasting

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POSTERS_ABSTRACTS

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Residual Analysis for Space-Time Earthquakes Occurrence Models

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Point processes and probability theory allow to study in depth several aspects of seismological research, such as the definition of models describing space-time occurrence of seismic events, the simulation of seismic catalogs to better understand the real process, the definition of predictive strategies for the assessment of seismic risk.
A more realistic description of seismic events often requires the relaxation of the assumption of statistical independence of earthquakes. Therefore, since second-order properties of point processes, together with models that account for the complexity of data, may have a relevant role in the study and the comprehension of the seismic process and its realization, complex models process and features like self-similarity, long-range dependence and fractal dimension, are reviewed.
Second-order properties of point processes may have a relevant role in the study and the comprehension of the seismic process and its realization, together with models that account for the complexity of data.
When models describing earthquakes occurrence are fitted, residuals analysis is carried out to test the goodness of this fitting. Here a diagnostic method is proposed and applied to real data; it is based on a transformed version of second-order statistics, weighting the original point process by the inverse of its conditional intensity, so that features such as clustering and inhibition may easily be interpreted. Indeed, the null hypothesis model is an arbitrary conditional intensity model, rather than a stationary Poisson process.
The proposed diagnostic method is applied to seismic data and interpreted after estimating and fitting a particular space-time process (ETAS model – Epidemic Type Aftershocks-Sequences model) to seismic events.

Self-Similar Properties of Interevent Times and Distances of Earthquakes Around Marmara Sea, Turkey

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The main objective of the current study is to determine the patterns in the elapsed times and distances between the epicenters to obtain a statistical earthquake distribution model. The self-similar properties of above-mentioned parameters of the seismic events, which have occurred in the surroundings of Marmara Sea, are determined by taking the threshold magnitudes between 2.5 and 4.5. The changes in the scaling properties prior to and after large earthquakes are investigated and evaluated according to the faulting characteristics. The study is a part of the fractal modelling project with the number 585/14082006, which is supported by the Research Fund of Istanbul University.

Maximum Likelihood Based Declustering of Simulated and Observed Seismic Catalogs

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In previous works we proposed a clustering technique to separate and find out the two main component of seismicity: the background seismicity and the triggered one. We started from the hypotesis that a seismic catalogue is the realization of a non homogeneous poisson clustered process: the method assigns each earthquake to a cluster (of earthquakes) or to the set of isolated events according to the intensity function estimated by maximum likelihood methods and iteratively changing the assignment of the events; the process is iterated until there is no more improvement in the whole likelihood. The method and all the computational procedures needed for the practical implementation, has been improved in order to cover a wider number of situations, since the algorythm, specifically for the choice of some starting values, needs to be tuned for the particular catalogue. In the poster, besides some application to real catalogues, the results of some simulation are presented, used to asses the robustness of the procedure to departures from assumptions; especially for the simulation for Poisson clustered models or from ETAS models, and our method is compared with ETAS model estimation.

Dynamic Triggering of Aftershocks: Investigations in Different Catalogues

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Aftershocks are generally understood to be earthquakes that follow a larger event and are caused by static and dynamic stress perturbation of the earlier event. A recent study by Felzer and Brodsky (2006) of the decay of aftershock density with distance suggests that dynamic triggering is in fact the primary cause for aftershock occurrence; at least for small to moderate sized earthquakes. This controversial interpretation would have a number of important implications for earthquake forecasting related research as well as for the physical understanding of earthquake interactions; stress shadows and subsequent seismicity rate changes, for example, would not be commonly observed.

To address this important question we first of all re-investigate the dataset analysed by Felzer & Brodsky for California, also testing the sensitivity of the results to the input parameters and the data processing steps. We then analyse two high quality data sets from Japan: the JMA data since 1997, and the NIED data available for the Tokai and Kanto region for the period 1981 - 2005. The independence of the two data sets allows us to study systematic effects of location accuracy and completeness. Our final goal is to move towards the formulation of a testable hypothesis of triggering, to be implemented as a prospective test within the CSEP framework.

Universal Earthquake-Occurrence Jumps, Correlations with Time, and Anomalous Diffusion

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Spatiotemporal properties of seismicity are investigated for a worldwide (WW) catalog and for Southern California in the stationary case (SC), showing a nearly universal scaling behavior. Distributions of distances between consecutive earthquakes (jumps) are magnitude independent and show two power-law regimes, separated by jump values about 200 km (WW) and 15 km (SC). Distributions of waiting times conditioned to the value of jumps show that both variables are correlated in general, but turn out to be independent when only short or long jumps are considered. Finally, diffusion profiles reflect the shape of the jump distribution and are found to be independent on the magnitude, contrary to what the waiting-time distributions suggest.

Coulomb Stress Changes at Etna Volcano Calculated from Three-Dimensional Finite Element Model

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During the past decade, the application of Coulomb stress changes in tectonic areas has become a widely used tool to understand earthquake interaction. Recently, such studies have also been applied in volcanic areas, where the dynamics of volcanic processes involve high strain and stress changes in the surrounding rocks. The strong perturbations induced in the local stress regime can reach much larger values than the regional tectonic stress field. We investigated the complex interaction between magmatic intrusions and tectonic processes responsible for the kinematics of the seismogenic structures at Etna volcano during the intensive eruptive period from 2001 to 2006.
The medium heterogeneity and topography effect strongly alters the magnitude of the stress change, which is very sensitive to the variations in the rigidity crustal layers. Therefore, we used 3D Finite Element Model (FEM) to include both the irregular geometric and the complex tectonic structures for which analytical models are no longer applicable. Our findings show a very good correlation between positive Coulomb stress changes areas and earthquake locations. The estimate of the variations in the Coulomb stress together with a statistical analysis of the intercurrence times of seismic and volcanic crises at Etna could supply a quantitative esteem of the reactivation probability of the seismogenetic structures.

Worldwide Earthquake Doublets: How Do Mainshocks Influence Each Other?

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Recent analysis of seismicity rate variations after two earthquake doublets (the 1999 Izmit-Duzce sequence, and the June 2000 Icelandic doublet) lead us to the conclusion that far-field triggering of aftershock is very likely to occur, and could eventually be followed by a period of relative quiescence.

In addition, we have shown that aftershock productivity of a mainshock may be related to the time that passed since the last magnitude-equivalent event (see Daniel et al., in prep).

We thus investigate for such systematic behaviour of earthquake sequences from a global catalogue of seismicity. We aim at presenting correlation between inter-mainshock time, aftershock productivity and static vs. dynamic dominant triggering mechanism.

Properties of the Aftershock Sequence of the 1999 Mw 7.4 Kocaeli Earthquake: Implication for Aftershock Hazard

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The long-term probabilistic seismic hazard of Marmara Region has been investigated by Erdik et al. (2004) using time dependent and time independent models for specified levels of probability of exceedence over a long time period in the order of 50 years. However, a time-dependent “forecasting” approach to hazard assessment is also needed in order to respond to changing societal needs and emerging capabilities. Based on the short-term earthquake probability method (Gerstenberger et al., 2004), we expand the concept of a time independent hazard map by incorporating information about short-term earthquake clustering. In this study, we investigate the spatial and temporal seismicity parameters and the related probabilistic aftershock hazard for the aftershock sequence of the 1999 Mw 7.4 Izmit Kocaeli earthquake by using ZMAP (Wiemer, 2001). Using the catalog prepared by the NEMC - the National Earthquake Monitoring Center (formerly the Seismology Labotarory) of KOERI monitoring earthquakes in Turkey, we determine the earthquake size distribution (b-value), the aftershock decay rate (p-value) and the seismic activity rate (a-rate). The seismic parameters (a-, b- and p-values) are then estimated at each node and temporal changes of these parameters are mapped. From the modified Omori and Gutenberg-Richter laws, the rate of aftershocks is described (Reasenberg and Jones, 1989, 1990 and 1994).

Quantifying Early Aftershock Activity of the 2004 Mid Niigata Prefecture Earthquake (Mw 6.6)

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We analyse the early aftershock activity of the 2004 Mid Niigata earthquake, using both earthquake catalogue data and continuous waveform recordings. The frequency-magnitude distribution analysis of the Japan Meteorological Agency (JMA) catalogue shows that the magnitude of completeness of the aftershocks changes from values around 5.0, immediately after the mainshock, to about 1.8, twelve hours later. Such a large incompleteness of early events can bias significantly the estimation of aftershock rates. To better determine the temporal pattern of aftershocks in the first minutes after the Niigata earthquake, we analyse the continuous seismograms recorded at six Hi-Net (High Sensitivity Seismograph Network) stations located close to the aftershock distribution. Clear aftershocks can be seen from about 35 sec. after the mainshock. We estimate that the events we picked on the waveforms recorded at two seismic stations (*NGOH* and *YNTH*) situated on opposite sides of the aftershock distribution are complete above a threshold magnitude of 3.4. The *c*-value determined by taking these events into account is about 0.003 days (4.3 min). Statistical tests demonstrate that a small, but non-zero, *c*-value is a reliable result. We also analyse the decay with time of the moment release rates of the aftershocks in the JMA catalogue, since these rates should be much less influenced by the missing small events. The moment rates follow a power-law time dependence from few minutes to months after the mainshock. We finally show that the rate-and-state dependent friction law or stress corrosion could explain well our findings.

Statistical Analysis of the Time-Dependent Earthquake Occurrence and its Impact on Hazard in Low Seimicity Regions

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Standard seismic hazard analysis assumes constant temporal earthquake occurrence probabilities even though there is clear evidence that earthquakes are not random in time. Most known in this context are aftershock sequences following crustal earthquakes.

The goal of this work is to quantify the impact of non-Possonian earthquake occurrence on Probabilistic Seismic Hazard Analysis (PSHA) on different time scale. We study the so called short-term cluster as well as the long-term behaviour of the seismicity in order to estimate the most likely and the maximum possible impact of time-dependent earthquake occurrence for hazard estimation on different time intervals.

Probabilistic Modelling of Earthquake Occurrence: First Examples of Data Integration Within a Bayesian Framework

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Building upon our recent experience in the analysis and integration of isotropic creep experiments into numerical models of interseismic fault processes, we study creep under deviatoric stresses, and then perform time-forward simulations of interseismic fault behaviour. Given a shear loading rate and a rupture criterion, our model provides probability density functions for the time to failure and fault zone physical properties at the onset of failure. The first step in the forward modeling is the point-source model, in which we evaluate the robustness of the modeling results in response to uncertainties in the input parameters and alternative models for the creep law.
Our modeling framework addresses two big issues in seismic hazard assessment: the evaluation of the aleatory uncertainties and the reduction of the epistemic uncertainties (via model selection).
Current efforts also include extending the approach to study the relative influence of more complex simulations (with 2D to 3D faults), to provide a modular probabilistic "synthetic earthquake simulator". This will allow us to test the impact of different sources of heterogeneity in fault zone physical properties and loading conditions on the statistics of time to failure.

PI, RI and RTL: Three Earthquakes Forecasting Methods Applied to Moderate Earthquakes in the Northeastern Italy and Western Slovenia Areas

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In this poster, we present the performances of three earthquake forecasting algorithms, originally formulated to reveal the variation of seismicity patterns before large earthquakes, in the forecasting of 5 moderate-sized earthquakes with $MD \geq 4.1$, that occurred in the Friuli-Venezia Giulia region (northeastern Italy) and in western Slovenia. The algorithms proposed are the RTL (Region-Time-Length) algorithm (Sobolev and Tyupkin, 1996), that takes into account the temporal, spatial and magnitude variation of seismicity around the site of the future earthquake, the PI (Pattern Informatics) technique (Tiampo et al., 2001; Rundle et al., 2003), that is based on the study of space-time fluctuations of the number of earthquakes, and the RI (Relative Intensity) method (Holliday et al. 2005), that selects regions with higher seismic activity in a time period before the future earthquake. The performances of the methods are compared.

Dynamical Scaling in Branching Models for Seismicity

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We propose a branching process based on a dynamical scaling hypothesis relating time and mass. In the context of earthquake occurrence, we show that experimental power laws in size and time distribution naturally originate solely from this scaling hypothesis. We present a numerical protocol able to generate a synthetic catalog with an arbitrary large number of events. The numerical data reproduce the hierarchical organization in time and magnitude of experimental inter-event time distribution.

Applying Bayesian Inference to Correlating Hypocenters and Southern California Community Fault Model (CFM): Quantifying Spatio-Temporal Evolution of Background Seismicity

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We have applied the Bayesian inference approach of *Wesson et al.* (2003) to correlate hypocenters with individual fault segments of the Southern California Earthquake Center, community fault model (SCEC CFM 2.5). We analyzed the waveform relocated earthquake catalog from 1981 to 2005. We have included error estimates using the NonLinLoc method, which provides accurate Bayesian based error ellipsoids. The 3D distances from each hypocenter to the nearest 3D CFM fault segment were determined using GOCAD.
We have extended the method to include geologic slip-rates as additional prior information for determining a probability for each hypocenter to occur on a CFM fault segment. In general, small faults have higher productivity of small earthquakes than large faults. The San Jacinto fault system shows high association probabilities for many earthquakes because of the high rate of background seismicity and high slip-rate. In contrast, the San Andreas fault system has less earthquakes with high association probabilities. This is caused by a lower rate of microseismicity along the San Andreas, and the background seismicity appears to be more distant from the fault trace. The b-values associated with individual fault segments often decreases toward the fault implying that the large earthquakes are more likely to occur on the mapped faults. This also results in higher association probabilities for large earthquakes as compared to smaller ones. The results suggest that as faults evolve and accumulate a significant amount of slip, the rate of associated seismicity evolves from being high and focused on the primary fault trace, where large earthquakes occur, and in the close-in fault zone to a lower rate that is more diffuse and spread over a broader region.

Investigating Earthquake Patterns and the Effects of Fault Interaction Using a Cellular Automata Based Model

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Stress interaction between faults due to the occurrence of earthquakes has been shown to have a first order control on earthquake spatial and temporal patterns. We investigate the effect of interaction by using a fault network with individual faults modelled by discrete cellular automata. Complex nearest-neighbour transfer rules allow realistic stress concentrations to occur at the rupture front. If interaction between faults is allowed, stress is transferred to other faults using boundary element rules that allow minimum stress transfers of 0.1bar. Here we present results from a simulated fault network based on the active faults in the San Francisco Bay Area, California which is used to investigate the effects of interaction. For interacting and non-interacting models we compare magnitude frequency distributions and examine the recurrence behaviour of large events.

Estimation of Fault Plane Geometry Using a Bayesian Approach

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The geometrical properties of fault structures are important to many issues, including seismic hazard. The resolution of fault geometry at depth with waveform data is very difficult, and in many situations the only source of information are seismic catalogs, i.e. the origin times, magnitudes and hypocenter locations (with location errors) of earthquakes. In this work we discuss a method based on Bayesian inversion of catalog data to calculate the likelihood that the hypocenters in a given area reside on various narrow tabular zones. We scan the space of all possible zones by using a Hesse (normal form) representation of the possible fault zones. This allows us to compute an a posteriori probability density in the space of fault zones given the catalog data. An additional refinement of the method consists in using "an exclusion principle" where an earthquake prevents new events to happen for some time in a disk region with size related to the magnitude of the earlie r earthquake. The time dependency of this exclusion region models the healing and post-seismic stress increase of a slipping zone.

Analysis of the Data of Tangshan Deformation Station with the Statistical Model

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In China, besides seismology data, several kinds of data are applied for earthquake prediction, such as the data of geodetic, groundwater, geophysics, geochemistry, but many effect factors are consisted within the above observation results. The effect factors are caused from the measurement method, environment condition, weather factor, and so on. A statistical model is necessary for resolution the effect factors of the original observation data. The Tangshan deformation data are research example for the analysis and evaluation predictability of deformation data for Tangshan after shocks.

The Characteristic Earthquake Model vs. the Gutenberg-Richter Relationship

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We compared an occurrence rate of the characteristic earthquake(CE) with the seismicity around 98 major active faults and in nine interplate source regions in Japan to examine whether the G-R relationship or the CE model describes the magnitude frequency distribution well. The number ofobserved events turned out to be much smaller than the one expected from the G-R relationship in most cases. Moreover, we found a tendency that the larger an average slip rate is, or the shorter an average recurrence interval is, the larger becomes the magnitude gap.

Analysis of Earthquakes Correlations at Parkfield, California

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We present an analysis of time correlation and space-time correlation performed on earthquakes that occurred in the vicinity of Parkfield, California. We used the relocated earthquake catalogue of Thurber et al. (BSSA 2006). We first focused on earthquakes that occurred before the M6 28/09/2004. We show that the correlations found reflects some triggering process and analysed this triggering. We show that triggering occurs up to 2-5 km for times-scales less than 1 day. We also present analysis of the correlations found in the aftershocks sequence of the M6. Finally we present an analysis of earthquake recurrence time based on the selection of earthquakes cluster. We show that earthquake recurrence time at Parkfield do not obey the universal law of earthquake recurrence time found by Saichev and Sornette (*in press*) and are rather much more periodic.

Detecting Aseismic Stressing-Rate Changes Using a Combined ETAS/Rate-State Model

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Recent studies suggest that aseismic deformation triggers large amounts of seismicity [e.g., *Dodge et al.*, 1996; *Toda et al.*, 2002; *McGuire et al.*, 2005; *Hsu et al.*, 2006; *Lohman and McGuire*, 2007]. Therefore, this triggered seismicity can be used to detect changes in stressing rates caused by aseismic processes that are otherwise difficult to observe. In the rate-state model of *Dieterich* [1994], observed seismicity rates are integrated to obtain the stressing rates acting in a given space and time window [e.g., *Dieterich et al.*, 2000; *Toda et al.*, 2002]. However, these seismicity rates have three primary components: a coseismically-triggered component reflecting aftershocks, a background component reflecting long-term tectonic loading, and the aseismically-triggered seismicity rate of interest. In catalogs which are dominated by directly triggered aftershocks (i.e., branching ratios >~0.7), the coseismically-triggered seismicity rate will be much larger than the aseismically-triggered seismicity rate, making it difficult to isolate the aseismic stressing rate from the coseismic stressing rate. The ETAS model [*Ogata*, 1988] provides a natural separation of the aseismic and coseismic seismicity rates, as the ETAS parameter essentially reflects the aseismically-triggered seismicity rate (in addition to the background seismicity rate). Therefore, the ETAS model can be used to estimate the aseismically-triggered seismicity rate, which can then be integrated to obtain the aseismic stressing rate using the rate-state model. We are combining the ETAS and rate-state approaches into a data assimilation algorithm that will estimate not only the ETAS parameters but also the temporal evolution of the underlying state variables (stressing rate and in the Dieterich formulation). We will utilize it to map spatial and temporal variations in aseismic stressing rates from seismicity data. This tool can then be used to identify the space and time evolution of such aseismic processes as afterslip, fluid migration, or magmatic intrusion.

A Comparison of the Omori, Stretched Exponential and Band Limited Power Law Aftershock Decay Models by Maximum Likelihood Estimation of Simulated Sequences

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The Modified Omori Model (MOM) is the mostly used relation to describe aftershock rate decay, although it unreasonably predicts an infinite number of shocks when, as often occurs, the power law exponent p is lower than 1. A couple of alternative models proposed in the last decades, the Stretched Exponential (STR) and the Band Limited Power Law (LPL), resolve this problem by assuming that a negative exponential decay dominates at long times thus making the total number of aftershocks finite for any power law exponent. Such models are based on reasonable physical considerations but some previous analyses have shown that they are able to fit only a minority of real sequences better than the MOM. In order to strengthen the reliability of these comparisons, we first studied the relations existing among the parameters of the different decay models. To this purpose we defined two new parameters for the LPL, named t_b and t_a, which can easily compared with the delay time c of the MOM and the exponential decay relaxation time t_0 of the STR respectively. Analyzing synthetic sequences generated according to the MOM and the STR, we show that the maximum likelihood estimates of t_b and t_a well reproduce c and t_0 in most cases as well as, for most sequences generated according to the LPL, estimated c and t_0 reasonably correspond to the assumed values of t_b and t_a. We also show that when the assumed values of t_0 or t_a are definitely larger than the observed duration of sequence, the MOM satisfactorily reproduces the sequences generated as STR or LPL, but usually not better than the true model. This means that, for real sequences, there should be the possibility to identify the emergence of a negative exponential decay even in these cases. On the other hand, for lower t_0 or t_a, the fit of the MOM is poor and the estimated values of MOM p are definitely higher than the power law exponent assumed in the simulation. We can infer that high values of p (>1.5-2.0), actually observed in some real sequences, might be the deceptive result of the early startup of the negative exponential decay and of the interplay of p and c.

A Comparison of Gutenberg-Richter *b*-Value with Tectonic Deformation Style in the Mediterranean Area

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Some recent analyses, using available CMT catalogs, evidenced the existence of a relation between the Gutenberg-Richter *b*-value and the tectonic style of seismic release, both at a global (Harvard CMT) and a regional scale (California and Japan). In particular extensional mechanisms show higher *b*-values than compressive ones. In this work we attempted to verify such findings for the Mediterranean area using a different procedure. We first subdivide the area in small cells of equal size in each of which we compute an average mechanism as moment tensor sum of all available focal mechanisms. Then we group the cells with similar average mechanism and compute the *b*-value of each group basing on the data of available hypocentral catalogs. Focal mechanisms are taken from global and regional moment tensor catalogs (Harvard, INGV and ETH) as well as from an upgraded implementation of EMMA database, including more than 8000 focal solutions taken from the literature. Hypocentral data come from the ISC, with the moment magnitude consistently recomputed from various magnitude estimates. In agreement with previous analyses, we find higher *b*-values in areas with prevailing extensional style, lower values in compressive areas and intermediate values where strike slip mechanisms dominate. The *b*-value variations can be well described as a function of the rake angle γ by a sine law of the type

$$b = \overline{b} - \Delta b \sin(\gamma)$$

Regional differences of ETAS parameters in Japan

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In order to revise 'National Seismic Hazard Maps for Japan (2005)', regional parameter values of ETAS model were examined with the recent data and the background seismicity is compared to the ones expected in the map.

Rigorous Observational Tests of the Accelerating Moment Release Hypothesis

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Using data from California, Nevada, and Sumatra, we test the hypothesis that accelerating moment release (AMR) is a precursor to large earthquakes. Spurious cases of AMR may be identified by data-fitting because the time period, area, and sometimes magnitude range analyzed before each mainshock are often optimized to produce the strongest AMR signal. Optimizing the search criteria may identify apparent AMR even if no such physical process exists. For both California-Nevada and the 2004 M9.3 Sumatra earthquake, by data-fitting we can find two contradictory patterns in the data: AMR and decelerating moment release. We next compare the amount of AMR found in the real data to four types of synthetic catalogs and show that when realistic spatiotemporal clustering is included in the simulations, similar AMR signals are found by data-fitting in both the real and synthetic data sets even though the synthetic data sets contain no real AMR. These tests demonstrate that apparent AMR is a combination of data-fitting and the earthquake clustering such as foreshocks and aftershocks. Therefore, AMR has no more predictive power than existing forecasts that more directly (and optimally) utilize earthquake clustering (e.g. Reasenberg and Jones, Science, 1989, 1994; Gerstenberger et al., USGS-OFR 2004-1390). In principle, data-fitting could be avoided if the free parameters were determined from scaling relationships between the duration and spatial extent of the AMR pattern and the magnitude of the earthquake that follows it.

However, we demonstrate that these previously proposed scaling relationships are unstable, statistical artifacts of using a minimum magnitude for the earthquake catalog that scales with the mainshock magnitude. Some recent AMR studies have used spatial regions based on hypothetical stress loading patterns, rather than circles, to select the data. We show that previous tests contained a bias and that unbiased tests do not find this change to the method to be an improvement. Given the ease with which data-fitting can find desired patterns in seismicity, future studies of AMR-like observations must include complete tests against synthetic catalogs that include realistic spatiotemporal clustering.

Accelerating Seismicity Before Large Earthquakes and the Stress Accumulation Model

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Large earthquakes can be preceded by a period of accelerating seismic activity of moderate-sized earthquakes but this phenomenon has yet to be clearly understood. The recent Stress Accumulation model, based on the concept of elastic rebound, simulates accelerating seismicity from theoretical stress changes during an idealized seismic cycle. In this view, accelerating seismicity is simply the consequence of the decrease, due to loading, of the size of a stress shadow due to a previous earthquake. First, we show that a power-law time-to-failure equation can be expressed as a function of the loading rate on the fault that is going to rupture. We also show that accelerating seismicity occurs preferentially in the stress lobes predicted by the Stress Accumulation model. Second, we present a new methodology to extract accelerating seismicity from background seismicity and new statistics to test the robustness of the extracted accelerating patterns.

Completeness Magnitude for Switzerland and Japan

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A reliable completeness magnitude is vital for many seismicity and hazard related studies. We adopted a new method for determining a probabilistic magnitude of completeness (PMC), proposed by Schorlemmer and Woessner (2007) for California. PMC uses only empirical data (e.g., earthquake data, phase-picks, and station information) to estimate the probabilistic magnitude M_P. In order to check the applicability of PMC to regions of moderate to low seismicity, such as many European regions, we applied it to Switzerland. Using data that can be used for estimating M_P at Oct. 1, 2006, we found that M_P is above 2 in the areas close to the national boundaries while M_P is almost as law as 1.0 in the Valais area. We also evaluated the temporal evolution of M_P for the period 1983-2006 and compared the results with a study of the completeness based on detecting the point of deviation from a power-law distribution of earthquake magnitudes. Our results confirm the applicability of PMC to seismically less active regions. A next question is how our method is applicable to regions of heterogeneous seismicity like Japan. We will present results on M_P for Japan.

Real-Time Earthquake Forecast Using the ETAS Model

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Recent research associated with earthquakes forecasting has centered on investigating the spatial and temporal patterns in seismicity, and any anomalous seismic activity, such as quiescence and activation, can be identified with a significant deviation from the rate density.

Short-term occurrence rate of earthquakes in a region can be predicted using the ETAS model of clustered seismicity. The occurrence rate density, at any instant of time and any geographical point, is computed by the contribution of every previous events using a kernel function that takes in proper account: (a) the magnitude of the triggering earthquake, (b) the spatial distance from the triggering event, and (c) the time interval between the triggering event and the instant considered for the computation. The magnitude distribution adopted here is the Gutenberg-Richter law. Retrospective tests on real seismicity of Italy, California, Greece, Japan and comparison with a plain time-independent Poisson model through likelihood-based methods were made, proving the validity of this model.

In a recent practical application, a software package has been developed and implemented in a real-time test bed. The results are displayed as time-dependent maps showing both the expected rate density of Ml≥4.0 earthquakes and the probability of ground shaking exceeding Modified Mercalli Intensity VI in an area of 100 km^2 around the zone of maximum expected rate density in the next 24 hours. For testing purposes, the overall probability of occurrence of an Ml≥4.5 earthquake in the same area of 100 km^2 is also estimated.

We do statistical tests using the Molchan and Relative Operating Characteristic (ROC) error diagrams as commonly used to assess the skill of earthquake prediction. A few preliminary results are shown.

The seismic hazard modeling approach so developed is expected to provide a useful contribution to real time earthquake hazard assessment, even with a possible practical application for decision-making and public information.

Application of Poisson Hidden Markov Models on Foreshock Sequences

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Seismic events occurring in a particular area usually tend to be dependent. Thus, appropriate statistical models must accommodate this dependent structure. Poisson Hidden Markov Models (PHMM) have already been applied to data sets for the seismic areas of Athens (Central Greece), Samos (East Aegean Sea), as well as of Killini and Zakynthos (Ionian Sea). For each area, both Poisson rates and transition probabilities were estimated. However, these estimates remain constant for the entire period examined. We further propose the application of Hidden Markov Poisson Regression Models (HMPRM) with variable transition probabilities over time. In HMPRM the transition probabilities depend on covariates through a logit link function. We are particularly interested to examine whether b-value variations affect the transition probabilities and whether the model is able to detect seismicity patterns including variations that precede the mainshock occurrence, that is long-term and short-term foreshocks. We applied HMPRM to model monthly frequencies of earthquakes in the area of Killini. The results of HMPRM are compared to the results obtained by using PHMM and ordinary seismological statistics.

Fractal Approach to the Seismicity of Marmara Sea and Environs, Turkey

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The present work aims to contribute to a better understanding of the occurrence systems of earthquakes in the area of Marmara Sea and environs, by means of multifractals, b-value and p-value, using the data obtained from the web site of the Bogazici University Kandilli Observatory and Earthquake Research Institute (KOERI). Earthquakes in the investigation area are examined and contour maps of capacity dimension of active faults, information and correlation dimensions of epicentral distribution, b-value and p-value are prepared for time intervals of 0.5 days. Then correlations between these seismicity and scaling parameters are evaluated according to earthquake mechanisms and tectonic characteristics of the region.

Possibilities of Short-Term Earthquake Prediction from Foreshocks

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Earthquake statistics in many regions of the world indicates that short-term foreshocks precede only some mainshocks but not others. For example, in Greece at least 50% of strong mainshocks are preceded by foreshocks. Such a result, however, is based mainly in monitoring by national earthquake networks which produce standard catalogues with relatively high magnitude cut-off. The study of recent Greek sequences showed that small magnitude foreshocks, recorded only in one station, are missing and not introduced in the standard catalogue, which means that the percentage of mainshocks preceded by foreshocks certainly exceed 50%. On the other hand, the magnitude of the largest foreshock do not seem to depend on the mainshock magnitude, M, which implies that M may depend on other conditions, such as crustal heterogeneity (e.g. Abercrombie and Mori, 1996). However, foreshock sequences, when happen to occur, exhibit some characteristic properties which are important in the context of mainshock prediction. Firstly, foreshock activity develops in time intervals ranging from hours to a few months and accelerates before mainshock. Secondly the *b*-value usually, but not always, is lower than *b*-value in background seismicity and aftershocks. However, the *b*-value of foreshocks is systematically lower than the *b*-value of swarm activity. The combined evaluation of short-term seismicity acceleration in a particular area along with the significant change of *b*-value may be used as a potential precursory tool for the short-term prediction of the time and place of strong mainshocks. We discus recent characteristic cases of foreshock sequences in Greece and the progress in creating an automated system for the daily monitoring of seismicity variations with the early recognition of foreshocks in Greece.

Seismicity Changes in the SISZ, Iceland: Plate Tectonics or Inter-Event Triggering?

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A model of the stress field changes in the South Iceland Seismic Zone using 13 large events since 1706 investigates the relation between earthquakes with respect to the question if later events are triggered by shear or Coulomb stress changes induced by preceding ones. Despite taking into account plate tectonic, co- and post-seismic stress changes, no clear connection between two successive events could be found unless they occurred in the same sub-series.

Time-Dependent Hazard Through Nonparametric Bayesian Estimation of the Interevent Time Probability Density

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We assume that the hazard depends on the time elapsed from the last event. Though this is a simplification of the actual earthquake generating process and notwithstanding this approach is extensively applied, many issues are still open:

(a) the choice of the functional expression for the distribution of t - in fact standard distributions have not given completely satisfactory results;

(b) how to treat the outliers, and are some assumptions concerning, e.g., the unimodality acceptable?;

(c) the paucity of data - interevent times - satisfying the independence and identical distribution condition.

We propose an answer for each of these points:

(a) the maximum flexibility is obtained by assuming that the probability distribution is a random function belonging to a large function space, distributed as a stochastic process;

(b) non-parametric estimation method is robust when the data contain outliers or are far from normal;

(c) Bayesian methodology allows to exploit different information sources so that the model fitting may be good also for scarce samples.

The method has been applied to a subdivision of the Italian territory in macro-regions where the events with $M_w \geq 5.3$ are associated with the recognized seismogenic areas. Hazard maps are evaluated for different time horizons of forecast.

Time, Distance and Magnitude Dependence of Foreshocks in New Zealand: Real Data and Comparison to ETAS Models

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The possibility that a moderate earthquake may be followed by a larger one (termed the foreshock probability) can increase the hazard in its immediate vicinity for a short time by an order of magnitude or more. Thus, foreshock probabilities are of increasing interest for the development of time dependent seismic hazard forecasts. It has furthermore been suggested that foreshocks may follow the same statistics as aftershocks, i.e., that a foreshock is a "mainshock that happens to have a larger aftershock". If true, such an assumption would allow simpler calculations of earthquake probabilities, since the more numerous aftershocks could be used to determine the proper model parameters. The "ETAS" model is a popular version that uses such assumptions. Yet stochastic cluster models of Japanese catalogues suggest that foreshocks may behave differently from aftershocks, and some preliminary models of New Zealand (NZ) earthquakes suggested different behaviour of foreshocks and aftershocks. We re-examine these studies by determining maximum likelihood estimates of foreshock decay parameters in distance and time for both real catalogues in NZ, and synthetic catalogues fitted to the NZ and Californian catalogues using the ETAS model. We separate the NZ earthquake catalogue into events within and outside of the Taupo Volcanic Zone (TVZ). We use events with magnitude ≥4.0 and shallower than 40 km that are not aftershocks and that occurred between 1964 and 2003. We find: (1) The method of fitting makes a significant difference to the decay parameters determined; binning data in linear intervals before fitting returns more rapid apparent decay than fitting the unbinned dataset. (2) Using the parameters from the unbinned dataset, decay of foreshock probability in NZ with distance and time is similar to that measured in California by Felzer et al. and is similar to aftershocks (3) Differences between the TVZ and other areas are not as strong with the unbinned dataset. (4) The absolute values of foreshock probabilities are larger in the synthetic catalogues than in the real catalogues, but the decay with distance and time is similar in all catalogues. We are currently examining the possibility that the difference in absolute probabilities is caused by contamination in the declustered catalogues by aftershock sequences that are not fully removed in the routines used to determine foreshock parameters.

Physical Bases of Scaling Laws of Earthquake Physics Relevant to Seismic Hazard

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The physical bases for a variety of scaling laws from earthquake physics relevant to seismic hazard will be discussed, including: The probabilities of jumping fault segment stepovers relevant to cascading ruptures; Slip-length scaling laws relevant to moment budgets and repeat times of large events; and the coefficient of variation of large event repeat times and slip.

Numerical Modelling of Failure at Strike-Slip Faults: Interevent Times of Large Failure Events

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Numerical simulations using strike-slip fault models are performed to generate synthetic earthquake catalogues. Because available data of inter-event times at any existing fault are typically scarce (always less than ten events, but normally much less), the datasets from these simulations are used to check the fits of well-known statistical distributions (the gamma, lognormal, Weibull, and Brownian Passage Time). For a distinct dataset considerable differences exist for the fits. But if the fits for all datasets are compared, no favoured distribution exists everywhere. Since the checked distributions have very different behaviour in the short- and long-time range, this result can lead to uncertainties in time dependent probabilistic seismic hazard assessment.

Use of the Stress Tensor Field for Improving Short Term Earthquake Warnings, Examples from Iceland

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If the microearthquakes are recorded and analyzed the crustal stress tensor field can be estimated. When the stress field is known the locations of coming earthquakes are also known. This limits the volumes needed to monitore with short term EQ warning algorithms which reduces the false alarm rates. The very promising results from Iceland for the years 1992-2005 are presented.

b-Value Mapping of Fault Structures: Comparison of Two Different Tectonic Environments

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Local variations in spatial seismic b-value distributions can represent changes in the state of stress and/or material properties. This dual capability of b has been utilised in laboratory experiments and seismotectonic studies to infer fault structures that can influence rupture initiation and propagation. However, there are still open questions to what extent and at what time the seismic b-value reflects either material or stress heterogeneities and whether tectonic environments have an influence on this issue.

For the present study, two cases were available: the aftershock sequences of the Mw=8.0, 1995, Antofagasta subduction earthquake in Northern Chile, and the Mw=6.9, 1997, Cariaco-Casanay strike-slip event in North-eastern Venezuela. In both cases the b-value variations could be related to other seismological, geophysical and geological parameters. These correlations will be interpreted in terms of the imposed questions and first result show that in both environments high post-seismic b-values are present where material gradients are high as well.

A New Seismic Zonation Model for Switzerland Based on Synthetic Seismicity Distributions with Spatially Fractal Properties

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A critical step in the assessment of probabilistic seismic hazard (PSHA) is the accurate definition and characterization of relevant seismic sources. This is particulary challanging in low-seismicity regions, because seismicity is often diffuse and active faults are difficult to identify. For this reason, large areal source zones are commonly used, and the seismicity is uniformly distributed inside each areal seismic source zone. However, observed seismicity in seismogenic regions is generally not uniform, but clustered in space. In fact, seismicity is a classical example of a complex phenomenon that can be quantified using fractal concepts. In particular, fault networks and epicenter distributions are know to have fractal properties.
Preparing for the next generation of PSHA for Switzerland, we are trying to move towards a more realistic characterization of seismicity within each zone. Based on the work by Beauval (2006), we are evaluating the usefulness of fractal distributions of seismicity, instead of a uniform one. First, we quantify the potential impact of this assumption on PSHA in Switzerland by generating sets of synthetic spatial seismicity distributions, with different fractal dimensions and also with added noise in hypocenter distributions. We then measure the actual fractal properties of seismicity in the region, combine it with a description of the preferred orientation of faults and information of the prevailing stressing regime, and try to build a realistic regional zonation model.

Aspects of Seismic Risk Assessment in the Frame of a Non-Extensive Approach

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Seismic risk assessment is mainly estimated on the basis of scale-invariant (fractal) statistics of earthquakes, although their fractal character may be hidden behind the logarithmic definition of earthquake magnitude, leading to a power-law size distribution, where earthquake sizes are measured in terms of released energy.
In the present work some aspects of seismic risk assessment are discussed in the frame of the non-extensive model for earthquakes introduced by Silva et al., (Physical Review E, 73, 026102, 2006) and Sotolongo-Costa and Posades (Phys. Rev. Lett., 92, 048501, 2004). In the frame of this approach the role of the minimum and maximum event size and a fractal generalization of scale between earthquake energy and size of fragment is given.

Coulomb 3.0, an Interactive Tool for Studying Earthquake Interactions

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We have redesigned and ported the FORTRAN-based Mac OS 9 dislocation software, Coulomb 2.6, to multi-platform MATLAB environments for Windows, UNIX, Linux and Mac OS X, with enhanced 3D visualization capabilities, a more intuitive interface, and filters to access fault databases. Coulomb lets one calculate and display static displacements, strains, and stresses caused by fault slip, point sources of inflation, and dike expansion/contraction in an isotropic elastic half-space using the Okada (1992) formulae. Its principal features are ease of input, rapid interactive modification, and on-the-fly visualization of the results. Coulomb 3.0 uses a MATLAB GUI (Graphical User Interface) for menus, submenus, check-items, and dialogue boxes. The program lets users locate fault positions, cross-section and calculation points on the map by mouse clicks or input files. The new version also incorporates several ancillary programs that were formerly separated, to help make input files, taper fault slip, split a fault into sub-fault patches, and convert geographic fault positions into Cartesian coordinates. New overlay functions permit users to overlay coastlines, mapped faults, and earthquakes on the stress maps. This speeds publication-ready figures and illuminates spatial correlations between stress changes and seismicity. To encourage stress triggering studies, we will be developing subroutines for analysis tools such as ZMAP (Wiemer, 2001). Coulomb can now read complex fault datasets such as the 1400-patch USGS/CGS/SCEC California Reference Geologic Fault Parameter Database, the ETH database of finite-source ruptures models, and the Global CMT catalog. We hope this program supports research and classroom instruction for active faulting and volcanism. The application, user guide, and tutorial files can be freely downloaded from http://www.coulombstress.org.

Testing Short Term Probabilistic Seismic Hazard Forecasts in Terms of Ground Motion

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Seismic hazard models produce estimates of exceedance of ground motions that are expected within a certain return period. For long return periods, methods are being established that test the models' ground motion forecasts against actually observed ground motion data, e.g. precarious rock studies and long historical records of felt intensities. However, no such methods have yet been standardised for short-term forecasts. Most validation processes still concentrate on the model components, mainly the seismicity rate forecasting.
We present a basic approach to this new dimension of time-dependent seismic hazard forecasting validation, performing simple statistics to allow for a comparative analysis of ground motion forecasting successes from different models.
For the case study of New Zealand data, we compare the forecasts provided by the Poissonian-based National Seismic Hazard Model and the time-dependent Dynamic Seismic Hazard model based on clustering. We test the models in terms of the ground motion acceleration data that they forecast for every day over 40 years and for the locations of 156 strong motion instruments in the country and compare the forecasts to the 74 observed triggers of the recording stations. Preliminary results show a discrepancy between forecasts and observations for both models, with the models considerably underpredicting the observed hazard.

Having a methodology to test the forecasting performance on the level of expected ground motions in addition to the models' components will considerably improve the understanding of uncertainties in short term seismic hazard forecasting and allow insight into the origins of possible discrepancies. We hope to finally integrate the new approach as an additional procedure to the testing framework of CSEP.

How Does Volcano Seismicity Depend on Magma Transfers?

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The aim of this work is to investigate how volcanic seismicity is related to fluid movements within the volcanic edifice.

We analyse foreshock and aftershock sequences from catalogues of seismicity recorded at basaltic effusive volcanoes. In particular we analysed seismicity at Vesuvius (1972-2006, dormant), Piton de la Fournaise (2005-2006, 3 eruptions), Etna (1988-2001, 9 eruptions), Icelandic volcanoes: Krafla and Askja (1991-2006, one intrusion).

Starting from the null hypothesis that natural seismicity can be modeled by epidemic-type aftershock sequences, we compare volcano seismicity with ETAS synthetic catalogues. This procedure aims at estimating the relative role of earthquake interactions and volcanic processes in the triggering of volcano seismicity.

Preliminary results show that ETAS model succeeds in reproducing dormant state of volcano seismicity (e.g. Vesuvius activity and Icelandic volcanoes), while evidences of volcano-driven activity emerges as departures from ETAS predictions for the case of active volcanoes (Piton de la Fournaise and Etna volcano).

At active volcanoes we observe that, on average, foreshock rate increases ten days before the mainshock are much larger than those predicted by ETAS or tectonic seismicity. In contrast, aftershock rates are lower than expected. The power law increase in foreshock rates preceding mainshocks mimics the average power law acceleration recovered before eruptions at the same volcanoes which also starts on average ten days before the eruption. This result suggests that magma transfer drives the seismicity over a time window of at least ten days before eruptions or intrusions at basaltic effusive volcanoes.

Recurrence Time Distributions of Large Earthquakes on Individual Faults and Coupled Fault Systems

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The recurrence time distribution of large earthquakes in seismically active regions is a crucial ingredient for seismic hazard assessment. However, due to sparse observational data and a lack of knowledge on the precise mechanisms controlling seismicity, this distribution is unknown. We present a strategy of combining model simulations with observational data in order to estimate recurrence intervals between large earthquakes and the seismic hazard on individual faults. In particular, we focus on the treatment of sparse data with high uncertainties. Furthermore, we address the problem of fault interaction on the recurrence time distribution in a stochastic model of interacting faults. We present a parameter space study and compare the results for different realisations with analytical distributions, e.g. the Brownian passage time distribution and the Weibull distribution.

How Far Can We Trust Declustering Algorithms?

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Seismic declustering is widely used in statistical seismology and hazard assessment for removing aftershock sequences and for determining background seismicity. All declustering algorithms require setting of free parameters. For example, the widely used Reasenberg declustering algorithm has 8 free parameters and is often used with default parameter settings suggested by Reasenberg for Northern California. The lack of a unique statistical or physics-based definition of aftershocks leads to the fact that no general rules exist for correctly setting the free parameters, or in other words, no obvious metric for successfully identifying aftershocks exists. Often parameters are chosen based on the outcomes of declustering, turning the process upside down.
We perform a sensitively analysis to improve the understanding of the impact of declustering algorithms on commonly performed tasks, such as determining background activity and estimating the significance of seismicity rate changes. We apply different declustering algorithms to the ANSS catalog and to stochastic simulated catalogs which combine an assumed Poissonian background activity with Epidemic Type Aftershock Sequences.

Nonstationary Markov Processes in Phase Transition Modelling

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The geophysical and geological features of a seismic region determine the succession of the earthquake occurrences; we assume that their temporal variations produce state changes in the physical system. We model these temporal variations and, at the same time, the seismic sequence by a state-space model.
A state-space model is composed by two stochastic processes respectively called state and observed process. The state process drives the state changes of the physical system, while the observed process models the sequence of the earthquakes all through the stay in each state. We choose the observed process to be a point process such that its risk function has a different expression for each state.
In a previous preliminary study we defined the state process to be a homogeneous Markov process that is the transition probabilities from a state to another were constant in time. In the present work, we consider the state process to be a non-homogeneous Markov process and we investigate how to define time-dependent transition probabilities by exploiting the available physical knowledge.

Comparison of Two Earthquake Predictability Evaluation Approaches: Molchan Error Trajectory and Likelihood

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The Regional Earthquake Likelihood Models (RELM) working group has begun a collaborative earthquake predictability experiment involving a dozen five-year forecasts of earthquake occurrence in a California natural laboratory. The forecasts are probabilistic in the sense that they consist in expected number of earthquakes in space-time-magnitude bins. Statistical hypothesis testing of the forecasts is achieved via three scores based on likelihood. Earthquake forecasts that do not adhere to the RELM template cannot at this time be accommodated.

In order for the Collaboratory for the Study of Earthquake Predictability (CSEP) to succeed, it is desirable to expand the scope of predictability experiments; in doing so, additional evaluation techniques must be considered. We explore a score based on the Molchan error diagram, which plots miss rate versus the fraction of space occupied by alarms, and is commonly used to assess the skill of earthquake prediction methods using a single alarm set (i.e., one point on the error diagram). We supplement the point wise approach with a cumulative performance measure based on the normalized area under an error trajectory. We call this the area skill score; a score of unity indicates perfect skill and a score of zero indicates perfect non-skill.

Both the RELM and the Molchan error trajectory techniques incorporate statistical hypothesis testing and both can be applied to the five-year forecasts of California seismicity. We compare the two methods both conceptually and practically – that is, by examining the results of their application to over a dozen five-year forecasts and observed seismicity.

Problems with Magnitude Scale Conversions Based on Linear Regressions

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Recently a renewed interest has arisen on the old problem of magnitude scale conversions (Castellaro et al., 2006). When dealing with earthquake data that was compiled at different time stages, with different magnitude scales or from different station networks it is often necessary to deal with the problem of magnitude homogeneity. It is clear that any statistical analysis that is carried out on flawed data cannot yield results of significance. Nevertheless, many people still employ magnitude conversions without regard for the type of original observations which they stem from. The problem can be exacerbated when dealing with magnitude scales that are drawn upon incompatible measurements at a particular magnitude range. Such is the case, for example, with body wave magnitude and surface wave magnitude regressions at the M~4 level. In this study we compare relations obtained through direct linear regressions with those based on the frequency magnitude distributions via the *a* and *b* values. The idea is to provide a relation that preserves the same *b*-value as that of the most robust magnitude set. Results from different regions are compared and magnitude regressions for common magnitude scales are provided.