Competence Center Environment and Sustainability
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COGEAR: COupled seismogenic GEohazards in Alpine Regions

COGEAR

Module 2

Developing new approaches for time-dependent hazard assessment and forecasting

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Introduction

Developing of new approaches for earthquake forecasting and time-dependent hazard for the purpose of a better description of seismicity in and around the Swiss territory focused in the last months on developing and testing the applicability of short-term forecasting approaches to the low seismicity rates. Based on research in the framework of the EU-FP6 project Seismic Early Warning for Europe (SAFER, www.saferproject.org, Deliverable D5.6), we implemented a real-time Short-term Earthquake Probability (STEP) model for the Swiss territory in 2007. We tested this model against other short-term forecasting models on specific aftershock sequences (Woessner et al., 2011) and contributed two STEP-models versions to the forecasting experiment that started prospective testing of multiple 1-day forecast models on August 2009 for the Italian territory (Woessner et al., 2010).

For Switzerland, we tested further modifications of the STEP model. This document describes in Section 1 the current implementation and enhancements for the Swiss application, highlights some examples in different regions of Switzerland and elaborates in Section 2 on the calibration of model parameters for Switzerland, in particular for the abundance model (Christophersen and Smith, 2008; Christophersen and Gerstenberger, 2010). The abundance model is of particular interest because the parameter calibration for seismicity relations of aftershock sequences such as the Omori-law in low-productivity regions is most problematic in the development short-term time-dependent hazard models.

The current models can be used to forecast seismicity in a time-dependent hazard model for Switzerland. It needs to be noted that a STEP-LG model likely overpredicts and a STEP-NG (Abundance) model likely underpredicts the rate of events following a larger event in Switzerland – meaning events above $M \geq 2.8$. The models are implemented and retrospective tests have shown that the cumulative fit is acceptable, but that the productivity model may need to be revisited with a different abundance model. Both, forecast testing and investigating new functional forms for the abundance model are ongoing over the next year.

1 Near-real time time-dependent hazard maps for Switzerland

The STEP-model for the Swiss territory is implemented as real-time system beginning end of 2007. In its current implementation it is used since June 2008 providing 24h forecasts of seismicity rates and probabilities of exceeding ground shaking of EMS V or larger in the upcoming 24h. The forecasts are updated every half hour and a new system is tested that is tailor-made for the alarm system of the SED for earthquakes in and around Switzerland: the major difference is that more frequent updates of the hazrd maps will be computed during any triggered earthquake sequence while only every 24h a new maps is calculated in case of no relevant activity. The system relies on a regional implementation of the Short-Term Earthquake Probabilities (STEP, Gerstenberger et al., 2005; Woessner et al., 2010) model in which the spatial heterogeneity of aftershock sequences is translated in spatial and temporal heterogeneity of time-dependent hazard. Data and maps are archived and the latest map of probabilities are copied to the web-server of the Swiss Seismological Service for displaying the results. The web-site is restricted to scientists of the Swiss Seismological Service.

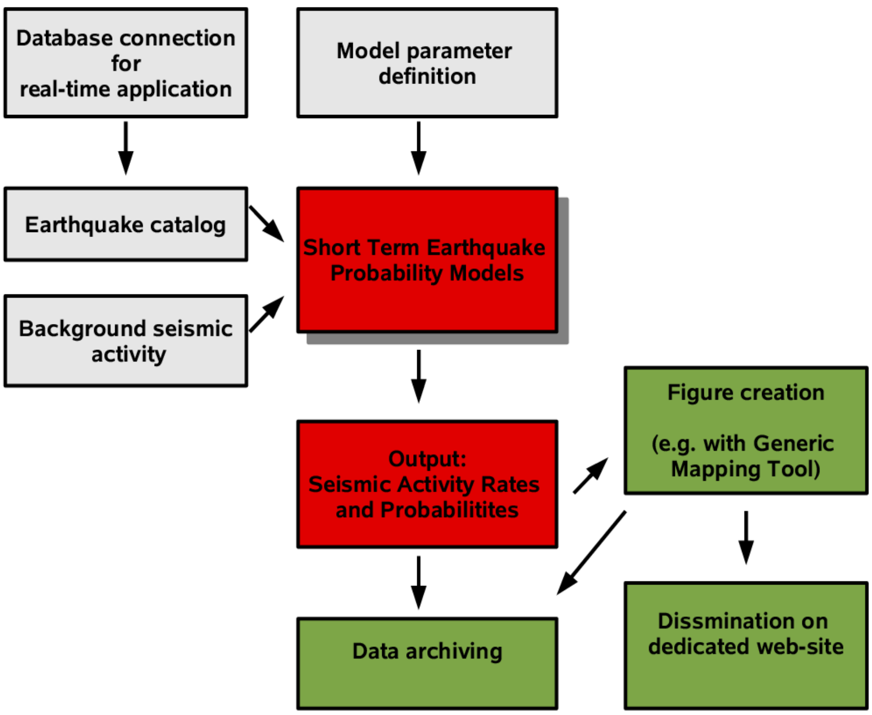


Figure 1: Sketch of the a STEP-system. Gray modules are preparatory elements, red indicates the computational moduls and output, green the dissemination and archiving modules of the system.

Technical requirements of the real-time system

We have implemented a system that is used for model developments and testing of new features until sufficient scientific credibility and computational stability of the results is obtained. A sketch of the program elements is seen in Figure 1. The crucial model computation is indicated by the red boxes in Figure 1. Generically, this is called Short-Term earthquake probability model which means that all types of models being able to forecast seismicity for short-time periods.

The system, implemented on Linux-machines at the SED uses the MATLAB software package for the computation of the hazard model. Data is drawn from the earthquake data base at the SED using either Perl or Python to query the SQL-database and deliver the updated catalog to the hazard computation. The programs are triggered via cron-jobs or from the alarm system (in future). Mapping of the results can be done with GMT software (Wessels, 1995, Version 4.1.4 or higher) and is now changing to use Mapserver on the web-portal implementation.

1.1 Examples

1.1.1 The Basel induced seismic sequence

As first example, Figure 2 shows a snapshot of a 24h forecast for an M_L=3.4 earthquake that occurred in the city of Basel due to a geothermal hot-dry rock experiment on 8 December 2008 at 4.48.39pm. Figures 2A and B show the probability of exceeding ground shaking of intensity EMS V within the next 24h before and after the event. Figure 2C and 2D display zoom into the Basel area without and with site amplification based on Kästli and Fäh (2009). While intensities are first calculated for a rock site, typical intensity amplifications of defined site classes are calculated from the median intensity residuals between observed and calculated intensities Kästli and Fäh (2009). In Figure 2D, we observe increased probabilities in the sedimentary valley of the Upper Rhinegraben, also slightly elongated in the directions of the valley. Additionally, the probabilities increase in the alpine foreland compared to the maps that do not include this information.

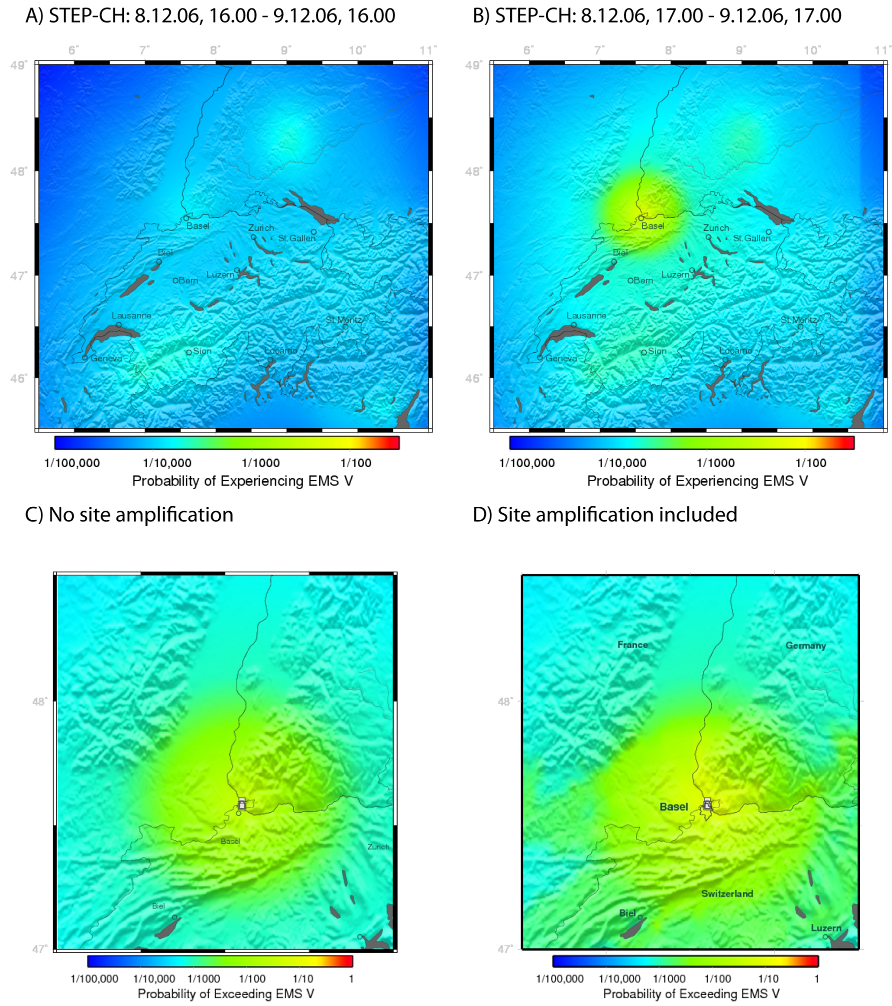


Figure 2: Snapshot of the Short Term Earthquake Probability model for Switzerland A) from 8.12.2006, 16.00 to 9.12.2006, 16.00, B) from 8.12.2006, 17.00 to 9.12.2006, 17.00 showing the Probability of Experiencing EMS V. C) Zoom to the Basel area for the period 8.12.2006, 17.00 to 9.12.2006, 17.00 without and D) with site amplification included (Kästli and Fäh, 2009).

1.1.2 The Vallorcine sequence in September 2005

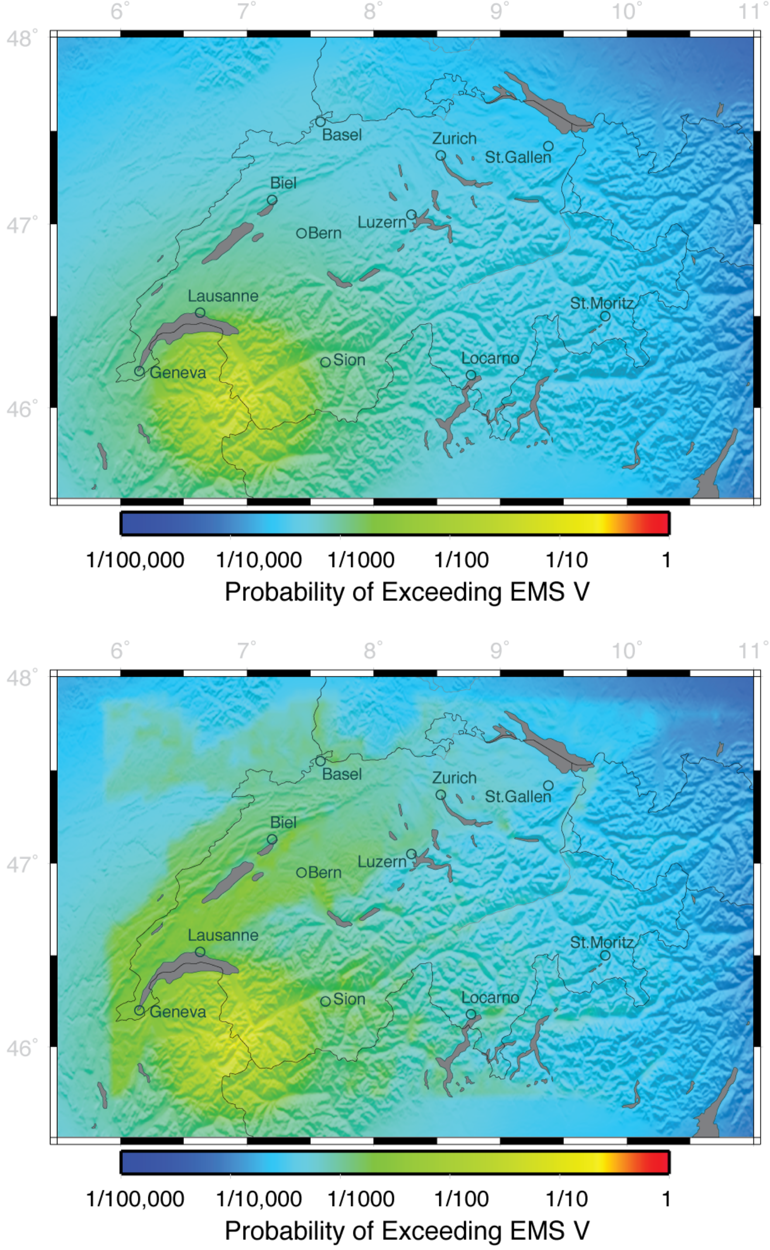


Figure 3: Snapshot of the Short Term Earthquake Probability model for Switzerland for the Vallorcine event on September 2009. Forecasts are shown for the period 09.09.2005, 0.00 to 10.09.2005, 0.00. Maps are shown without (Top) and with (Bottom) site amplification included (Kästli and Fäh, 2009).

Figure 3 shows the 24h forecast model for the 2009 September 8 ML=4.9 Vallorcine earthquake with (bottom) and without (top) site amplification based on Fäh and Kastli (2009). The figure shows that site amplification factors have a strong influence on the final spatial distribution of the expected hazard results and that these should be included.

1.1.3 The Sierre Sequence in 2009

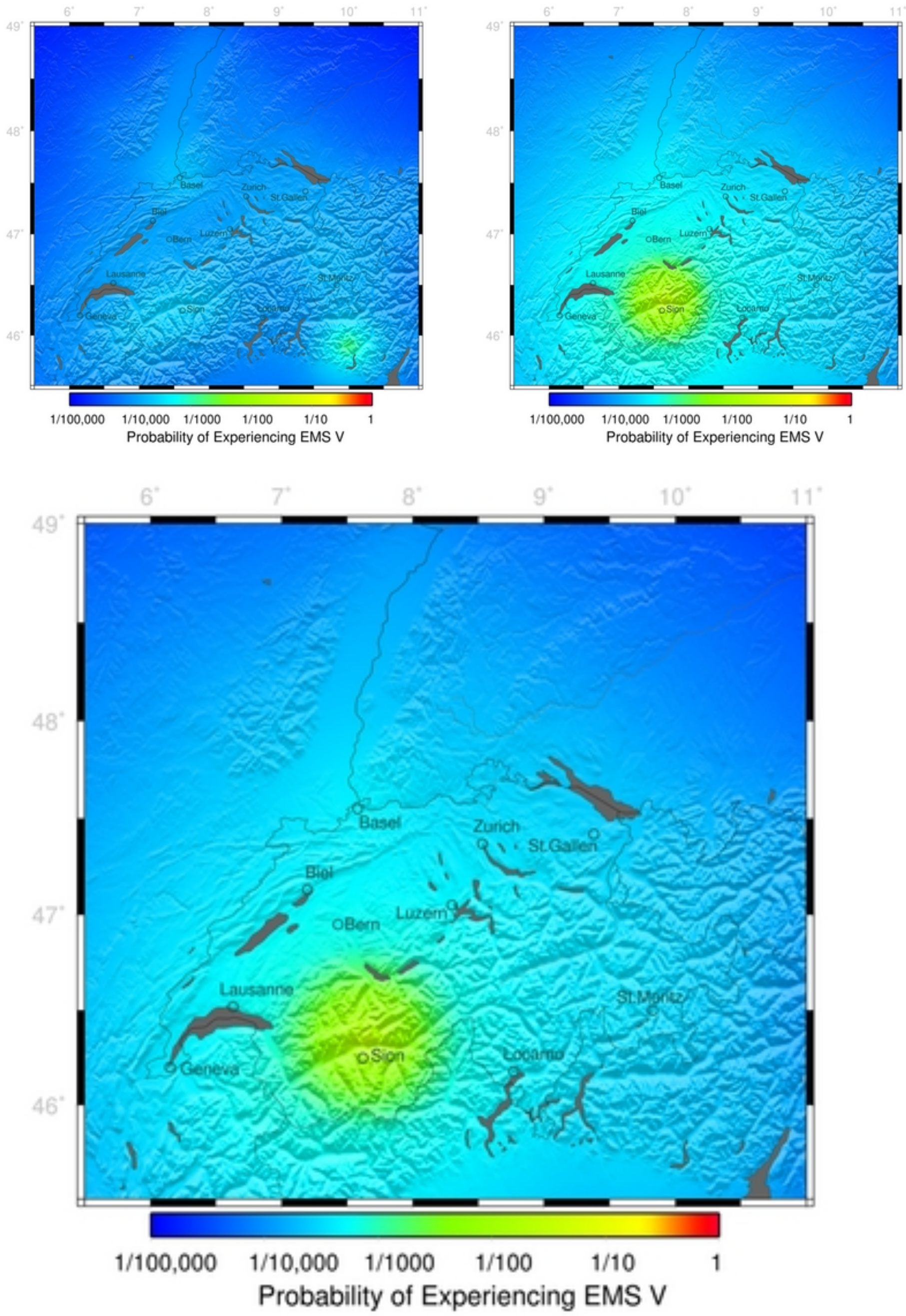


Figure 4: Snapshots of the Short Term Earthquake Probability model for Switzerland for the January 2011 Sierre sequence. (Top left) Forecast from 01.08.11, 21.00 – 01.09.11, 21.00, (Top Right) 01.08.11, 22.00 – 01.09.11, 22.00, , following the ML=2.4 event (Bottom) 01.08.11, 23.30 – 01.09.11, 23.30, following the magnitude ML=3.3.

The last example shows the performance of the STEP-model for swarm-type sequence of events that started on January 8, 2011 with a magnitude ML=2.4 event. Figure 4 shows the exceedance probabilities before the event and following the first ML=2.4 quake and the first ML=3.3 earthquake yet without the site amplification.

2. Deriving an abundance model for Switzerland

2.1 Introduction

The STEP-model in its current implementation for Switzerland using the generic parameters of California (Reasenberg & Jones, 1989, 1994) as well as those from Lolli & Gaperini (2003, 2006) lead to an overestimation of the observed events for the Swiss territory;

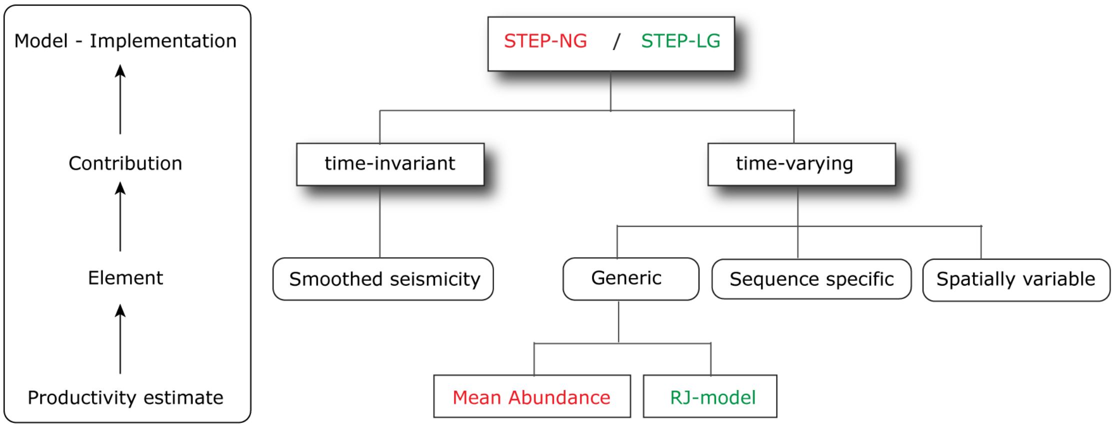
The STEP model includes a spatial extension of the simple aftershock model of Reasenberg and Jones (1989; 1990; 1994):

$$\lambda(\mathrm{t,M}) = \frac{10^{\mathrm{a'+b(M_m - M_{th})}}}{(t+c)^p} \quad (1)$$

where $\lambda(t, M)$ is the rate of aftershocks with magnitudes greater than magnitude threshold M_{th} and occurring at time t, Mm denotes the main shock magnitude. The constants *a'* and *b* are derived from the Gutenberg-Richter relationship (Gutenberg and Richter, 1944), and *p* and *c* result from the Omori-Utsu law (Utsu, 1961; Ogata, 1983). As aftershock sequences progress, model parameter values are re-estimated. The parameter *a'* is determined by equating the numerator of equation (1) to *k* and solving for *a'*:

$$a' = \log k - b(M_m - M_{th}) \quad (2)$$

it is therefore necessary to develop a model that characterizes the productivity of earthquake sequences differently. With the experience of developing models for the CSEP-Italy region, I apply the methodology of Woessner et al. (2010) to determine the abundance model based on data of the ECOS-09 catalog. Sketch 1 schematically describes that the Mean Abundance Model or New Generic model (indicated in red) basically defines the generic element of the time-varying model part. The generic parameters are used to forecast the rate of upcoming earthquakes in case the algorithm is not able to estimate sequence specific or spatially variable parameters for a sequence in real-time due to too small numbers of events in the sequence – this is the general case in particular for low-seismicity regions and thus it is especially important to define the generic parameter.



Sketch 1: STEP model hierarchy. The model implementations (STEP-NG/STEP-LG) are composed of model contributions (time-invariant/time-varying), which consist of model elements. The elements of the time-varying contribution were weighted using an AICc criterion [Gerstenberger et al. 2005]. The generic element can be based on the mean abundance model by Christophersen and Smith [2008] or the model by Reasenberg and Jones [1989] (RJmodel). For the latter, we used parameters determined by Lolli and Gasperini [2003] and Gasperini and Lolli [2006] (see Woessner et al., 2010).

2.2 Data

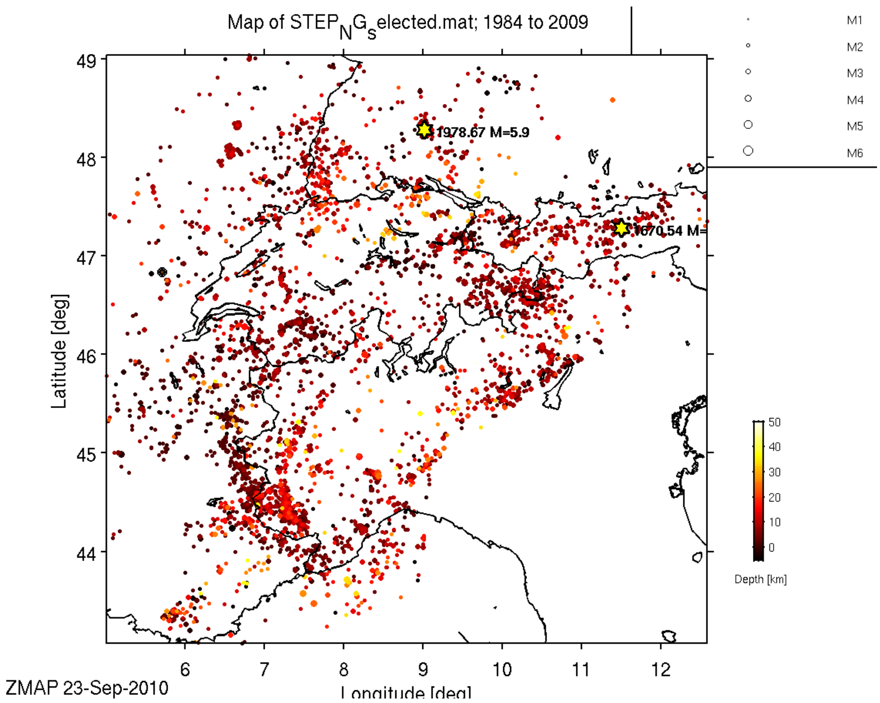


Figure 5: Seismicity map of selected events from ECOS-09.

We determine parameter values based on the ECOS-09 earthquake catalog (Fäh et al., 2010). The catalog is a compilation of national earthquake catalogs in which all instrumental earthquakes have either a local magnitude determined by the Swiss Seismological Service, ML(SED), or a converted ML(SED-conv) – this means the local magnitude has been converted to the ML(SED) using a linear regression technique (Fäh et al., 2010). This somewhat superficial step is necessary to enhance the data set available to fit the abundance model. The catalog is constricted to a region that comprises the territory for which the Swiss network provides acceptable location and magnitude estimates as well as extending into other regions which can be assumed to be similarly productive. We disregard seismicity from the Appenines to the South as this resembles a different tectonic regime and thus may lead to an overestimation of the productivity.

The seismicity map in Figure 5 shows data in the period 1984-2008 in the magnitude range ML ≥ 1.95, Figure 6 displays the cumulative number of events in this period as well as the frequency-magnitude distribution.

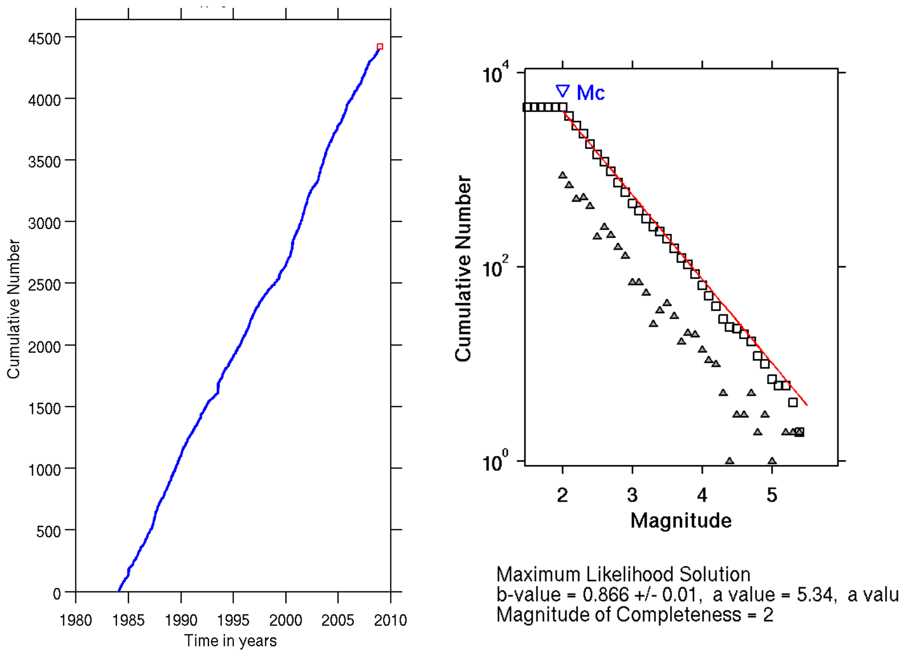


Figure 6: Cumulative number of events with M≥1.95 in the period 1984-2008 and accordingly the frequency-magnitude distribution.

2.3 The Abundance Model

Christophersen and Gerstenberger (2010) derived an alternative description for the average productivity as a function of main shock magnitude based on mean abundance, $N_{ma}(M_m)$, the mean number of aftershocks for a main shock with magnitude M_m. The mean abundance can be used to replace the Omori-law productivity k-value. The average productivity is derived from stacked earthquake sequences. For active tectonic regions the mean abundance in general grows exponentially with main shock magnitude M_m:

$$N_{ma}(M_m, M_{th}) = 10^{\alpha(M_m - M_1(M_{th}))} \quad (3)$$

where α is the growth exponent and $M_1(M_{th})$ is the magnitude that, on average, has one aftershock above the threshold magnitude M_{th} (Christophersen and Smith, 2008). The mean abundance can then be converted to the productivity *k*-value of the Omori-law (details see Woessner et al., 2010).

Mean abundance can be related to the Omori-Utsu *k*-value (Utsu, 1961; Ogata, 1983) by integrating over the time interval used to estimate mean abundance N_{ma}:

$$N_{ma} = \int_S^T n(t)\,dt = k(M_{th}) \int_S^T (t+c)^{-p}\,dt = k(M_{th})\, I_{OU}(S,T) \tag{4}$$

Here, S and T are the start and end times of the period analyzed, respectively. We call $I_{OU}(S,T)$ the Omori-Utsu integral with

$$I_{OU} = \begin{cases} \ln\left(\frac{T+c}{S+c}\right) & : \quad p = 1 \\ \frac{(T+c)^{1-p} - (S+c)^{1-p}}{1-p} & : \quad p \neq 1 \end{cases} \tag{5}$$

In the following sections we estimate the abundance model parameters taking into account the sensitivity to completeness levels and different periods as a short sensitivity test. I used selection parameters similar to the ones used for the Italian region. Event clusters where searched for in a time window of 10 days to find foreshocks and a period of 30 days for aftershocks. For fitting the mean abundance model, I define a lapse time of 0.1 days to compensate for completeness issues.

I use two completeness magnitudes at Mc=1.95 and 2.45 which is then also the minimum magnitude a main shock can have to trigger events. Parameter values for the abundance model are then estimated for different starting years (1984 and 1990) to cluster and fit the mean abundance parameters to check the sensitivity of the parameter estimation process.

2.3.1 Result assuming a completeness magnitude of Mc = 1.95

This completeness threshold is very optimistic and likely too low (Nanjo et al., 2010); however, since small magnitude events are occurring more often and since the threshold of the Swiss Digital network will be improved in terms of completeness, I did estimate values with this completeness threshold to find out the sensitivity of the estimated mean abundance parameters.

Figure 7 shows a map view of the clusters to understand which clusters are used to determine the parameter values. In addition, I separated the clusters in sequences with 5 and more events (red square) and sequences with 1-4 events in the cluster in addition to the main shock (green); grey squares display seismicity that is not clusterd. Clusters with this parameter selections are distributed over the entire region.

Figure 8 shows statistics from the data preparation to estimate the abundance parameters. Figure 8A shows the raw data for fitting, so the average number of aftershocks as a function of magnitude determined from the stack of clusters. Figure

8B shows the number of events of each cluster and Figure 8C a CDF of the cluster size, a different look at Figure 8B essentially.

Figures 9 and 10 then show the Alpha and M1 values from the fit as a function of mainshock magnitude when including clusters in the time window 1984-2008 (Figure 9) and 1990-2008 (Figure 10). Figure 10 is therefore based on less data but Mc is maybe more appropriate.

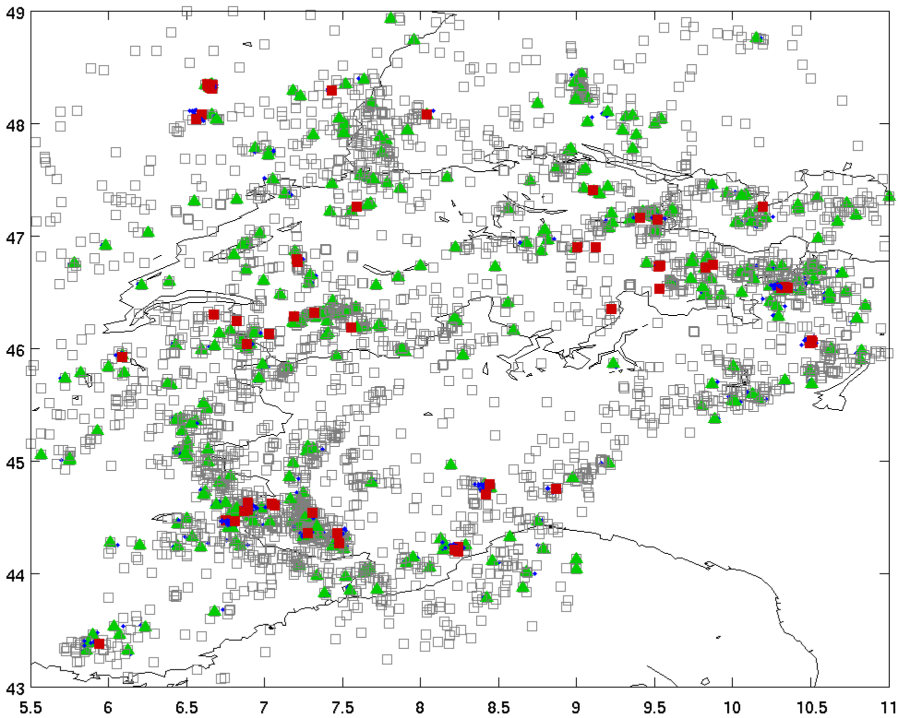


Figure 7: Map of seismicity (gray all events with M≥1.95). Mainshock with 1 to 4 aftershocks (green squares), main shocks with 5 and more aftershocks in red. Aftershocks plotted in blue.

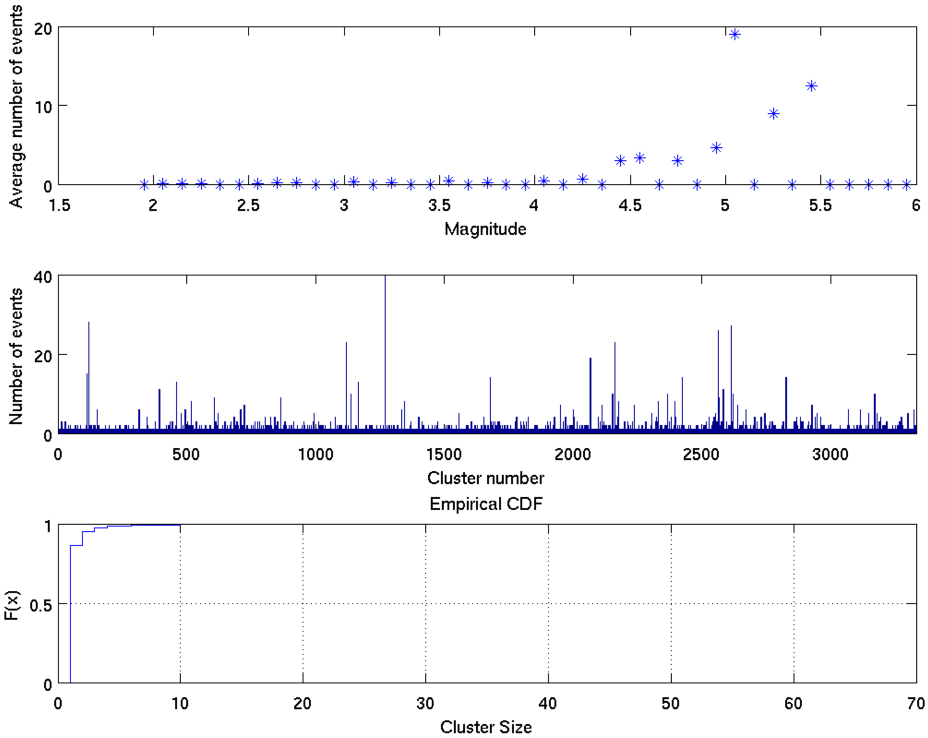


Figure 8: (Top) Average number of events as function of mainshock magnitude (from getMeanabu.m). (Middle) Number of events in cluster as a function of the cluster number. (Bottom) CDF of total number of events in cluster (=cluster size).

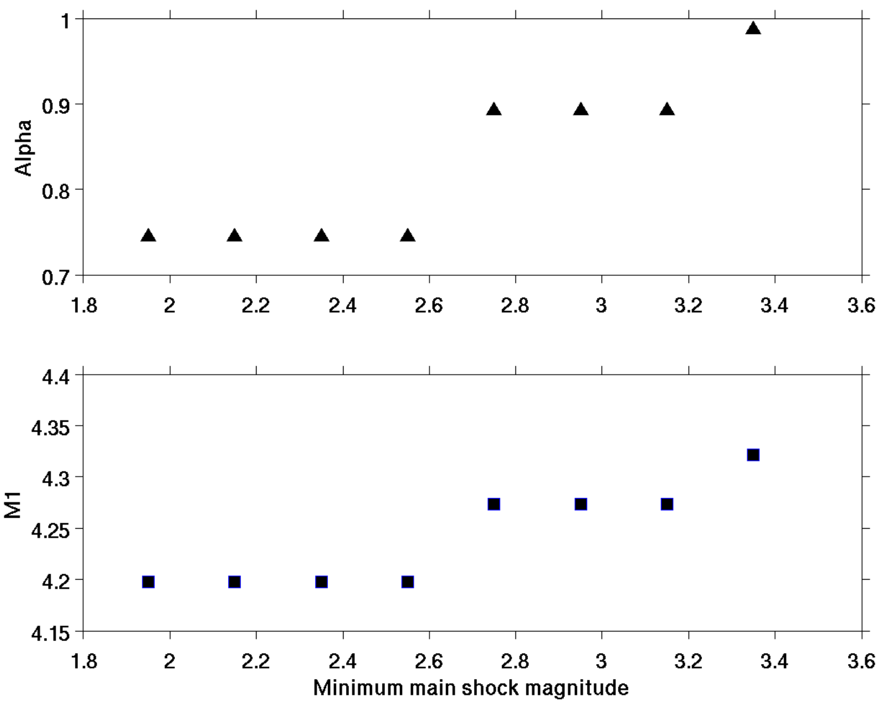


Figure 9: Mean abundance parameters Alpha and M1 for the period 1984-2008 as a function of increasing minimum mainshock magnitude. Mc = 1.95.

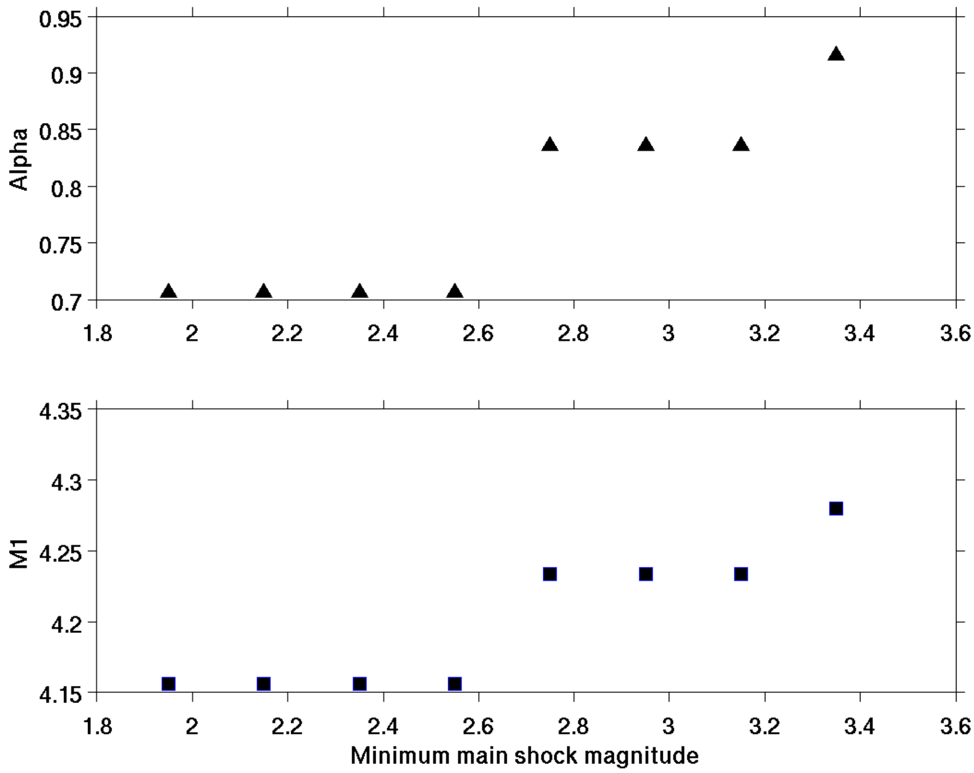


Figure 10: Mean abundance parameters Alpha and M1 for the period 1990-2008 as a function of increasing minimum mainshock magnitude. Mc = 1.95.

2.3.2 Results using a completeness magnitude of Mc = 2.45

Figure 11 shows a map view of the clusters to get an idea about the location (see caption). Figure 8 shows statistics from the data preparation to estimate the abundance parameters . Figure 12A shows the raw data for fitting, so the average number of aftershocks as a function of magnitude determined from the stack of clusters. Figure 12B shows the number of events of each cluster and Figure 12C a CDF of the cluster size, a different look at Figure 12B essentially.

Figures 13 and 14 then show the Alpha and M1 values from the fit as a function of mainshock magnitude when including clusters in the time window 1984-2008 (Figure 13) and 1990-2008 (Figure 14). Figure 14 thus is based on less data but Mc is maybe more appropriate.

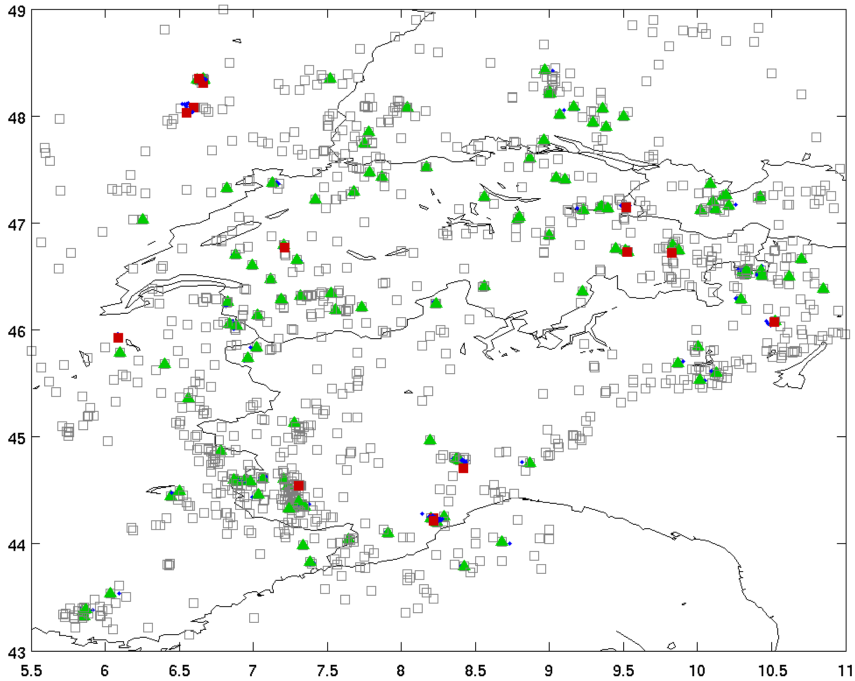


Figure 11: Map of seismicity (gray all events with M≥2.45). Mainshock with 1 to 4 aftershocks (green squares), main shocks with 5 and more aftershocks in red. Aftershocks plotted in blue.

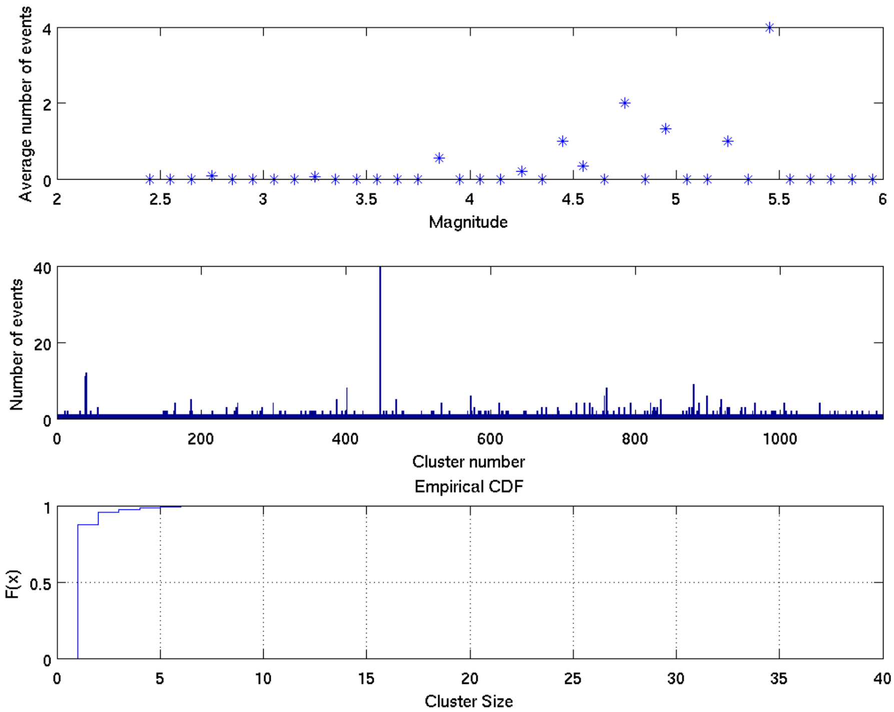


Figure 12: (Top) Average number of events as function of mainshock magnitude. (Middle) Number of events in cluster as a function of the cluster number. (Bottom) CDF of total number of events in cluster (=cluster size).

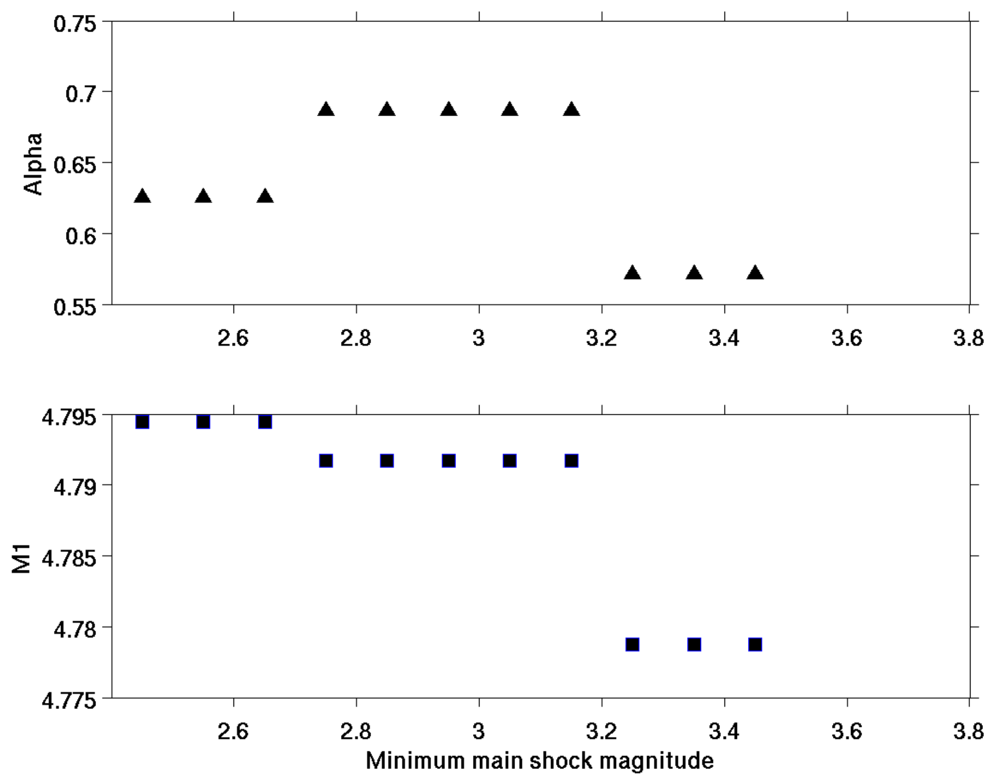


Figure 13: Mean abundance parameters Alpha and M1 for the period 1984-2008 as a function of increasing minimum mainshock magnitude. Mc = 2.45.

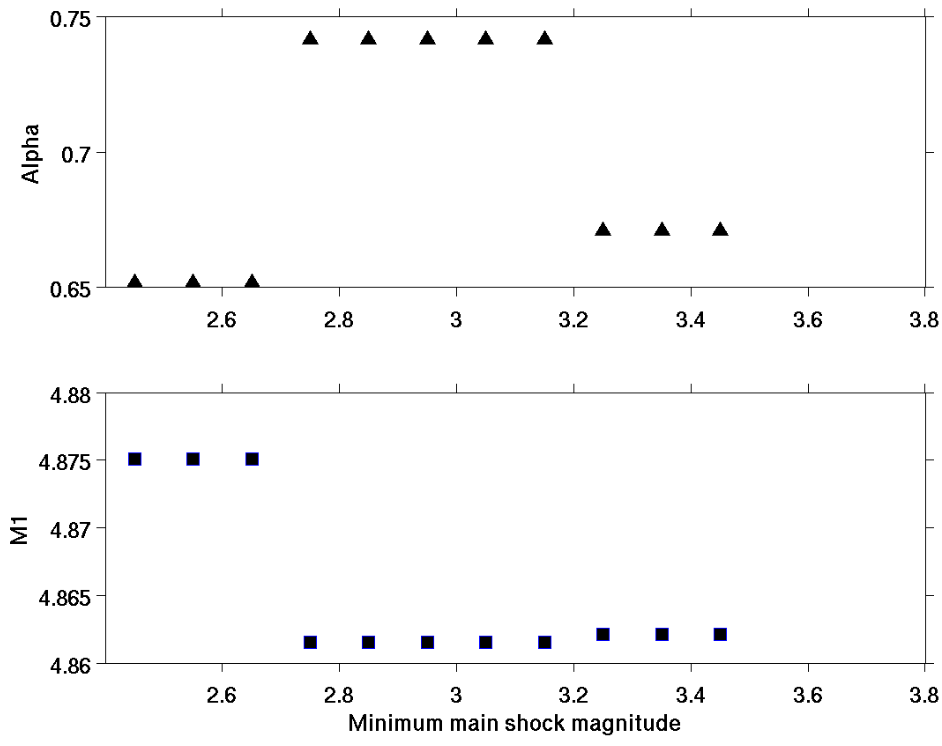


Figure 14: Mean abundance parameters Alpha and M1 for the period 1990-2008 as a function of increasing minimum mainshock magnitude. Mc = 2.45.

Summary

Based on the above sensitivity study for the parameters of the abundance model and considering the completeness level over the entire area, values seem to stabilize for the period starting in 1990 for a completeness of Mc=2.45 and a main shock magnitude of M=2.8. The study implies that the α-value ranges between 0.7-0.75 and M_l varies around 4.8. With this selection, we find the best parameters to be $\alpha = 0.74 \pm 0.34$ and M_l=4..86 ± 0.39 plotted in Figure 15. Table 1 lists all model parameter values and highlights the abundance model parameters (column (STEP-NG Abundance (Swiss Data)), the α-value and M_l.

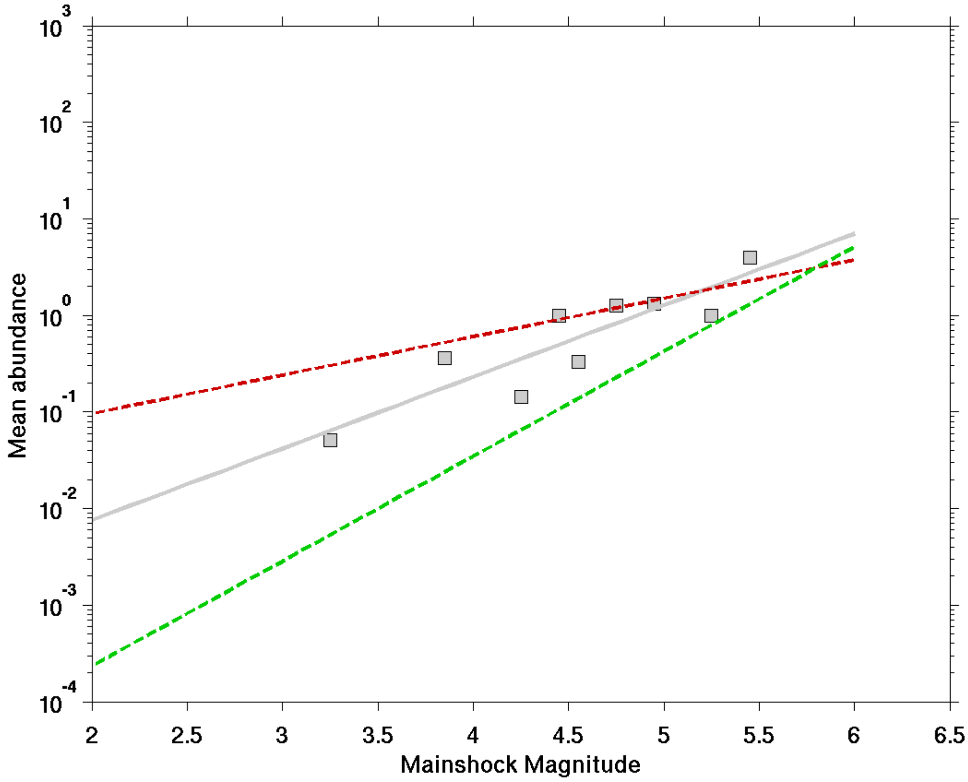
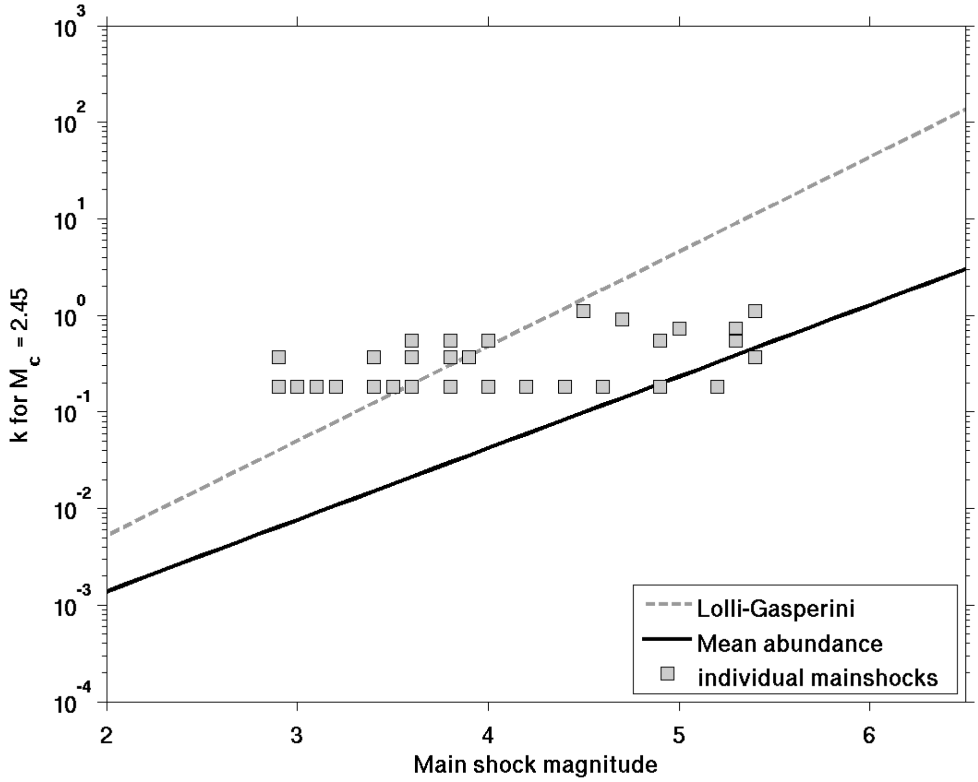


Figure 15: Abundunce model showing the expected number of events as a function of main shock magnitude. Red and green line show uncertainties, gray line the best fitting function.



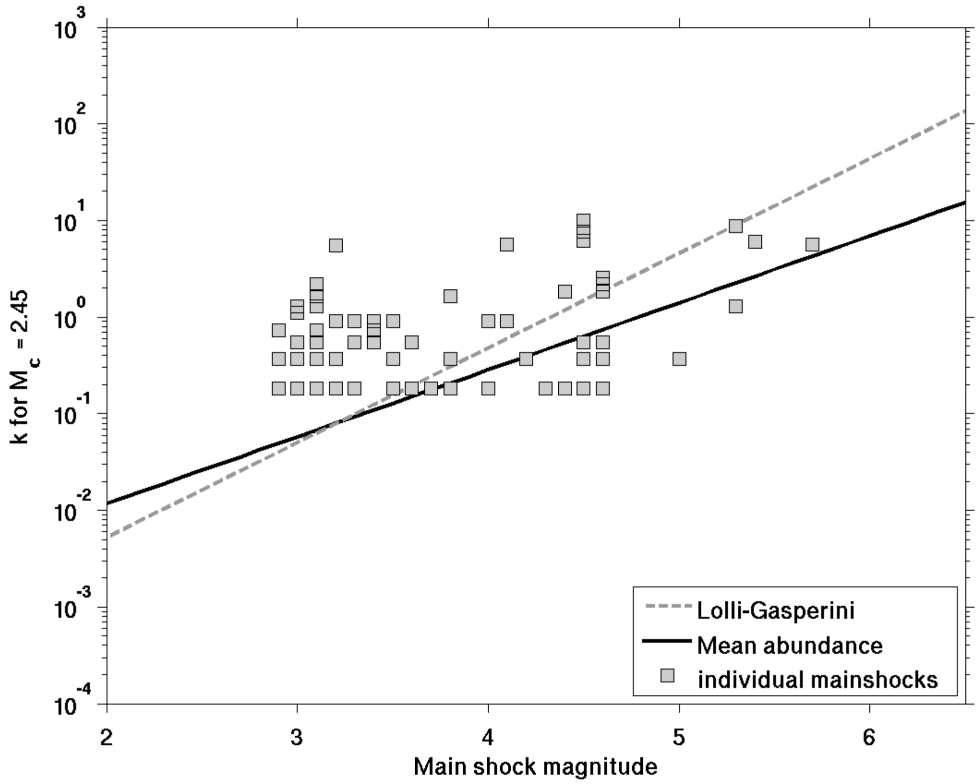


Figure 16: Productivity as a function of main shock magnitude in comparison to individual sequence productivities in for the Swiss territory (top, see data Figure 5) and for data from Northern Italy (bottom). Note that in the top figure the mean abundance model (black line) is at a level about a

Figure 16 shows the comparison to the actual data per sequence for the selected data set from ECOS-09 for Switzerland (top) and a complementary data set in Northern Italy including the northern Apenninens (bottom).First we observe that the STEP-LG model (dashed gray line) forecasts a much higher rate than the abundance model (black line). Second, we observe that the Italian sequences are more productive when compared to the Swiss. Third, a major difference is found for the Swiss and the Italian data set which is also valid for the study published by Woessner et al. (2010): the abundance model for Italy implies that below a main shock magnitude around 3.2, the productivity should be higher compared to the STEP-LG model. This is not the case for the Swiss model as the best fitting lines do not cross each other in the magnitude range I determined the model for.

Parameter	**STEP-LG**	**STEP-NG Abundance (Swiss data)**	**STEP-NG Abundance (Italy data)**
a-value	-1.84 ± 0.12	-1.84 ± 0.12	-1.84 ± 0.12
b-value	0.98 ± 0.03	0.98 ± 0.03	0.98 ± 0.03
c-value	0.09 ± 0.27	0.09 ± 0.27	0.09 ± 0.27
p-value	0.92 ± 0.06	0.92 ± 0.06	0.92 ± 0.06
α-value		**0.74 ± 0.34**	**0.69**±0.65
$\boldsymbol{M_1}$		**4.86 ± 0.39**	**3.73**±0.60
I_{OU}		5.47	5.47
M_c correction	0.2	0.2	0.2
$N_{min,SS}$	100	100	100

Table 1: *Model parameters for STEP-LG, STEP-NG based on ECOS-09 as shown in Figure 5, and STEP-NG for ECOS-09 derived for the Northern Italy region.* M_c *correction is an adjustment factor for data quality based on Woessner and Wiemer (2005),* $N_{min,SS}$ *is the minimum number to estimate parameter values for the sequence specific and spatially variable time-varying model elements.*

The current model can be used to forecast seismicity in a time-dependent hazard model for Switzerland. It needs to be noted the a STEP-LG model overpredicts and a STEP-NG (Abundance) model most likely underpredicts the rate of events following a larger event in Switzerland – meaning events above $M \geq 2.8$. The models are implemented and retrospective tests have shown that the cumulative fit is acceptable, but that the productivity model may need to be revisited with a different abundance model. Both, forecast testing and investigating new functional forms for the abundance model are ongoing over the next year.

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