Stress-based, statistical modeling of the induced seismicity at the Groningen gas field

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Abstract

To model the seismicity at the Groningen gas field we test if the statistical response of fault networks with rate-and-state dependent frictional behavior can describe the spatial and temporal pattern of the observed seismicity. The long and detailed data set from Groningen is ideal to test the model in regard to the changes in production history and to different parameters like fault density. The Rate-and-State model (RS) is compared to two simpler models: a stationary Poisson model and the Coulomb model with the seismicity rate proportional to the induced stressing rate. The RS model can spatially and temporally well explain the observed seismicity and yields better results as the other models. The results of the RS model are for the different input data consistent and can be improved by taking the fault density into account.

The Groningen gas field

The Groningen gas field is located in the Northeast of the Netherlands (Fig. 1). The reservoir is in the Upper Rotliegend Group in about 3000 m depth covered by a Zechstein salt layer. Production started in 1963 and since 1991 an increasing number of earthquakes was observed. The largest earthquake with M3.6 occurred in August 2012. In 2014 the production rate was drastically reduced followed by a significant decrease in seismicity.

Pressure drop and compaction values provided by NAM are taken as Coulomb failure stress proxy for the model assuming stress is proportional to pressure drop and compaction strain in the reservoir layer, where as well the seismicity occurs. Additionally, reservoir thickness and fault density are considered.

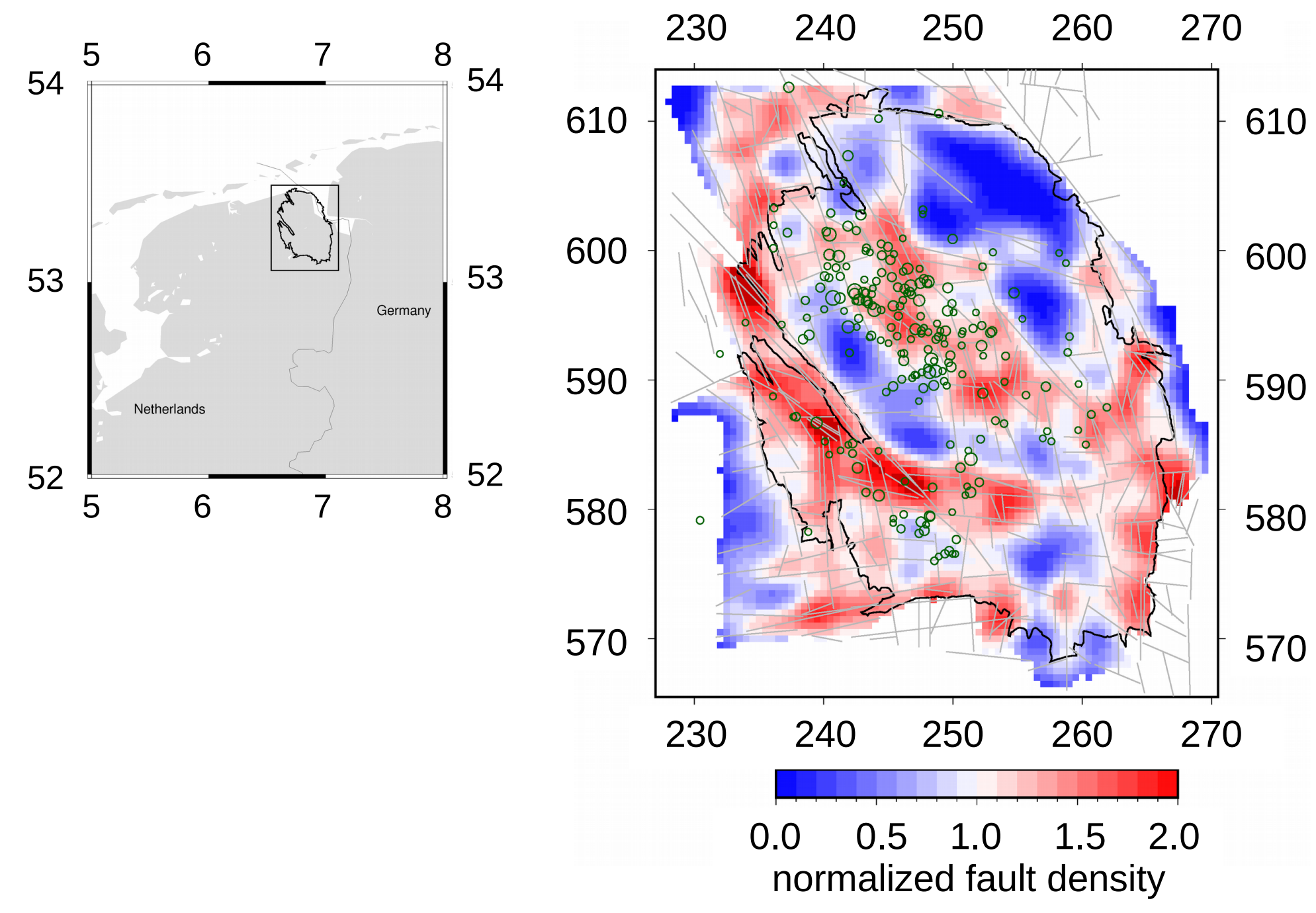


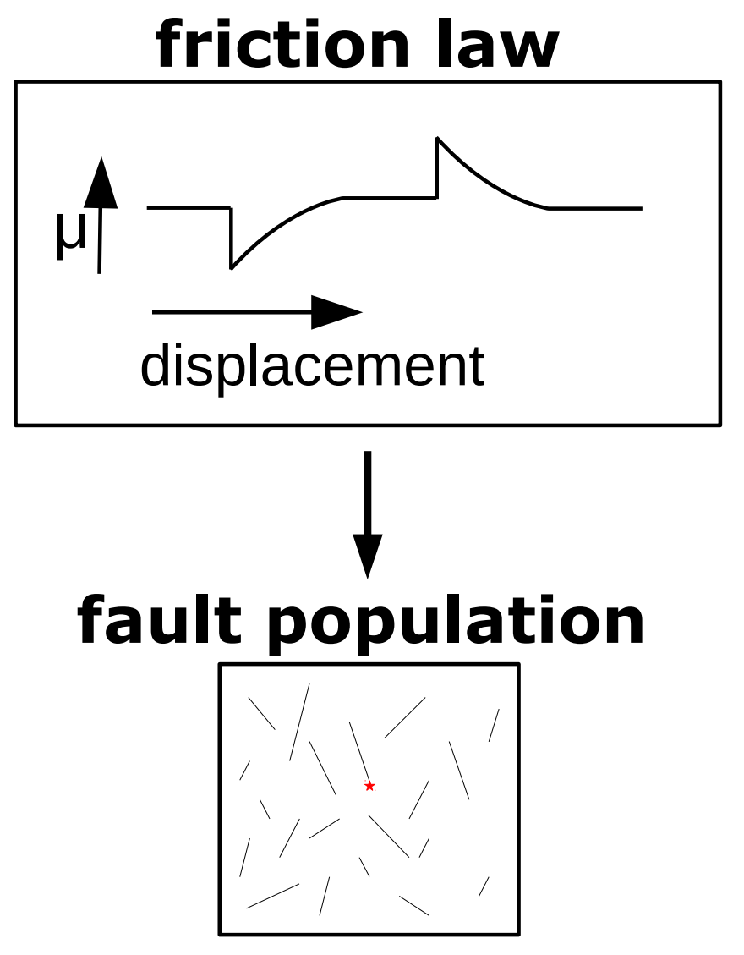
Fig. 1: Location map and the Groningen gas field with the normalized fault density map based on shown faults and observed earthquakes.

The Rate-and-State seismicity model

The Rate-and-State model (RS) is based on the experimental derived rate and state dependent friction law which is transferred to earthquake nucleation on heterogeneously distributed faults. The observed earthquake rate can be described as (Dieterich, 1994):

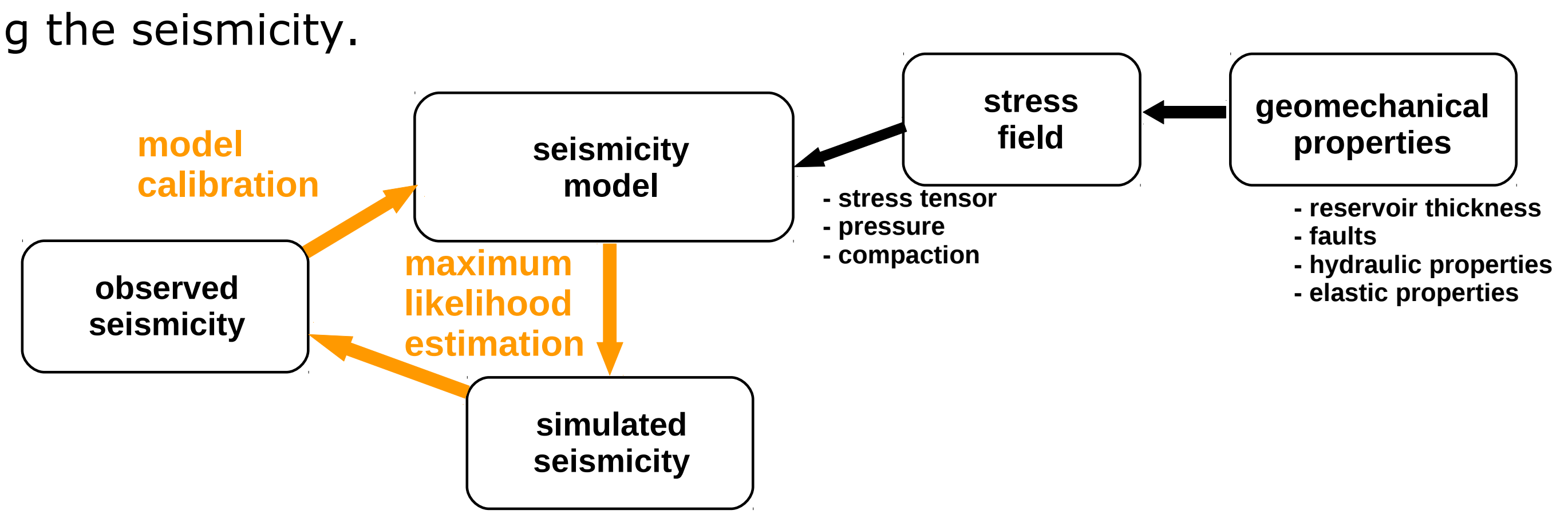
$$R=\frac{r}{\dot{\tau}\,\gamma} \qquad d\gamma=\frac{dt-\gamma\, dCFS}{A\,\sigma} \qquad t_a=\frac{A\,\sigma}{\dot{\tau}}$$

r - background rate; $r(\vec{x}) \sim \textit{fault density}$
A - friction parameter
$\dot{\tau}$ - tectonic stressing rate
CFS - Coulomb failure stress
γ - state variable
σ - normal stress



For a given stress history derived from production information and geomechanical information the spatial and temporal occurrence of earthquakes is modeled. Through a maximum log-likelihood estimation (LL) the modeled earthquake rate is compared to the observed seismicity and the three model parameters are estimated.

Fig. 2: Work flow for modeling the seismicity.



Model results and comparison to alternative models

The results of the RS model are compared to a stationary Poisson model and the Coulomb model (CFS), where the seismicity rate is direct proportional to the induced stressing rate. Fig. 3 shows the temporal variations in the seismicity rates of the three models summed for the complete field for two time periods based on pressure changes. For each model the best solutions for the temporal fit and the spatial and temporal fit are shown. The seismicity rates of the RS model look for the model results in Fig 3 similar, but comparing the seismicity maps in Fig. 4 (b) and (d) distinct changes are found. Most prominent is the focusing of seismicity at the zones of high fault density due to the weighting with fault density.

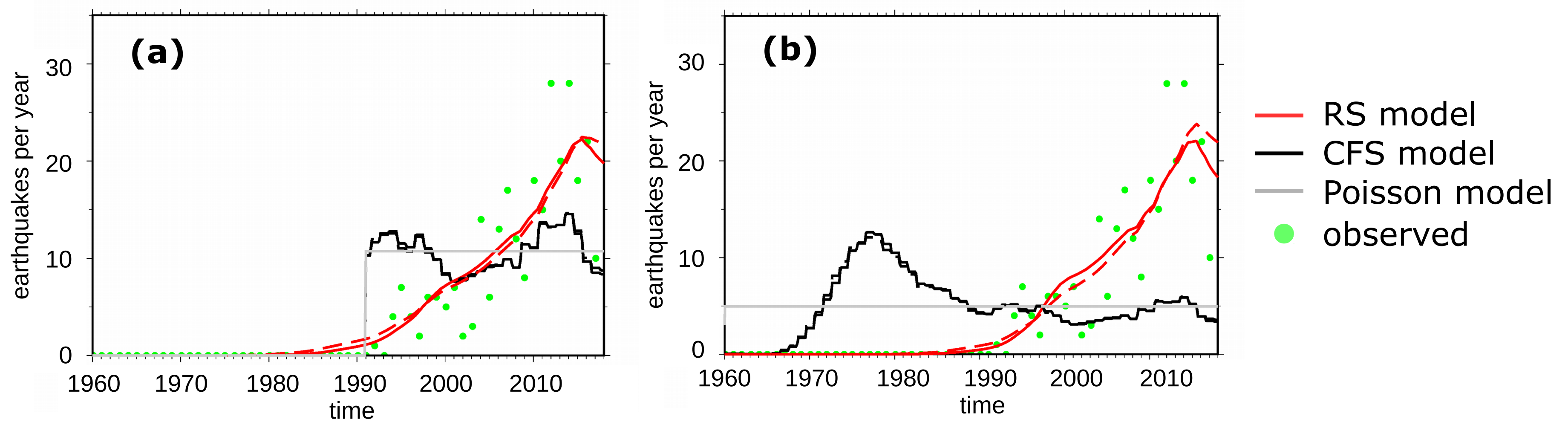


Fig. 3: Seismicity rates for the three models compared to the observed seismicity. For two fitting time periods (a) 1991-2017 and (b) 1960-2017. Solid lines: only temporal fit; dashed lines: spatial and temporal fit.

model		ΔAIC(t) 1960/1991	ΔAIC(x,t) 1960/1991
Poisson		0	0
CFS	pr	54/-20	-29/-111
	c	54/-23	-84/-162
RS	pr	-546/-111	-657/-226
	c	-547/-100	-655/-247

Tab. 1: Model comparison with the AIC relative to the AIC of the Poisson model AICp: ΔAIC. pr – stresses based on pressure change data, c – stresses based on compaction strain.

The Akaike Information Criterion (AIC) is used to compare different models which may have different numbers of free parameters with respect to be consistent with a given data set. The preferred model is characterized by the lowest AIC value. The results are summarized in Tab. 1 for the different models and fitting time periods.

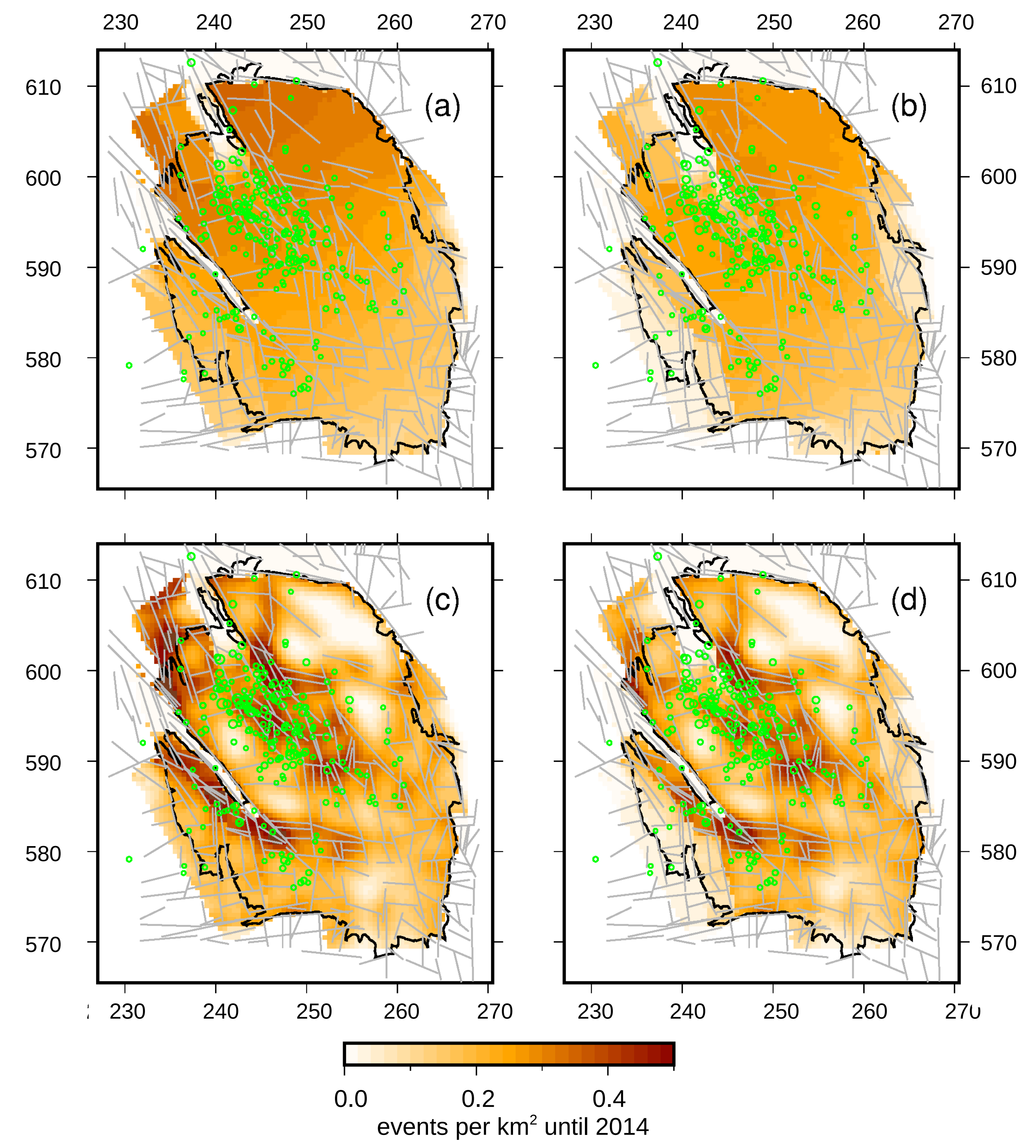


Fig. 4: Maps of modeled seismicity until 2014 based on pressure data for the linear CFS model in (a) and (c) and for the RS model in (b) and (d) with observed seismicity. Figures (c) and (d) show models with fault density weighting. Green circles: observed earthquakes.

Acknowledgments
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