Statistical Modeling of Seismic Moment Release

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Frederic Paik Schoenberg
frederic@stat.ucla.edu
Dept. of Statistics
University of California, Los Angeles

Suresh Kumar
sureshk@cs.unr.edu
Dept. of Mathematics and Statistics
University of Nevada, Reno

Ilya Zaliapin
zal@unr.edu
Dept. of Mathematics and Statistics
University of Nevada, Reno

Yan Kagan
kagan@moho.ess.ucla.edu
Dept. of Earth and Space Sciences
University of California, Los Angeles

Abstract

Connecting geodetic and tectonic estimates of long-term regional seismic moment release to observed seismicity is an important problem in statistical seismology, and is tightly connected to seismic hazard assessment and earthquake forecasting. However, many studies have reported wild fluctuations of observed seismic moment release as well as dramatic discrepancies between the observed moment rate and its geodetic/tectonic predictions. This poses the following questions: How should one interpret the discrepancy between observed and predicted moment release? In particular, does the moment deficiency consistently observed in southern California (as well as some other regions) imply an increased risk of a large earthquake? Here we report results that address these and related questions. Specifically, we use and further develop a methodology for statistical modeling of moment release based on the heavy-tailed Pareto distribution. This approach allows us to explain quantitatively and with high precision the discrepancies between observed and predicted moment releases in Asia during the 20th century. We establish three regimes in moment release depending on the range of magnitudes considered and the number of earthquakes actually observed. The so-called moment deficit phenomenon is shown to be the most likely pattern to be observed given the amount of data currently available in many regions. An important implication is that the substantial seismic moment deficits observed in many seismically active areas are to be expected and may not imply an increased risk of a large earthquake in the future.

1: Introduction

- **Scalar seismic moment** M_0 is one of the best measures of earthquake size. Cumulative seismic moment $S=\ M_0$ released in a region can be used as a proxy to the total regional deformation of the Earth surface due to earthquakes (formally, the strain rate for a volume of deforming crust is proportional to the sum of tensor moments of individual earthquakes.)

Seismic moment

shear modulus, rupture area, slip

$$M_0 = \ A\,u$$

Cumulative seismic moment

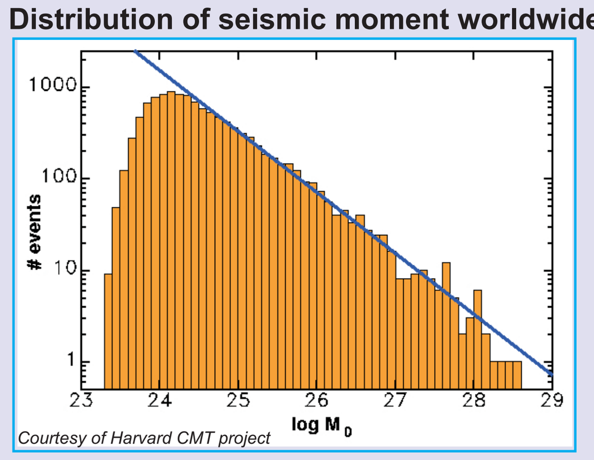
$$S:\ M_0 \ \sum_{k\ 1}^{n} M_0^k$$

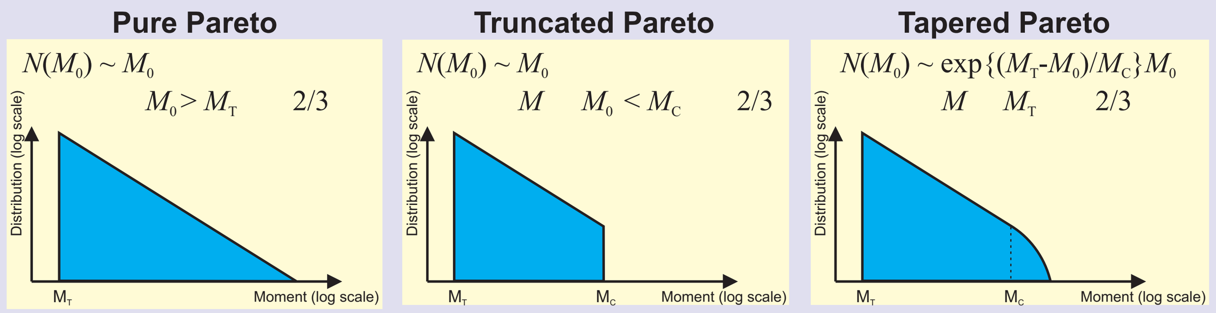
Moment vs. Magnitude (m)

$$m = 2/3 \log_{10} M_0 - C$$

- **Scalar seismic moment** has approximately power law distribution. Accordingly, **moment magnitude** (logarithm of moment) has exponential (Gutenberg-Richter) distribution. Scalar seismic moment can be modeled by **pure, truncated,** or **tapered** **Pareto** (power) distribution. The truncated or tapered models are more realistic since they reflect the finiteness of the total seismic moment flux or deformation energy of earthquake generation.

Distribution of seismic moment worldwide





- **Seismic coupling** can be used to compare observed and predicted moment reease:

$$\frac{\text{Observed moment}}{\text{Predicted, reference moment}} \quad \frac{M_0}{\text{ref}}$$

ref can be obtained by

- Geodetic observations (*i.e.* GPS, VLBI)
- Plate tectonic model (*i.e.* NUVEL4A, or P. Bird, Y.Kagan, BSSA 2004)
- Another physical model (*i.e.* thermal area of contact, see M. S. Boettcher & T. H. Jordan, 2004)
- Integration of appropriate probability model

- **Large discrepancies** between observed and geodetic moment release are commonly observed and reported. **Moment deficit** is the most typical observation.

"Comparison between observed and predicted moment rates ... reflects the generally unstable process of inferring long-term seismic moment rates from a catalog of limited duration. An observation period of ~10,000 years would be required to reduce uncertainties... "
Holt *et al.*, **JGR**, 2000

*"[In **western United States**] Except for the Basin and Range province ... all other areas have a moment rate deficit. ... The total observed moment release rate is about 63% of the total long-term release rate. "*
Shen-tu *et al.*, **JGR**, 1999

*"In **Asia**, the total observed moment release rate is about 73% of the total long-term release rate. "*
Holt *et al.*, **JGR**, 2000

Similar conclusion is reported by:
McCaffrey, **BSSA**, *1997;* Shen-Tu et al., **JGR**, *1998;* *Kreemer et al.*, **GJI,** *2002;* *Kagan*, **GJI,** *2002;* *Meade and Hager, 2005*

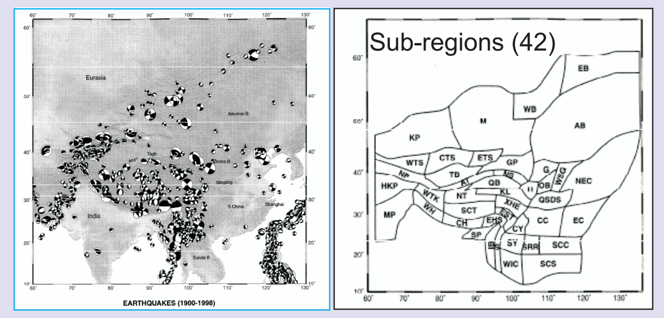
- **Moment deficit** is often interpreted in favor of coming large earthquake.
In the southern San-Andreas fault-San Jacinto fault zone, ... the strain rate ... can not be explained by aseismic deformation, so in the long term, a higher rate of large (M_w>7) earthquakes is expected here. Shen-tu *et al.*, **JGR**, 1998

- **Our analysis (theoretical and numerical) shows that moment deficit is a consequence of power-law distribution of seismic moments , a.k.a. Gutenberg-Rihcter law (Panel 2). In general, one can coarsely distinguish three regimes in seismic moment release, depending on the number of observed earthquakes and the range of magnitudes considered (Panel 3). Moment deficit is the most probable observation under currently available amount and quality of data.**

2: Modeling moment release in Asia

- Observations (from Holt *et al*., **JGR**, 2000)

Long-term moment release is inferred from the joint inversion of GPS and Quaternary rates of strain for Asia during 1965-1998. **Observed moment release** is estimated using m_b > 5.0 during 1900-1998. The analysis is done globally in Asia and in 42 subregions.



- Model

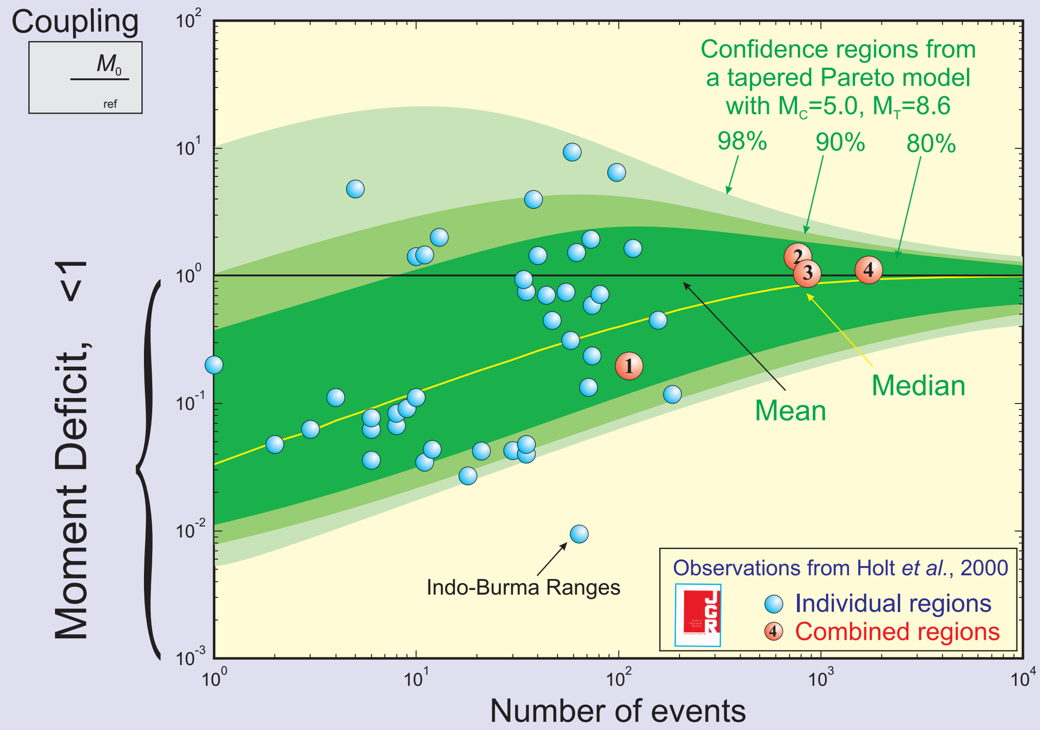
Tapered Pareto distribution:

$$N(M_0) \sim \exp\{(M_T-M_0)/M_C\}M_0$$
$$M \quad M_T \quad 2/3,\ M_C=5,\ M_T=8.6$$

Long-term release rate is given by the mean of the distribution.

- Conclusion: Moment deficit as well as irregular character of moment release is explained and can be quantitatively studied using the tapered Pareto model.

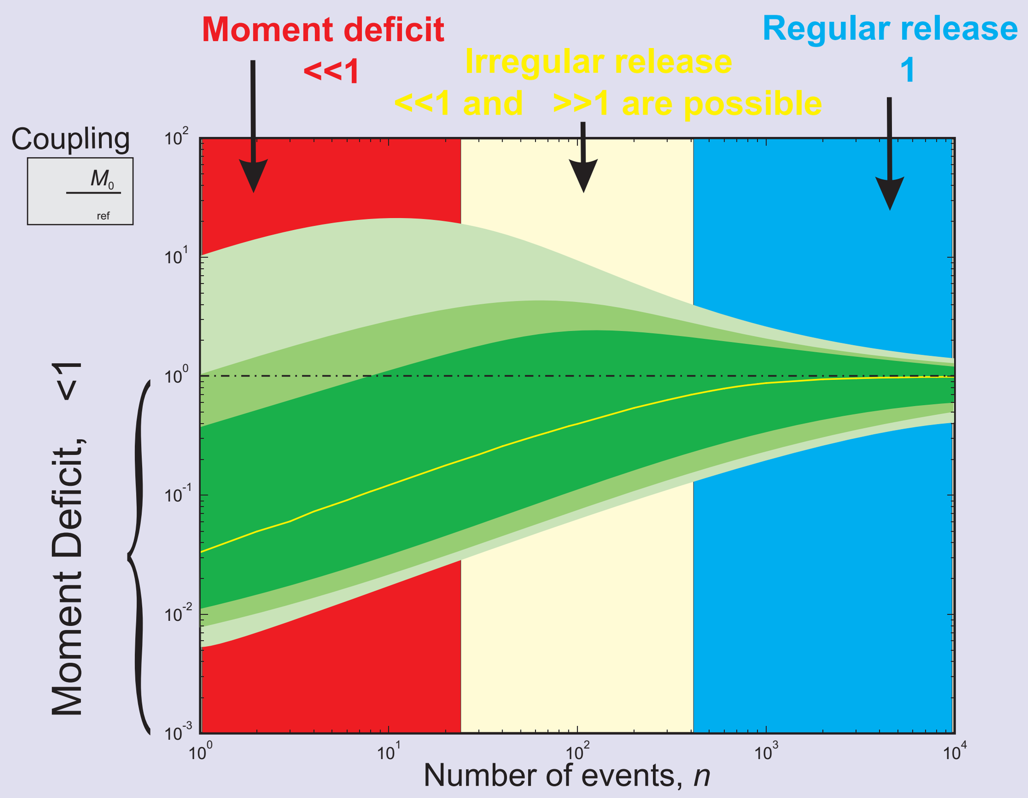
Observed moment release is well explained by the model



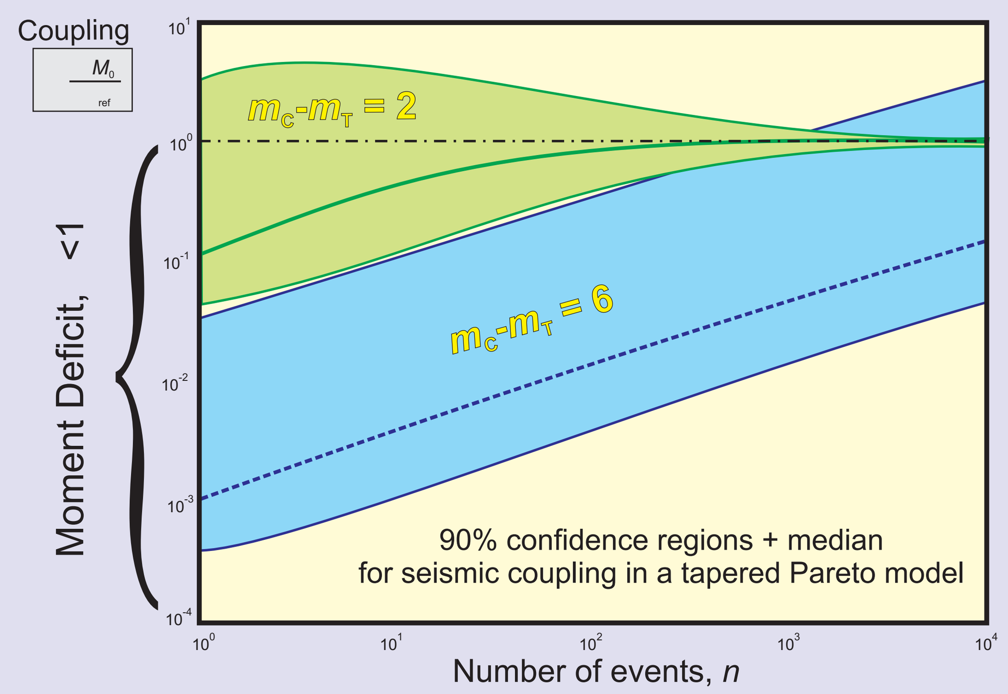
1. South China Sea, Thailand, Central, East, and NE China, Ordos
2. Makran, Pakistan, Pamir, Hindu Kush, Tien Shan, Mongolia, Baikal
3. Tibet, Himalaya, SW China, North Thailand, Myanmar
4. All regions together

3: Three regimes in moment release

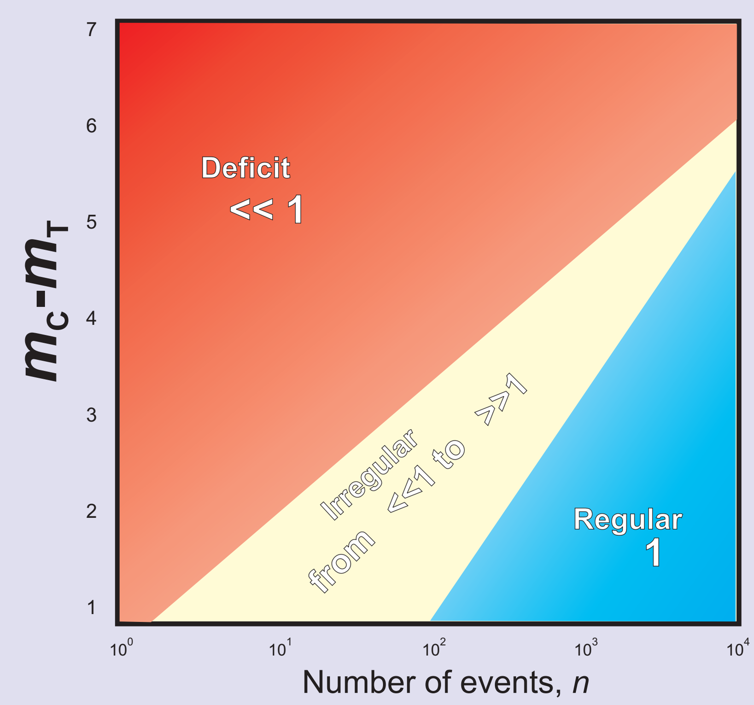
- Regime description for m_C-m_T = 2/3 $\log_{10}$(M_C-M_T) = 3.6



- Regime depends on m_C-m_T = 2/3 $\log_{10}$(M_C-M_T) and number n of observed earthquakes



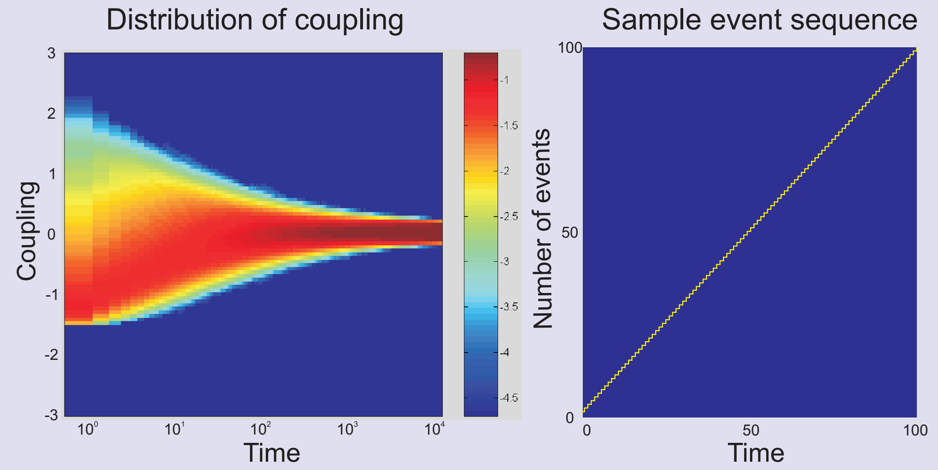
- Approximate location of moment release regimes



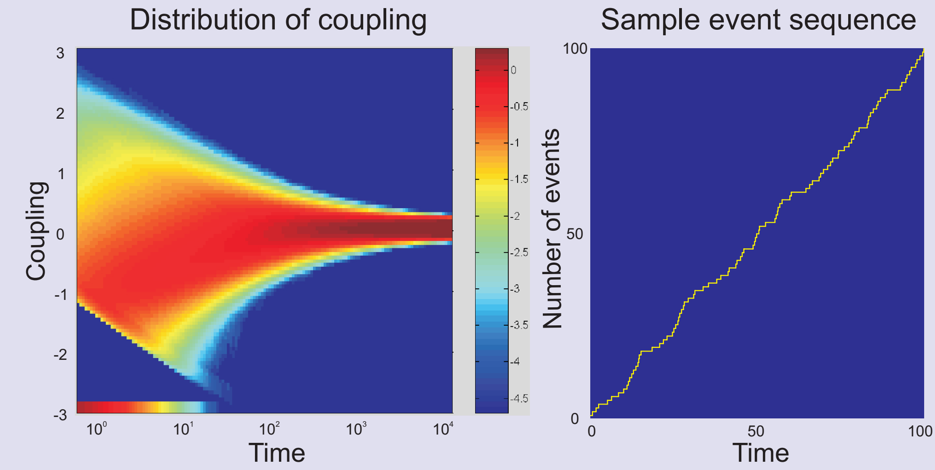
4: Time-dependent modeling

- Event clustering is one of the main features of seismicity. Here we show how clustering affects the distribution of seismic coupling in tapered Pareto model. We consider renewal processes with log-normal inter-event time and different clustering (measured by inter-event time's coefficient of variation C_V=std.dev/mean) with m_C-m_T=2. Notably, the event clustering has a much smaller impact on coupling that the magnitude range m_C-m_T.

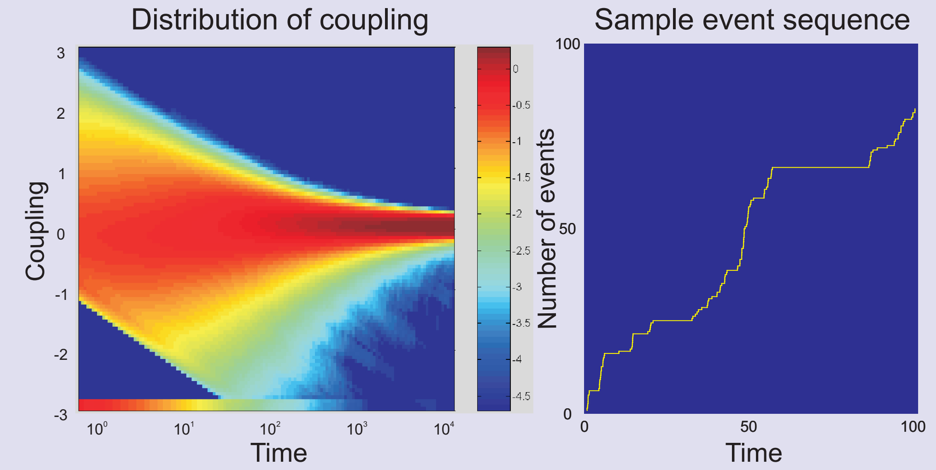
Periodic sequence, C_V=0



Random sequence, C_V=1



Clustered sequence, C_V=53



References and acknowledgments

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