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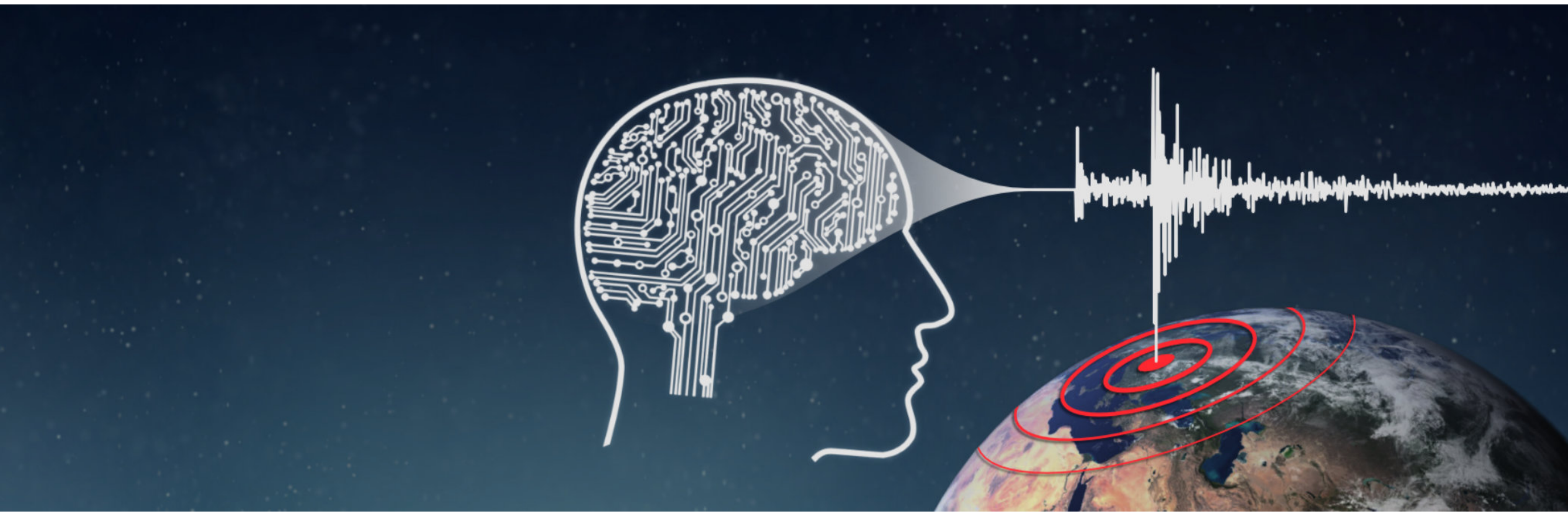

Seismology & Artificial Intelligence

Kickoff Workshop 27.09. - 01.10.2021

organized by:

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Monday, 27 September 2021

Spatial and Temporal Earthquake Data Analysis

10:00 - 10:25 **Introduction to the Workshop**

5 Minutes Setup Break

10:00 - 10:25 **Finding the Next Layer of Patterns in Seismicity**

Dr. Morgan Page
U.S. Geological Survey

There are four fundamental scaling laws in statistical seismology. These laws describe the earthquake size distribution, temporal aftershock decay, spatial aftershock decay, and mainshock productivity scaling. Put these laws together, as epidemic-type aftershock sequence (ETAS) models do, and you have an excellent first-order model of seismicity.

There is, however, a richer world of earthquake clustering and predictability beyond these scaling laws. To find these second-order signals, we need more sophisticated stacking techniques and to correct for finite-source effects as well as catalog heterogeneities and deficiencies. Care must be taken in interpreting the results, as apparent signals can be the result of known effects such as the inverse Omori law (or its equivalent in space) and temporal-spatial changes in the magnitude of completeness. With these considerations, I discuss how we can mine catalogs for "life beyond ETAS", in particular concerning where aftershocks are likely to occur.

5 Minutes Setup Break

11:05 - 11:35 **A Review on Physics Informed Neural Network with Constraints**

Prof. LongGang Pang
Central China Normal University

The deep neural network is widely used to represent solutions of partial differential equations (PDEs). The derivatives in the PDEs are provided by the auto differentiation in analytical precision, which are the derivatives of the network outputs to its inputs. The parameters of the network are learned by minimizing the residuals of the PDEs, the boundary conditions and the initial conditions. However, training this kind of physics informed neural network is data-eager and time-consuming. One idea is to construct a network which satisfies some constraints naturally, e.g., divergence-free or curl-free functions to represent electro-magnetic field, or anti-symmetric functions to represent the wave function of many-fermion quantum systems. This talk will review the recent progress in solving PDEs using constrained network.

5 Minutes Setup Break

11:40 - 12:10 **Earthquake Rupture Dynamics from Machine Learning?**

Prof. Paul Martin Mai
King Abdullah University of Science and Technology
Saudi Arabia

Machine Learning and Artificial Intelligence (ML/AI) are nowadays ubiquitously applied in all fields of science and technology, in the way we communicate using modern interconnected devices, and how we make decisions (or don't have to, anymore). Seismology, a data-rich field in the physical & natural sciences, has leveraged on ML-techniques for earthquake detection, earthquake location, prediction of earthquake interactions, estimation of potential future shaking levels, to name just a few applications. In the field of seismic exploration, ML-techniques are widely used for phase-arrival detection, interpretation of seismic sections, all the way to first-order construction of geological models. Recent work even proposes that lab-quakes – tiny earthquakes generated under idealized conditions in rock-physical laboratory experiment – may be predictable using ML-tools. Are we on the path to earthquake prediction, the 'Holy Grail' of earthquake seismology?

In this presentation, I review the physical fundamentals of the dynamics of the earthquake rupture process – from nucleation to propagation to arrest – of a moving crack in a rock volume. Stress, friction, material heterogeneity, and geometric complexity need to be factored into the equations of motion to model earthquake rupture dynamics, whereby we have to make further assumptions on nonlinear dissipative processes at the crack tip. As a consequence, earthquake rupture dynamics is a highly nonlinear process that is very sensitive to initial and boundary conditions (i.e., parameter choices in practice) that come with large uncertainties (due to limited knowledge of the properties of the Earth at depth). However, knowing (or being able to realistically model) earthquake rupture dynamics is of great importance for seismic hazard and tsunami generation studies, and to understand the space-time dependent stress-transfer processes in the Earth. Can ML/AI methods help to forecast the dynamic behavior of earthquake ruptures in the Earth?

12:10 - 13:15 Lunch Break

13:15 - 13:45 Deep Learning and Earthquake Forecasting

Prof. Geoffrey Fox
University of Virginia

We consider a variety of Machine Learning and Deep Learning approaches to Earthquake forecasting including principal component analysis, recurrent neural networks, and variants of the Transformer architecture.

We consider sensitivity to the choice of input data (magnitudes versus counts) and the time period of predictions. Measures of success are discussed. This is a work in Progress with John Rundle (UC Davis) and Bo Feng (Indiana University)

5 Minutes Setup Break

13:50 - 14:20 SAI Group Member Talk and Panel Discussion

Jonas Köhler
Frankfurt Institute for Advanced Studies

Tudesday, 28 September 2021
Seismic Waveform Analysis

10:00 - 10:25 **Introduction to the Workshop**

5 Minutes Setup Break

10:30 - 11:00 **Towards Blending Physics-Based Numerical Simulations and Seismic Databases Using Generative Adversarial Network**

Dr. Filippo Gatti
Université Paris Saclay

A new strategy to blend the outcome of physics-based numerical simulations with massive seismic databases is proposed. The approach relies on a set of adversarial learning techniques with a twofold purpose: (1) finding two reduced-dimensional non-linear representations of both synthetic and experimental data; (2) training a stochastic generator of fake experimental responses conditioned by the physics-based simulation results. This methodology is applied to earthquake ground motion prediction. Indeed, regional three-dimensional high-fidelity numerical models accounting for both extended sources and complex geology are still limited to a low-frequency range. Moreover, they are prone to significant uncertainties induced by a lack of data on small scale geological structures and rupture processes. Databases of broadband seismic signals recorded worldwide at seismological networks are used to retrieve some pieces of information on these small-scale data to generate realistic broadband signals from synthetic ones. Outstanding performances in encoding seismic signals are demonstrated, together with efficient generation capabilities, provided that the physics-based results carry enough information to properly condition the stochastic generator. In addition, the proposed method, fed only with raw data from both databases and numerical models, outperforms other random signal generators based on pre-existing expertise such as prescribed spectra and more or less complex phenomenological models.

5 Minutes Setup Break

11:05 - 11:35 **Earthquake Monitoring in Artificial Intelligence Era**

Dr. Mostafa Mousavi
Stanford University

Diverse algorithms have been developed for efficient earthquake signal processing and characterization. These algorithms are becoming increasingly important as seismologists strive to extract as much insight as possible from exponentially increasing volumes of continuous seismic data. Deep neural networks have been shown to be promising tools for this. We have developed a number of deep learning tools for more efficient processing and characterizing of earthquake signals. In my presentation, I demonstrate the performance of some of these tools applied to seismic data. AI-based techniques have the potential to improve our monitoring ability and as a result understanding of earthquake processes and hazards.

5 Minutes Setup Break

11:40 - 12:10 **Leveraging Coherent Wave Field Analysis and Deep Learning in Fiber-Optic Seismology**

Dr. Korbinian Sagar
Ludwig-Maximilians-University

Fiber-optic cables form an integral part of modern telecommunications infrastructure and are ubiquitous in particular in regions where dedicated seismic instrumentation is traditionally sparse or lacking entirely. Fiber-optic seismology promises to enable affordable and time-extended observations of earth and environmental processes at an unprecedented temporal and spatial resolution. The method's unique potential for combined large-N and large-T observations implies intriguing opportunities but also significant challenges in terms of data storage, data handling and computation. Our goal is to enable real-time data enhancement, rapid signal detection and wave field characterization without the need for time-demanding user interaction. We therefore combine coherent wave field analysis, an optics-inspired processing framework developed in controlled-source seismology, with state-of-the-art deep convolutional neural network (CNN) architectures commonly used in visual perception. While conventional deep learning strategies have to rely on manually labeled or purely synthetic training datasets, coherent wave field analysis labels field data based on physical principles and enables large-scale and purely data-driven training of the CNN models. The shear amount of data already recorded in various settings makes artificial data generation by numerical modeling superfluous - a task that is often constrained by incomplete knowledge of the embedding medium and an insufficient description of processes at or close to the surface, which are challenging to capture in integrated simulations. Applications to extensive field datasets acquired with dark-fiber infrastructure at a geothermal field in SW Iceland and in a town at the flank of Mt Etna, Italy, reveal that the suggested framework generalizes well across different observational scales and environments, and sheds new light on the origin of a broad range of physically distinct wave fields that can be sensed with fiber-optic technology. Owing to the real-time applicability with affordable computing infrastructure, our analysis lends itself well to rapid on-the-fly data enhancement, wave field separation and compression strategies, thereby promising to have a positive impact on the full processing chain currently in use in fiber-optic seismology.

12:10 - 13:15 Lunch Break

13:15 - 13:45 **SAI Group Member Talk** and Panel Discussion

EPick: Multi-Class Attention-based U-shaped Neural Network for Earthquake Detection and Seismic Phase Picking

Dr. Wei Li
Frankfurt Institute for Advanced Studies

5 Minutes Setup Break

14:05 - 14:35 **SAI Group Member Talk** and Panel Discussion

Convolutional Recurrent model for Earthquake Identification and Magnitude Estimation — CREIME

Megha Chakraborty
Frankfurt Institute for Advanced Studies

Wednesday, 29 September 2021

Remote Sensing, Geodetic and Seismic Data Analysis and Interpretation

10:30 - 11:00 To be announced soon.

5 Minutes Setup Break

11:05 - 11:35

Seismological and Geodetic Perspectives of Earthquake Activity in Northern Part of Cambay Rift – A Part of Stable Continental Region, India

Dr. Sumer Chopra
Institute of Seismological Research

The Gujarat state located in the western part of the Indian subcontinent is an active intraplate region of India. It is located at the trijunction of Kachchh, Narmada and Cambay rifts. Out of these three, Kachchh is seismically more active followed by Narmada and Cambay rifts. In last decade or so it has been seen that the northern part of Cambay rift adjoining the Kachchh rift has been experiencing more earthquakes as compared to background seismicity in that region. The region has high hydrocarbon potential. In view of this, the region is extensively explored with geophysical surveys. It is found that the region has high heat flow, shallow Moho and high possibility of the presence of rift pillow in the lower crust. In the past decade or so, more than 1000 earthquakes have been recorded with maximum earthquake up to 4.2. The Institute of Seismological Research is operating few continuous GPS stations in that region and the deformation is around 1.8 mm/yr is noticed. The GPS derived strain rates are around ~0.03 microstrain/yr. It is found that earthquakes in this region are mostly normal with small strike-slip component, which is corroborated with the geodetic strain tensors. The seismically active part of the Cambay rift comprises of basement ridges and plutonic bodies underneath. We infer that highly heterogeneous subsurface structure beneath the northern part of the Cambay rift is creating additional stress, which is superimposing on the regional stress field substantially, and this mechanism is plausibly facilitating the localized extensional tectonics in the region where compression is expected.

5 Minutes Setup Break

11:40 - 12:10

Clustering and Classification of Lightning Phenomena Observed in VHF with Unsupervised Learning

Dr. Lingxiao Wang
Frankfurt Institute for Advanced Studies

In recent years VHF observations of lightning have made rapid leaps forward. In particular, LOFAR is now capable of mapping lightning with meter and nanosecond precision. The increased complexity of this data, however, comes with the additional challenge of requiring more complex analysis. As such, lightning VHF mapping data is now ripe for application of machine learning. In this work we apply an unsupervised machine learning algorithm, the t-distributed stochastic neighbor embedding (t-SNE) method, to LOFAR lightning data and show that it can cluster the data by phenomena and that the shape of the clusters can indicate the type of phenomena (e.g. needles, negative leaders, or recoil leaders). This introduces a powerful new tool that can be used to analyze lightning data and help extract more detailed physical results in future work.

12:10 - 13:15 Lunch Break

13:15 - 13:45

Solving Inverse Problems with Deep Neural Networks

Dr. Shuzhe Shi
Stony Brook University

Deep Neural Networks (DNNs) have been widely employed a general and universal parameterization scheme to represent arbitrary continuous functions. The advantages of DNN lie in not only its generality but also the efficient computation of the parameter-gradients, via the Back-Propagation procedures. In ordinary deep learning problems, one is usually able to directly compare the output of DNN to the observed data, and train the DNN parameters accordingly. In some special problems, however, the relation between the observable and the underlying property of interest, represented by DNN, could be complicated or even implicit. In this talk, I will present a general discussion on how to adjust the BackPropagation algorithm according to such complicated/implicit problems. Then, I will focus on two realistic examples, the inverse Schroedinger equation solver and the inverse Laplace transformation, to discuss the application and possible limitation.

13:50 - 14:20 Seismicity Clustering in Support of Sesmic Source Zones Definition

Valentina Blasone
PG Visiting Student, University of Bristol

Flavia De Luca
Senior Lecturer in Structural and Earthquake Engineering, University of Bristol

Raffaele De Risi
Lecturer in Civil Engineering, University of Bristol

Unsupervised learning methods can provide insights into a given set of data. When it comes to seismic data, clustering algorithms can help in identifying regions of uniform seismicity. This is of particular interest because polygonal seismic source zones represent a widely used approach to modelling seismicity as input for PSHA analyses. However, the definition of such areas is a lengthy process requiring expert judgment, and a single standard procedure does not exist. The results of an automatic clustering procedure can therefore represent a homogeneous reference for already existing seismic source zones models and help define new models. In this study, a clustering-based approach to identify regions of uniform seismicity is developed. The performance of the method is investigated through a case study, considering the current zonation of Italy.

Thursday, 30 September 2021

Volcanology

10:30 - 11:00

Detecting Precursors and Forecasting Eruptions Using Time Series Feature Engineering at Whakaari

Prof. David Dempsey
University of Canterbury

Phreatic explosions at tourist-visited volcanoes are difficult to predict. Recent fatalities following the 2019 Whakaari eruption in New Zealand suggest there is a need for forecasts that can update on short time scales: hours to days. We used time-series feature engineering to identify eruption precursors in seismic data collected from Whakaari, New Zealand. We identified four-hour energy bursts that occur hours to days before most eruptions as particularly significant signals. We suggest these indicate charging of the vent hydrothermal system by hot magmatic fluids, which later can trigger an eruption. We trained a model to recognise these precursors in real-time data and developed a system for short-term alerts during periods of elevated eruption likelihood. Under cross-validation (pseudoprospective) testing and an optimized alert threshold, this forecasting system could anticipate six out of seven unseen eruptions, providing hours to days of warning. The system has been operating for 18-months, and we have since refined it to neglect regional earthquake noise and output a calibrated probability. This talk will discuss the practicalities and challenges of operational early-warning systems using machine-learning workflows, and suggest future avenues to improve their uptake and acceptance.

5 Minutes Setup Break

11:05 - 11:35

Introduction to Time Series Forecasting

Dr. Rajbir-Singh Nirwan
Amazon Web Services

One of the techniques in Machine Learning, which is often neglected, is the analysis of time series (TS). Methods to analyze time series are needed when we want to make predictions based on historical time stamped data. Applications of TS forecasting are very diverse and include, for example, weather forecasting, financial forecasting, retail forecasting and many more.

The objective of this talk is to provide an overview of classical approaches to solve TS related problems, as well as, methods to evaluate those forecasts.I will start with an introduction of very basic models and then talk about how to extend those models to more flexible once by using Deep Learning. At the end of the talk I introduce DeepAR, a model used to forecast multivariate time series.

5 Minutes Setup Break

11:40 - 12:10

Seismic radiation from wind turbines – observations and modeling approaches

Fabian Limberger
Institute of Geothermal Resource Management,
Goethe University Frankfurt

In response to efforts to reduce greenhouse gas emissions, the number of wind turbines for electricity generation has risen significantly in recent years. It may not be obvious that this increase may also have an adverse influence on seismic stations and observatories and their capabilities to detect small or distant earthquakes. The research project "KWISS" aims to characterize the seismic wave field emitted by single wind turbines as well as wind farms with the objective to develop tools to predict (and ultimately remove) the undesirable signals from wind turbines at seismic stations based on analytical and numerical modeling approaches. Long-term observations along dense profiles of seismic stations show that wind turbines typically emit seismic signals between 1 Hz and 10 Hz and that the signal amplitude decays characteristically with distance to the wind turbine. We present an analytical modeling approach that allows to estimate the expected spatial seismic radiation pattern of wind farms with arbitrary layouts. The model also explains the observed dependency on signal frequency. However, limitations can arise, e.g., in the case of complex topography. To study the effect of the topography on the seismic wave propagation, numerical FEM simulations are performed that include information from digital elevation models. Preliminary results show that the topography can have significant effects on the amplitude of the ground-motions emitted by the wind turbines. The results of the long-term observations along station profiles and the findings from forward modeling provide constraints on the feasibility to remove wind-turbine generated signals from the seismograms. In future developments, we intend to apply AI methods to predict ground-motion effects at distant seismometers based on seismic recordings obtained in the near field of wind turbines.

12:10 - 13:15 Lunch Break

13:15 - 13:45 Characteristics of Time Series in Volcanoseismology

Christoph Sens-Schönfelder
GFZ Potsdam

Analysis of seismic waves at volcanoes faces to challenges that make the interpretation of seismograms different from other seismological targets. First, the propagation medium is more complex than typical crustal material. Alternating layers of competent lava flows and soft ash layers or dykes cutting through highly fractured sills create a heterogeneous structure that scatters seismic waves far more efficiently that average crust. Second, the presence of fluids in the magmatic plumbing system allows for source a a multitude of source mechanism that produce signals which are usually more complicated and variable than shear fractures. In consequence we face complicated signals that propagate through a medium which makes them even more complex.

I will provide examples that illustrate the complexity of volcano seismology and discuss strategies to exploit this complexity. I will draw on scattering theory and seismic interferometry to show how highly scattering media can be imaged and why the strong scattering provides ideal conditions for monitoring tiny variation of the propagation material that inform about internal processes and environmental forcing acting on the volcanic edifice.

5 Minutes Setup Break

13:50 - 14:20 SAI Group Member Talk and Panel Discussion

AWESAM: Adaptive-Window Volcanic Event Selection Analysis Module

Darius Fenner
Frankfurt Institute for Advanced Studies

Friday, 1 October 2021
Seismic Hazard Modeling and Keynote

10:30 - 11:00

Estimating Earthquake Ground Motions: Background, Methods and Challenges

Prof. John Douglas
University of Strathclyde

Ground-motion models, also called ground motion prediction equations (GMPEs) and sometimes attenuation relations, play a key role in seismic hazard assessments. These models provide an estimate of the earthquake ground motion to expect at a site given the occurrence of an earthquake at a particular location. Hundreds of GMPEs for different measures of earthquake ground motions (e.g. peak ground acceleration) and for different regions have been published since the 1960s. In this talk I will provide an overview of GMPEs, including a discussion of their inputs, outputs and derivation, as well as highlighting some challenges that current research is trying to solve.

5 Minutes Setup Break

11:05 - 11:35

Modeling Fault Ruptures for Probabilistic Seismic Hazard Analysis

Dr. Kiran Kumar Thingbaijam
GNS Science

Characterizing earthquake sources is a key step in probabilistic seismic hazard analysis. Traditionally, frequency magnitude distribution is evaluated to prescribe annual occurrence rate (or probability) to each rupture. In contrast, recent approaches evaluate plausible ruptures on a specific fault, including their magnitudes and spatial extents. Thereafter, solving long-term earthquake rates on the fault is taken up as an inversion problem with multiple constraints such as fault-slip rates, paleoseismic recurrence and regional frequency magnitude distribution. This paradigm shift is motivated by the need to allow easy incorporation of complex fault geometry and intraevent rupturing of multiple faults, and integration of multidisciplinary datasets such as seismological, geological, geodetic and paleo-seismological data. In this context, I will discuss the following: (1) insights gained from finite-fault rupture models; (2) examples of modeling ruptures in different seismogenic regimes; and (3) research opportunities.

5 Minutes Setup Break

11:40 - 12:10

An Overview of Expressivity and Trainability in neural networks

Prof. Richard Xu
University of Technology Sydney

For the most part of last decade, deep neural networks have achieved many monumental empirical successes in various fields of machine learning. However, most of their inner workings remain a mystery. Recently, many researchers have tried to disentangle this mystery by observing what happens when the width of the neural network reaches infinity. To this end, there have been several important studies to address the expressivity and trainability of neural networks recently. In this talk, I will start by briefly describe what a Gaussian process is and why a neural network can be expressed as a Gaussian process. Then, through the lens of the so-called Neural Tangent Kernel, I will explain why using gradient descent in neural network training can be regarded as solving linear ordinary differential equations. Finally, I will show some exciting research directions in this area.

12:10 - 13:15 Lunch Break

13:50 - 14:20

Fourier Spectral Models: An Alternative Approach for Developing Ground Motion Models (GMMs)

Dr. Sanjay Bora
ITT Gandhinagar, GNS Science

Modelling Fourier amplitude spectrum (FAS) of ground motion is not new in the context of engineering seismology. Traditionally, the FAS of ground motion is explained in terms of Brune's omega-square model (representing the source-effect) along with geometrical spreading and an-elastic attenuation accounting for the path-effects. With the availability of the more recorded data, recently, there is renewed interest in Fourier spectral models vis-à-vis the traditional response spectral GMMs. In this talk, I shall provide a brief overview of the Fourier spectral models in the context of engineering seismology. Subsequently, I talk about the recent studies involving development of Fourier spectral models and how such models have become important in seismic hazard analysis studies. The talk will also include results from our recent studies on Japanese strong motion database.

5 Minutes Setup Break

14:00 - 14:30

Panel Discussion

15:00 - 16:00

Keynote Talks

Earth's Variable Rotation and its Influence on Decadal Fluctuations in Global Earthquake Productivity

Prof. Roger Bilham
CIRES Geological Science
University of Colorado

Roger Bilham has degrees in Physics, Geology and a PhD in Geophysics from Cambridge University. His expertise is related to geodesy and strain instrumentation applied to the study of earthquakes and volcanoes, tsunami and landslides.

At Colorado he founded UNAVCO, the University consortium for applying geodesy to tectonic studies, and has applied GPS to the study of tectonics in Pakistan, India, Nepal, Tibet, the Caribbean, Turkey, Iceland and North America. He has appeared in a handful of movies on mountain building and earthquakes and has published some 250 research articles.

From 1900 to the present, the rate of occurrence of major earthquakes (those exceeding Magnitude 7) has varied from less than ten to more than twenty per year. Maxima and minima in this annual rate fluctuate with a period of 25±10 years, similar to long-period changes in the rotation rate of the earth as revealed by the length of the day (LoD). Intriguingly, maximum decelerations in Earth's rotation rate correspond to maxima in global earthquake productivity delayed by roughly 5 years. Serendipidously, this implies that future global earthquake productivity can be forecast from LoD data. A forecast in 2018 of 15±2.7 earthquakes in 2020±2.5, for example, is currently within its forecast uncertainty. The reason for this curious relationship is obscure. Few atmospheric or oceanic signals have sufficiently long period to influence Earth's rotation rate at decadal periods. In contrast changes in the relative rotation rate between the lithosphere and the solid core of the Earth are known to occur at these long periods. Two causal mechanisms are discussed whereby fluctuations in global angular velocity may influence the lithosphere: one dynamic and the other kinematic. The first results in lithospheric overshoot during deceleration, and the second results in changes in the equatorial circumference of the Earth. Both effects decrease with increasing latitude, but since neither mechanism results in plate boundary stresses sufficiently large to significantly advance the timing of earthquakes, it is necessary, in addition to invoke synchronization theory to explain the observed correlation between LoD and earthquake productivity.

To be announced soon.

Prof Anima Anandkumar
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Technology,
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