# ON THE MUTUAL INTERRELATION BETWEEN EARTH ROTATION AND EARTHQUAKE ACTIVITY

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**ABSTRACT.** In this paper, we analyse the mutual interrelation between earthquake activity and Earth rotation. The influence of earthquakes on the Earth rotation has been the subject of several studies before (Varga et al., 2005; Bizouard, 2005; Gross et al., 2006; Xu et al., 2014). Based on our investigations we concluded that the relationship between these two phenomena could be detected in the reverse direction too: changes in the speed of Earth's rotation (that is, changes in the Length-of-Day (LOD)) may affect earthquake activity.

## 1. INTRODUCTION

The study of short periodic variations of Earth Rotation Parameters (ERP) became possible using atomic clocks in the 1950s (Essen and Parry, 1955), with the appearance of Very Long Baseline Interferometry and methods of space geodesy (Satellite and Lunar Laser Ranging and Global Positioning System) (Eubanks et al., 1988; Dickey et al., 1994; Gross 1993; Hide and Dickey, 1991). Precise Length-of-Day (LOD) and Polar Motion (PM) measurements have shown variations down to days and even subdaily frequencies. The formal error of PM data are less than 50 microseconds of arc ($\mu$as) and 10 microseconds ($\mu$s) in case of LOD. This development made it possible to examine the relationship between ERP variations and hydro-meteorological/geodynamic processes. Our present research is focused on the relationship between earthquake activity and ERP. In this respect, the momentum magnitudes (Mw) introduced by Hanks and Kanamori (1979) in earthquake research is of great importance, as it allows a reliable determination of the magnitude of major ($\geq 8$) seismic events. It is evident that the temporal distribution of earthquakes and the release of seismic energy are primarily determined by tectonic conditions. Despite the fact that the annual rate of earthquake energy ($9.5 \times 10^{18}$ J/a) is slightly lower than that of Earth's rotation ($1.6 \times 10^{19}$ J/a) (Varga, 2006), it is important to examine the possible relationship between earthquakes and ERP. On one hand, it helps to better understand the processes that trigger earthquakes. On the other hand, it is an interesting problem how the greatest earthquakes can affect the Earth's rotation.

## 2. DATA DESCRIPTION

For the earthquake parameters, the version 6.0 of the ISC-GEM Global Instrumental Earthquake Catalogue provided by the International Seismological Centre was chosen (Storchak et al., 2013; 2015; Di Giacomo et al., 2018). This catalogue contains Mw values that were re-computed such a way that the resulting catalogue is consistent for the whole period starting from 1904 until the end of 2015 (Di Giacomo et al., 2015). It is important for this work because the released seismic energy can only be accurately determined from Mw, especially for high (Mw $\geq$ 8) values, where

Mw does not saturate (Kanamori, 2004).
Furthermore, in order to obtain the 1D (radial) physical parameters of the Earth, the Preliminary Reference Earth Model (PREM) was used (Dziewonski and Anderson, 1981). The subduction zone lengths determined for 15° wide latitude zones were calculated for us by Dr. Friedhelm Krumm (University of Stuttgart, Institute of Geodesy). The ERP data were taken from the products of the International Earth Rotation and Reference Systems Service (IERS). The C04 time series was used as observations time series, and Bulletin A was used for the Earth rotation predictions (Bizouard et al., 2019).

## 3. BASIC INFORMATION ON EARTH'S SEISMICITY

The radiated energy by an earthquake can be calculated using the Gutenberg and Richter relation (Hanks and Kanamori, 1979; Kanamori, 2004):

$$logE_R = 4.8 + 1.5M_W. \quad (1)$$

The annual seismic energy varies significantly in time, as only a few earthquakes occur with very high moment magnitude (and thus, energy). This phenomenon can be seen on Figure 1, where the seismic events that cause the largest peaks (with energies above $10^{18}$ J) are identified.

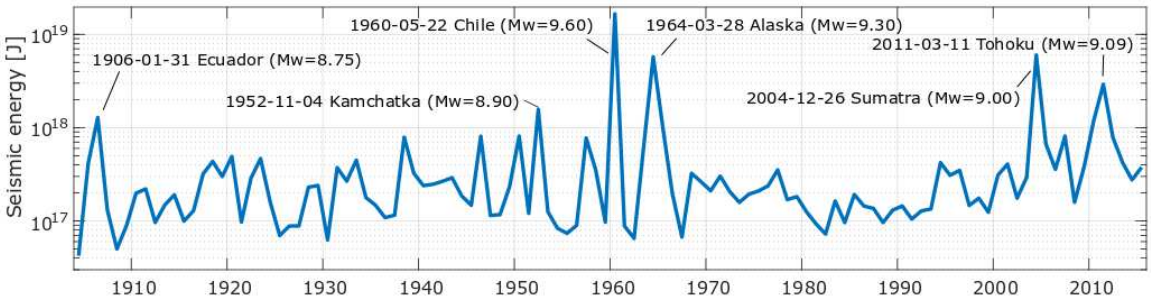


Figure 1: The released seismic energy from 1904 until the end of 2015, calculated from the Mw values of the ISC-GEM Catalogue. Events that cause the peaks of energy above $10^{18}$ J are identified.

## 4. THE EFFECT OF EARTH ROTATION ON GLOBAL SEISMICITY

The seismic energy distribution with respect to latitude was calculated from all events contained in the ISC-GEM Catalogue from 1904 until the end of 2015 (35 712 events). We aimed to determine the so-called 'effectiveness' of each latitude zone by dividing the radiated seismic energy with the subduction zone length. The result of this calculation is presented in Figure 2, which also contains the 'effectiveness' of the earthquakes in line with the depth zones.

The overall 'effectiveness' of the Earth's seismicity is determined by the shallow focus earthquakes, due to the fact that they produce most of the radiated elastic energy. The 'effectiveness' in this brittle outer part of the Earth (focal depth $\leq$ 70 km) has two sharp maxima at mid-latitudes which shows that the radiated energy is likely to be influenced by the stress built up by the despinning of Earth rotation. This means that the seismic activity of our planet in addition to the tectonic processes is affected by an external component too, through variations of the hydrostatic figure of the Earth. Comparison of the 'effectiveness' in different depth zones show the same tendencies (two large peaks) around mid-latitudes. As we look in deeper zones, the peaks of 'effectiveness' tend to move towards the equator. This difference of 'effectiveness' suggests that shallow and deep earthquakes have different tectonic origin. Another feature that can be observed is that the point of symmetry of the peaks is not precisely at the equator, but around $\phi = 15°$N. The cause of this asymmetry is still unknown. The presence of the two large peaks on Figure 2 are the result

of the constant change in the geometrical flattening of the Earth due to the secular despinning. Based on Melosh (1977), Amalvict and Legros (1996), Denis and Varga (1990) have derived the stress tensor components that would be caused by this variation. Denis and Varga (1990) have shown how changes in geometrical flattening cause variations in the stress tensor components. They found that at the so-called critical latitude ($\phi = \pm 48.2°$) the stress derivatives have their maxima, thus generating the greatest stress along the latitude.
Earth experiences a constant loss of rotational speed because of tidal friction. Due to this, the secular despinning of the Earth amounts to $\Delta$LOD = (2.31 $\pm$ 0.1) ms/century (Stacey, 1992). Changes in the rotational speed result in flattening variations. The results shown in Figure 2 hint that the two processes are related to each other through seismicity: tidal friction influences the seismic energy release at mid-latitudes significantly - variations of the rotational speed (the constant despinning of the Earth) highly affect the global seismicity.

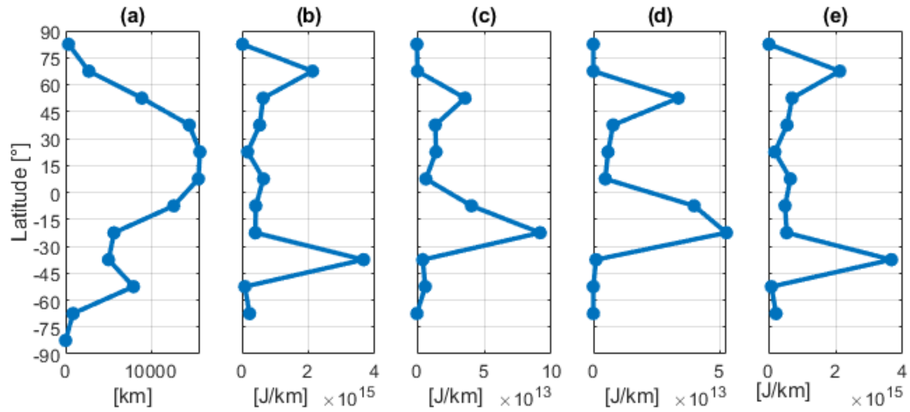


Figure 2: The latitudinal distribution of the subduction zone lengths (a), the 'effectiveness' of the shallow (0 - 70 km) (b), intermediate (70 - 300 km) (c) and the deep focus (300 - 700 km) earthquakes (d). The cumulative 'effectiveness' of seismic energy w.r.t. latitude (e).

## 5. IMPACT OF LARGE EARTHQUAKES ON THE ROTATION OF EARTH

### 5.1 Applied formulation

There have been two main approaches to calculate the co-seismic effect on Earth rotation: dislocation theory and normal mode method. Both are based on the fact that mass re-distributions caused by earthquakes cause changes in the Earth's inertia tensor, which affects the vector of rotation of the Earth (both its speed and direction) in the light of the angular momentum conservation. In this paper, the calculation of the co-seismic changes in Earth rotation was performed based on the formulation presented by Xu et al. (2014). One should note that the PM excitation is about 300 times more efficient than the excitation of $\Delta$LOD (Xu et al., 2014). Using this method, one can determine the co-seismic $\Delta$LOD and $\Delta$PM from the parameters of an earthquake: source parameters (strike, dip, slip), Mw and location (geographical latitude, longitude and focal depth). The paper by Xu et al. (2013) contains a detailed description how these parameters can change the results.

### 5.2 Result of the modelled co-seismic changes in Earth Rotation

With the procedure described in the previous section, using the earthquake parameters from the ISC-GEM Catalogue, the co-seismic changes in $\Delta$LOD and $\Delta$PM (displacement of the figure axis) were calculated from 2000 until the end of 2015 (Figure 3). This period was chosen because of the availability of the Earth rotation predictions provided by IERS Bulletin A. From Figure 3 one can see that the co-seismic changes both in $\Delta$LOD and $\Delta$PM are highly correlated with the released seismic energy of an earthquake. It is evident, that only a few large earthquakes can produce observable effects in PM, and co-seismic ΔLOD cannot be detected at the current level of data precision. Figure 3d illustrates more clearly the generated PM in 2D for case of four seismic events (Sumatra 2004 M=9.3, Chile 2010 M=8.9, Tohoku-Oki 2011 M=9.1, and Sumatra 2012 M=8.6). Details and exact co-seismic values of these four events are presented in Table 1.

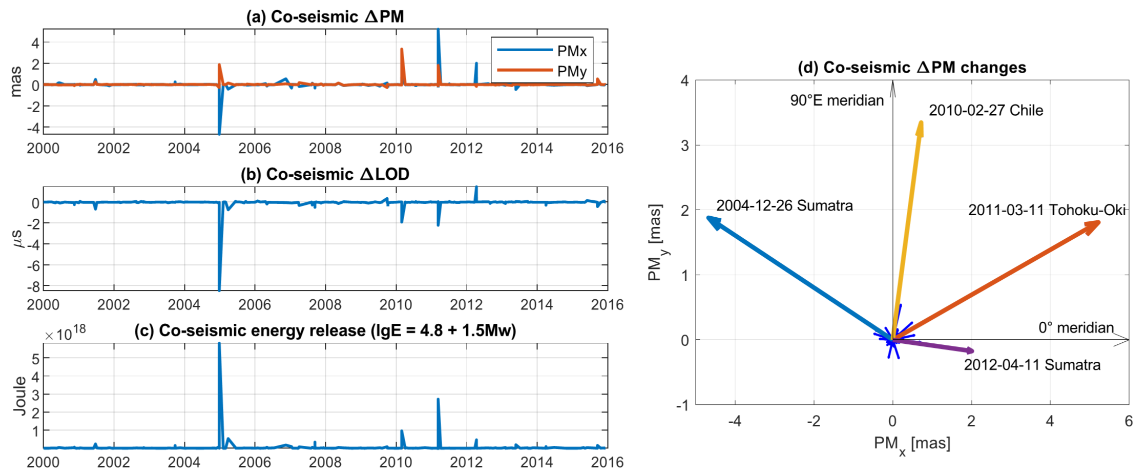


Figure 3: Coseismic changes in ERP (a-b, d) and released seismic energy (c) of Mw ≥ 7 earthquakes (235 events).

| | 2004. 12. 26. Sumatra | 2010. 02. 27. Chile | 2011. 03. 11. Tohoku-Oki | 2012. 04. 11. Sumatra |
|---|---|---|---|---|
| **Mw [ISC]** | 9.3 | 8.9 | 9.1 | 8.6 |
| **Depth [ISC]** | 30 km | 20 km | 25 km | 20 km |
| **ΔLOD [$\mu$s]** | -8.473 | -1.916 | -2.217 | 1.469 |
| **ΔPMx [mas]** | -4.675 | 0.720 | 5.217 | 2.009 |
| **ΔPMy [mas]** | 1.880 | 3.346 | 1.810 | -0.173 |

Table 1: Parameters and co-seismic changes of the largest co-seismic effects (2000-2016).

## 5.3 First results in the detection of co-seismic ERP changes

Using the modelled values of the co-seismic Earth rotation changes, our aim was to prove that this signal is present in the Earth rotation observations. However, this is a complicated task. Earth rotation is measured continuously and its variations are uniformly sampled. In contrast, earthquakes occur in a stochastic way, which means that special tools have to be applied when trying to determine their temporal characteristics. The second reason is that the signal to be proven has a magnitude in the vicinity of the current precision of ERP measurements. Lastly, the co-seismic signal is orders of magnitude smaller than the observed one. This means that one should remove each modelled signal from the observations, but doing this more errors are added to the resulting residual, and that is unfortunate given the fact that the co-seismic signal is already near the precision of the measurements.

In order to bypass the above mentioned difficulties, our first approach was to look into the prediction errors of Earth rotation. Because of the their hazardous occurrence the earthquakes cannot be accounted anyhow in ERP prediction. In this respect, the co-seismic excitation could impact the prediction error of ERP at the prediction dates when an powerful Earthquake occurs. The prediction error is estimated by removing from the ERP predictions (IERS Bulletin A) the corresponding observed values (IERS C04). Since Bulletin A is published every 7 days and each release contains 365 days of prediction, we always used the most recent predicted values in our analysis. The result of these calculations for 10 weeks before and after the four events listed in Table 1 is presented in Figure 4, where the vertical axis shows the days into the prediction and the horizontal axis the week of the prediction (with a total of 20 weeks centered around the seismic event).

There is a promising signal in the PMx component at the 2004 Sumatra event as high as the expected (modelled) co-seismic ΔPMx value. However, if we look further, there are no such promising results, in some cases, the large prediction errors are present a few weeks after or even before the earthquake. This suggests that this method is either unable to prove the existence of the co-seismic signal or that our hypothesis was somewhere wrong, in the worst case, that the model was wrong.

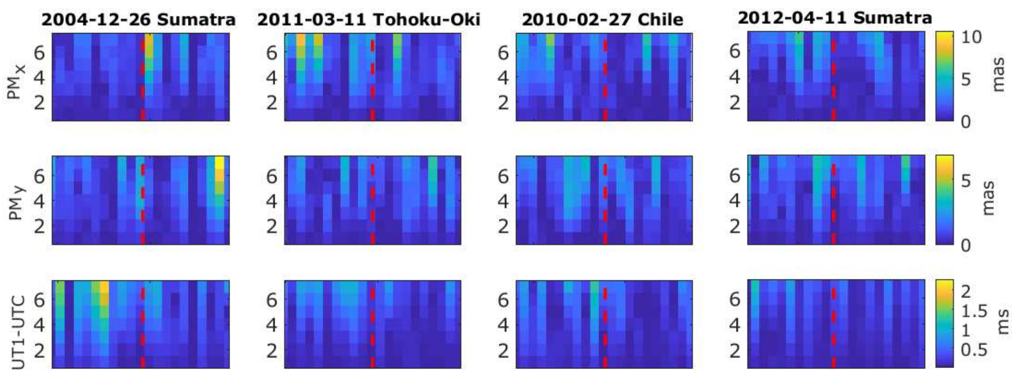


Figure 4: The prediction errors 10 weeks before and after the events listed in Table 1.

## 6. DISCUSSION AND CONCLUSIONS

In this paper, the interrelation of Earth rotation and seismicity is studied.
The seismic 'effectiveness' in line with the latitude shows two significant peaks at mid-latitudes. This is likely to be a result of the despinning of the Earth due to tidal friction. It was also seen that different depth zones show similar patterns but as we look into deeper zones, the energy peaks move towards the equator. This suggests that they have different tectonic origin. Also, the peaks present a symmetry with respect to $\phi = 15°$N, of which the reason is still unknown.
In the second part of this paper, we studied how individual earthquakes can affect Earth rotation. We have modelled co-seismic changes in the ERP and we presented the result of a preliminary approach in order to prove that the modelled signal is present in the observations. To this aim we have calculated the prediction errors and so far our results do not confirm the expectations. Further studies will be performed in order to draw a more sound conclusion in this topic.

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