Worldwide Statistical Correlation of eight years of *Swarm* satellite data with M5.5+ earthquakes: new hints about the preseismic phenomena from space

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Supplementary Materials

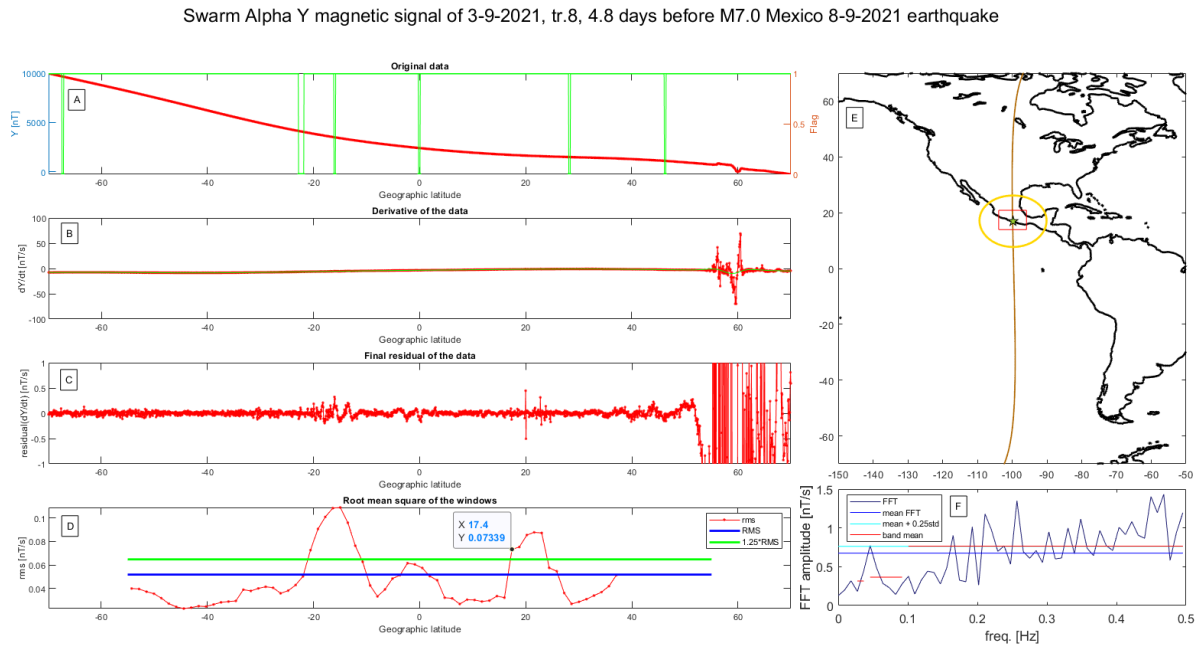

Figure S1: Example of processing of Y-East magnetic component in one track of Swarm Alpha satellite that crossed 4.8 days before the Dobrovolsky area of the M7.0 Acapulco, Mexico earthquake occurred on 8 September 2021 at 1:47UT at 20km depth. Swarm Alpha detected an anomaly that contributed to the maximum concentration of anomalies of the Figure 3B in the main text. A) Original data in red and quality check in green (0 = nominal data, 1 = some flags indicate possible problems on instrument or satellite). B) Numerical derivative of the data (i.e. first differences) with green line that is the fit by cubic-spline of the derivative. C) Final residual of the data where the anomalies are searched. D) Root mean square of the sliding 7° latitude window (red points). The Root Mean Square (RMS) of the whole track is indicated by blue line and the threshold used in Figure 3B is indicated by a green line. The datatip underlines an anomaly that is associated by the WSC to this earthquake and its Fast Fourier Transorm is shown in F. E) Map with the projection of the satellite track (brown line), the Dobrovoslky area (yellow circle), the epicenter (green star) and the anomalous window associated to this earthquake (red box). F) FFT of the signal in the anomalous window with the indication of the mean (dark blue line) and + 0.25 standard deviations (cyan line), as well as the mean intensity of the spectrum in the analysed bands (red lines).

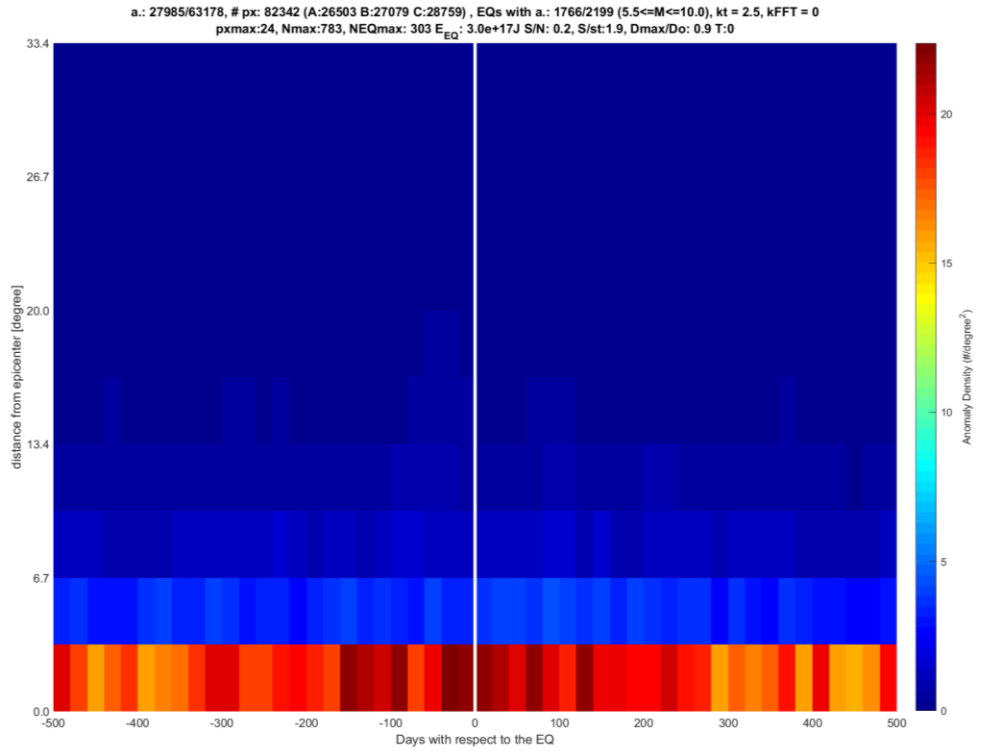

Figure S2: Worldwide Statistical Correlation of Swarm magnetic anomalies with M5.5+ EQs from 500 days before until 500 days after the EQ occurrence inside their Dobrovolsky areas.

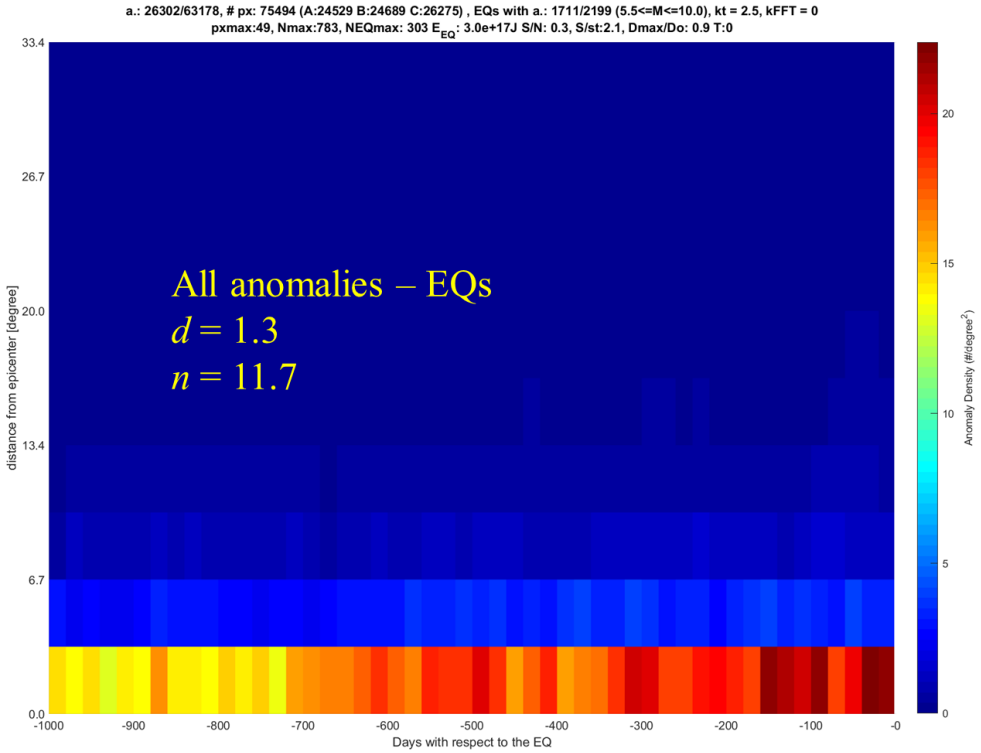

Figure S3 Worldwide Statistical Correlation of Swarm magnetic anomalies with M5.5+ EQs from 1000 days before the earthquake until its occurrence inside their Dobrovolsky areas.

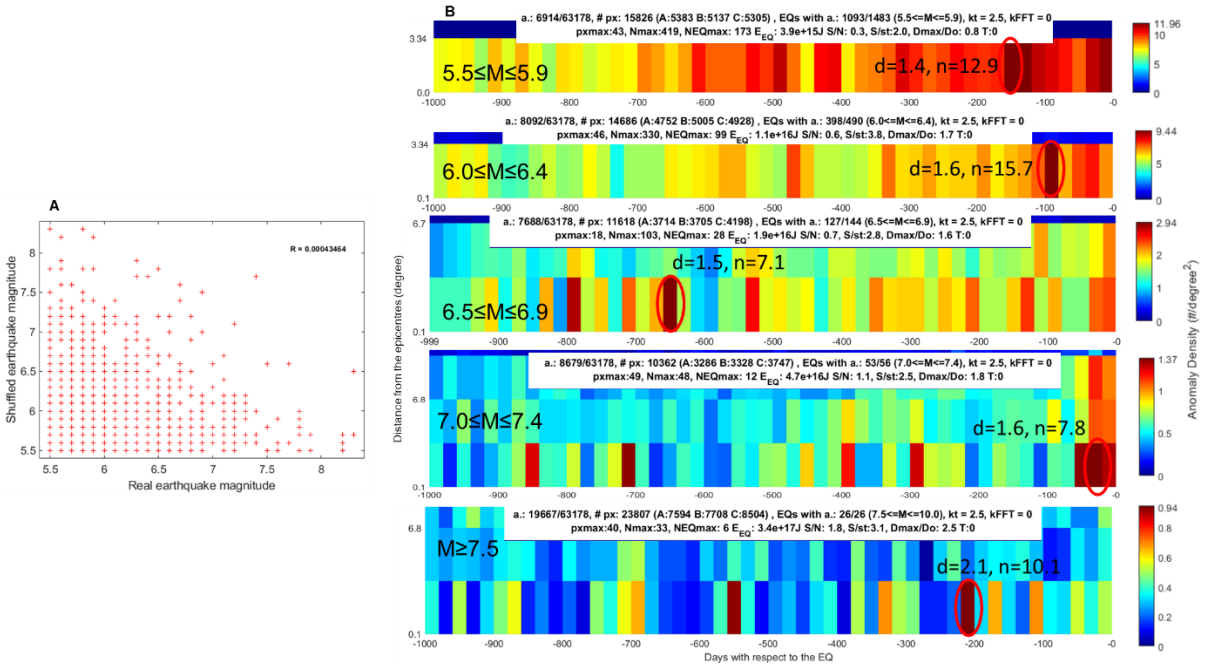

Figure S4 Worldwide Statistical Correlation of Swarm magnetic anomalies with earthquakes after shuffling their magnitudes and applying Method 1. A) Earthquake magnitudes after shuffling versus real magnitudes. B) WSC applied in the several magnitude bands of the shuffled events.

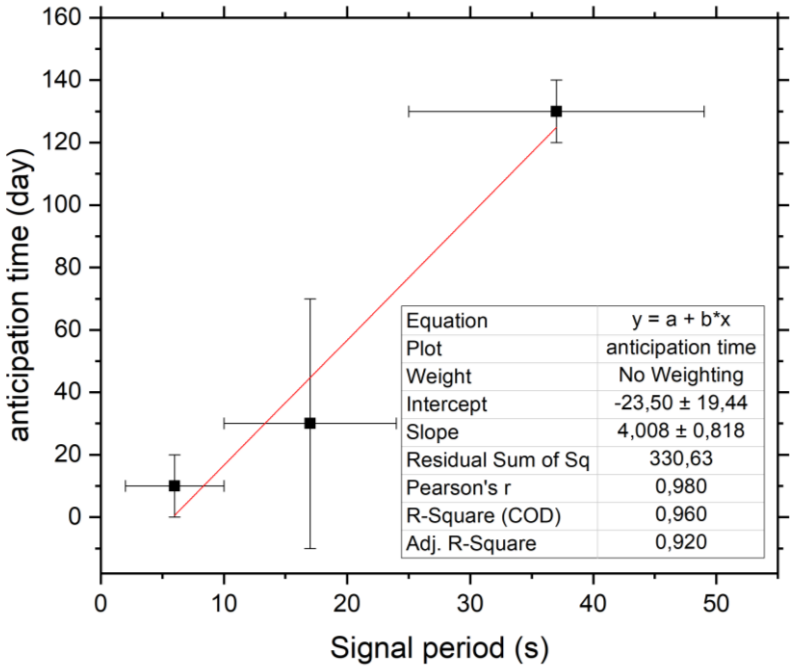

Figure S5: Fit of the anticipation time (as automatic maximum concentration extracted from Figure 3 of the main manuscript) in function of the period of the magnetic signal of Swarm investigating a time window fro 500 days before until 500 days after.

Table S1 Statistical evaluation of the results for the *Swarm* magnetic field.

Figure	Parameter, time-window, EQ magnitude	Method [1]	D_{MAX}/D_0 [2]	*d* [3]	*n* [4]	Maximum concentration [5] (days w.r.t. the EQ)	EQs in maximum concentration [6]
Figure S2	**Y, -500,500, M5.5+**	(1) all anom.-EQs	0.9	1.3	8.1	-30 ± 10 days	303 (14%)
Figure 2	**Y, -1000,0 5.5≤M≤5.9**	(1) all anom.-EQs	0.8	1.4	12.9	-90 ± 10 days	186 (13%)
	Y, -1000,0 6.0≤M≤6.4	(1) all anom.-EQs	1.4	1.3	8.5	-30 ± 10 days	97 (20%)
	Y, -1000,0 6.5≤M≤6.9	(1) all anom.-EQs	1.5	1.4	5.8	-290 ± 10 days	31 (22%)
	Y, -1000,0 7.0≤M≤7.4	(1) all anom.-EQs	1.9	1.5	6.7	-590 ± 10 days	12 (21%)
	Y, -1000,0 M7.5+	(1) all anom.-EQs	2.3	2.0	8.6	-850 ± 10 days	6 (23%)
Figure 1	**Y, -90,30, M5.5+**	(1) all anom.-EQs	1.8	1.7	12.5	-24 ± 1 days	46 (2%)
	Y, -90,30, M5.5+	(2) min [log(ΔT R)]	1.6	1.6	9.7	-12 ± 1 days	41 (2%)
	Y, -90,30, M5.5+	(3) max-Mag	1.7	1.8	16.0	+12 ± 1 days	35 (2%)
	Y, -120,0, M5.5+	(4) Rikitake	1.7	1.7	15.7	-25 ± 1 days	44 (2%)
Figure 3	**Y (2-10) s, -500,500, M5.5+**	(1) all anom.-EQs	1.3	1.6	16.0	-10 ± 10 days	146 (7%)
	Y (10-25) s, -500,500, M5.5+	(1) all anom.-EQs	1.0	1.3	6.3	-30 ± 10 days	137 (6%)
	Y (25-50) s, -500,500, M5.5+	(1) all anom.-EQs	0.9	1.2	5.7	-130 ± 10 days	146 (7%)

[1] Method: the method used to select which earthquake can be associated with the anomaly in the case more than one EQ is compatible with the same anomaly.

[2] D_{MAX}/D_0: Ratio between the maximum concentration of anomalies with respect to the density of homogeneous random distribution of all the anomalies..

[3] "*d*" represents the number of times that the maximum concentration is greater (if > 1) than the one expected for a space-time homogeneous random distribution.

[4] "*n*" is an estimation of how many standard deviations the real largest concentration is larger than that of the random one.

[5] Maximum concentration: the number of days with respect to the EQ occurrence where the code identifies the maximum concentration of anomalies in the closer distance with respect to the earthquake epicentre. Negative number indicates that the concentration is before the earthquake (so it is a possible precursor) and positive after the earthquake.

[6] EQs in maximum concentration: the number of earthquakes that have at least one anomaly in the maximum concentration. In bracket, it is indicated the percentage of earthquakes with respect to the total number of analysed earthquakes.

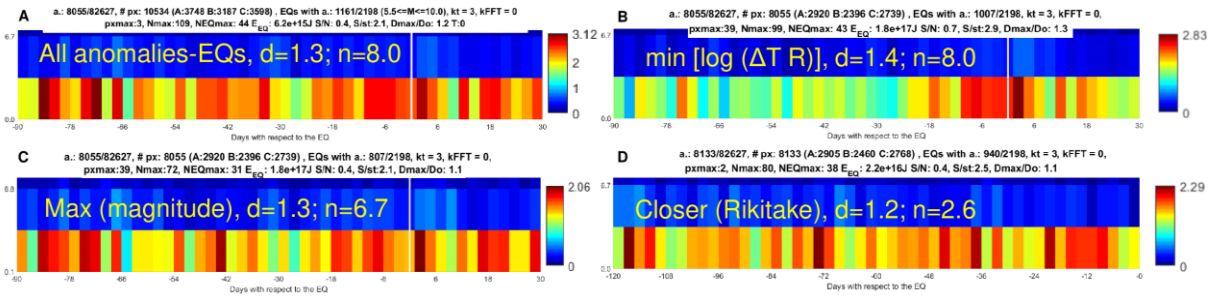

Figure S6: Correlation of Swarm Ne anomalies with M5.5+ earthquakes using four different methods: A) all anomalies are associated with all compatible earthquakes; B) each anomaly is associated with the closer earthquake in space and time, i.e. the minimum of log(ΔT R); C) the anomaly is associated with the greatest magnitude earthquake; D) the anomaly is associated with the earthquake closer to the Rikitake's law with coefficients from De Santis et al., [1]. The graphs are cut for the upper part without significant information.

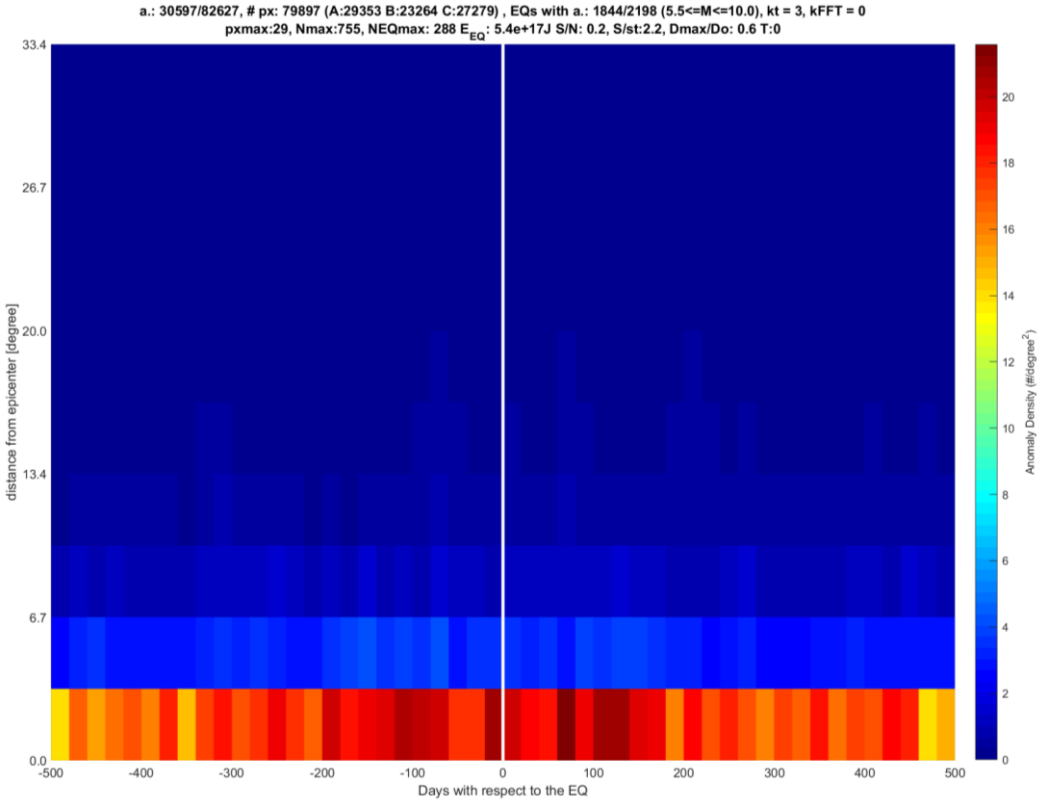

Figure S7: Worldwide Statistical Correlation of Swarm electron density anomalies with M5.5+ EQs from 500 days before until 500 days after the EQ occurrence inside their Dobrovolsky areas.

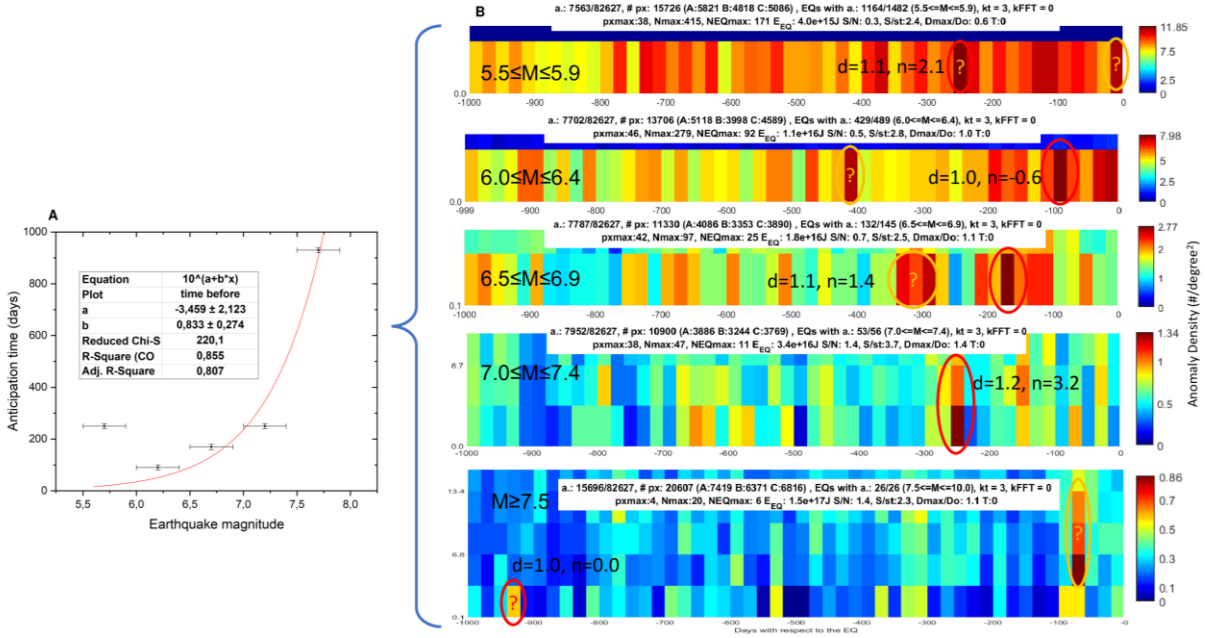

Figure S8: Correlation of Swarm Ne anomalies with earthquakes divided into 5 magnitude bands by applying Method 1. A) Fit of the anticipation time of maximum concentration (underlined by a red circle in subfigure B) in function of earthquake magnitude using the equation $\Delta T = 10^{a+b \cdot M}$ *. B) Details of the analysis in the earthquake magnitude bands of* $5.5 \leq M \leq 5.9$*,* $6.0 \leq M \leq 6.4$*,* $6.5 \leq M \leq 6.9$*,* $7.0 \leq M \leq 7.4$ *and* $M \geq 7.5$*. Only the significant part of the superposed space-time graph is represented. The statistical indication of d (i.e. how many times the maximum real concentration is higher than the random one) and n (i.e. how many standard deviations the real largest concentration is greater than the random one) are also shown. Other high Ne anomalies concentrations are underlined with orange circles and a question point is inserted when there is some visual ambiguity in the concentration.*

Table S2 Statistical evaluation of the results for the *Swarm* electron density (Ne).

Figure	Parameter, time-window, EQ magnitude	Method [1]	D_{MAX}/D_0 [2]	d [3]	n [4]	Maximum concentration [5] (days w.r.t. the EQ)	EQs in maximum concentration [6]
Figure S7	**Ne, -500,500, M5.5+**	(1) all anom.-EQs	0.6	0.9	-5.2	70 ± 10 days	288 (13%)
Figure S8	**Ne, -1000,0 5.5≤M≤5.9**	(1) all anom.-EQs	0.6	1.1	2.1	-250 ± 10 days	171 (12%)
	Ne, -1000,0 6.0≤M≤6.4	(1) all anom.-EQs	1.0	1.0	-0.6	-90 ± 10 days	92 (19%)
	Ne, -1000,0 6.5≤M≤6.9	(1) all anom.-EQs	1.1	1.1	1.4	-170 ± 10 days	25 (17%)
	Ne, -1000,0 7.0≤M≤7.4	(1) all anom.-EQs	1.4	1.2	3.2	-250 ± 10 days	11 (20%)
	Ne, -1000,0 M7.5+	(1) all anom.-EQs	1.1	1.0	0.0	-930 ± 10 days	6 (23%)
Figure S6	**Ne, -90,30, M5.5+**	(1) all anom.-EQs	1.2	1.3	8.0	-84 ± 1 days	44 (2.0%)
	Ne, -90,30, M5.5+	(2) min [log(ΔT R)]	1.3	1.4	8.0	+2 ± 1 days	43 (2.0%)
	Ne, -90,30, M5.5+	(3) max-Mag	1.1	1.3	6.7	+2 ± 1 days	31 (1.4%)
	Ne, -120,0, M5.5+	(4) Rikitake	1.1	1.2	2.6	-116 ± 1 days	38 (1.7%)
Figure 4	**Ne (2-10) s, -90,30, M5.5+**	(1) all anom.-EQs	4.2	1.7	8.8	-50± 1 days	17 (0.8%)
	Ne (10-25) s, -90,30, M5.5+	(1) all anom.-EQs	5.3	2.4	19.6	0 ± 1 days	19 (0.9%)
	Ne (25-50) s, -90,30, M5.5+	(1) all anom.-EQs	3.1	2.5	27.2	-59 ± 1 day	42 (1.9%)
	Ne (2-10) s, -500,500, M5.5+	(1) all anom.-EQs	1.1	1.3	8.0	+50 ± 10 days	101 (4.6%)
	Ne (10-25) s, -500,500, M5.5+	(1) all anom.-EQs	1.3	1.6	15.5	+50 ± 10 days	100 (4.5%)
	Ne (25-50) s, -500,500, M5.5+	(1) all anom.-EQs	1.3	1.8	31.3	-290 ± 10 days	230 (10%)

[1] Method: the method used to select which earthquake can be associated with the anomaly in the case more than one is compatible with the same anomaly.
[2] D_{MAX}/D_0: Ratio between the anomaly space-time density in the maximum concentration with respect to a uniform distribution of anomalies.
[3] "d" represents the times that the maximum concentration is greater (if > 1) than the one expected for a space-time homogeneous random distribution.
[4] "n" is an estimation of how many standard deviations the real largest concentration is more significant than the random one.
[5] Maximum concentration: the number of days where the code identifies the maximum concentration of anomalies in the closer distance with respect to the earthquake epicentre. A negative number indicates the concentration is before the earthquake (so it is a possible precursor) and positive after the earthquake.
[6] EQs in maximum concentration: the number of earthquakes that has one or more anomalies in the maximum concentration. In bracket, it is indicated the percentage of earthquakes with respect to the total number of analysed earthquakes.

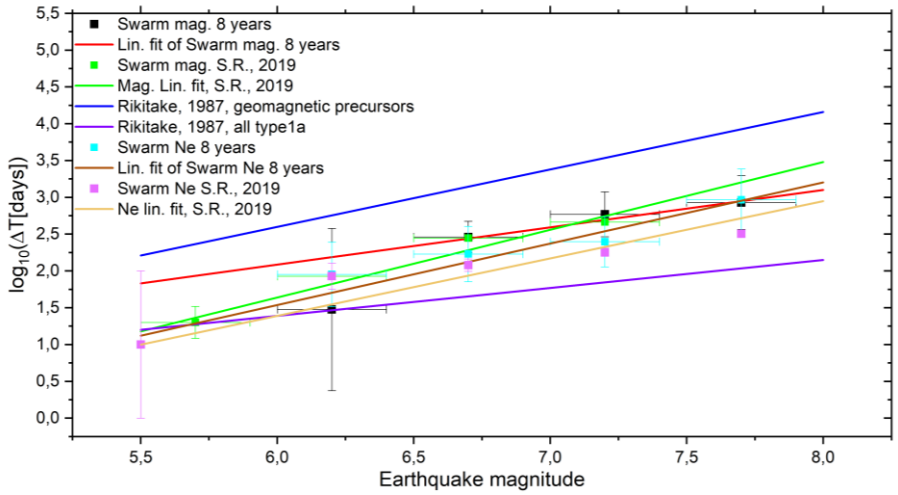

Figure S9: Comparison of Rikitake's law coefficients obtained in this work with previous ones published by Rikitake [2] and De Santis et al. [1].

References

1. De Santis, A.; Marchetti, D.; Pavón-Carrasco, F.J.; Cianchini, G.; Perrone, L.; Abbattista, C.; Alfonsi, L.; Amoruso, L.; Campuzano, S.A.; Carbone, M.; et al. Precursory worldwide signatures of earthquake occurrences on *Swarm* satellite data. Sci. Rep. 2019, 9, 1–13, doi:10.1038/s41598-019-56599-1.
2. Rikitake, T. Earthquake precursors in Japan: Precursor time and detectability. Tectonophysics 1987, 136, 265–282, doi:10.1016/0040-1951(87)90029-1.