Assessing the Interrelationship between Intense Geomagnetic Storms and Power Grid Dissruptions in Poland

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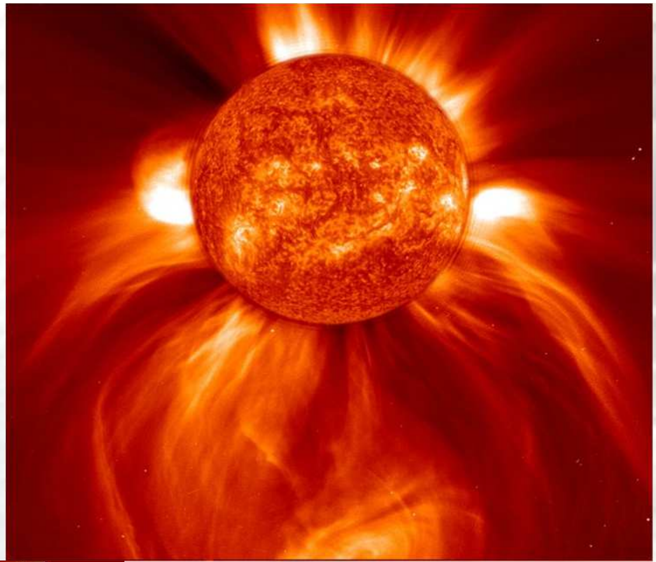
MOTIVATION: Our research focuses on investigating strong geomagnetic storms that occurred during the solar cycle 24. These kind of storms appeared not so often, and typically were accompanying by a southward-directed heliospheric magnetic field Bz. Through the use of different machine learning techniques such as self-organizing maps, we have demonstrated that an increase in the number of transmission line failures, potentially caused by solar activity, was observed during and immediately after strong geomagnetic storms. In addition, we analyzed the evolution of transmission line failures between 2010 and 2014 and observed a linear increase in their frequency, which may be associated with solar activity. To further investigate this connection, we compared these findings with the geoelectric field computed for the region of Poland, utilizing a 1-D layered conductivity Earth model.

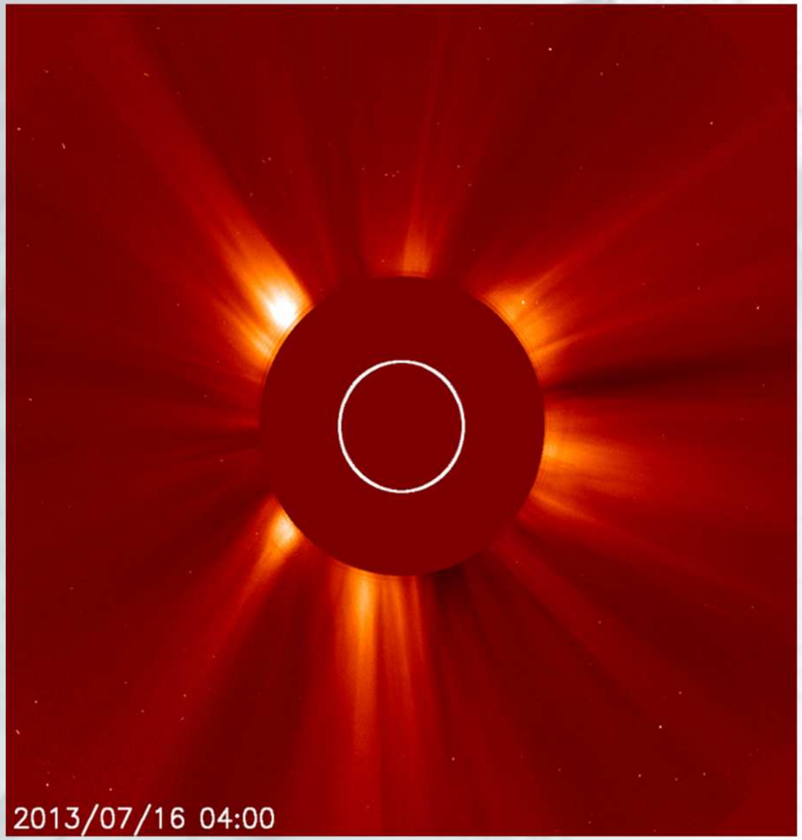
Over the Baltic Sea, 27.02.2023, by Rafał Krawczyk

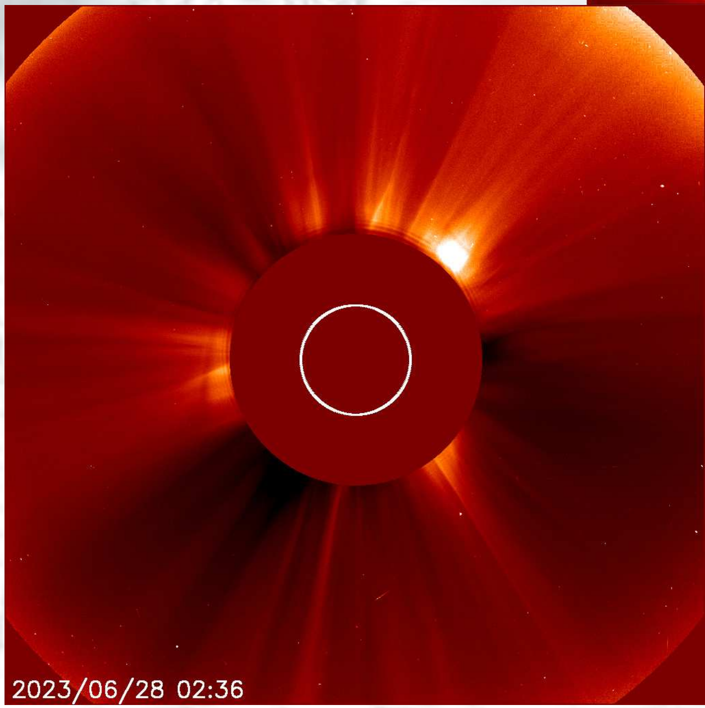
Gdańsk, 24.03.2023, from https://kontakt24.tvn24.pl/zorza-polarna-gdansk-gorki-zachodnie-24-03-2023,4038467,ugc

CME

LASCO
C2 coronagraph instrumen
t on the ESA-NASA SOHO
spacecraft, was taken 8
January 2002 and shows a
widely spreading CME

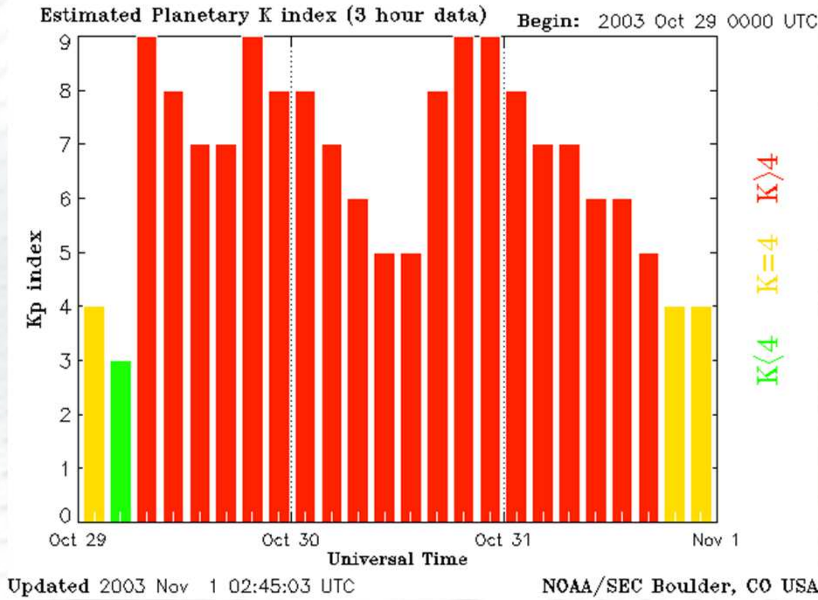


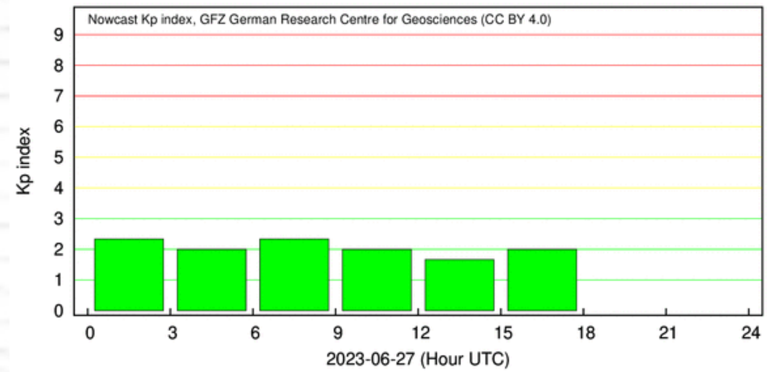


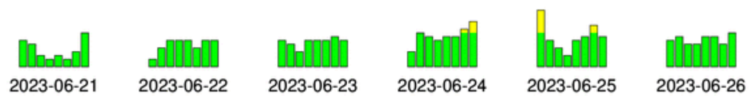


www.swpc.noaa.gov

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)







http://www-app3.gfz-potsdam.de

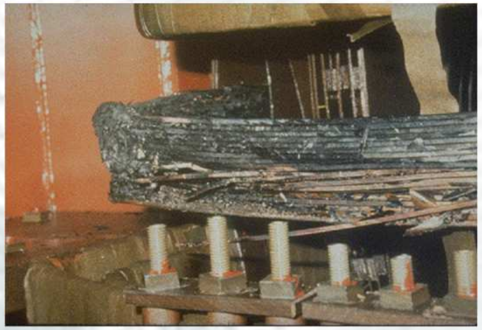
GIC among other effects

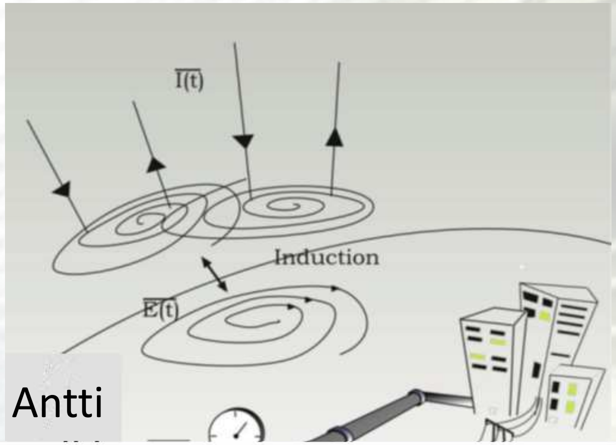
-electrical grids

- pipelines

-telecommunication cables

- railway

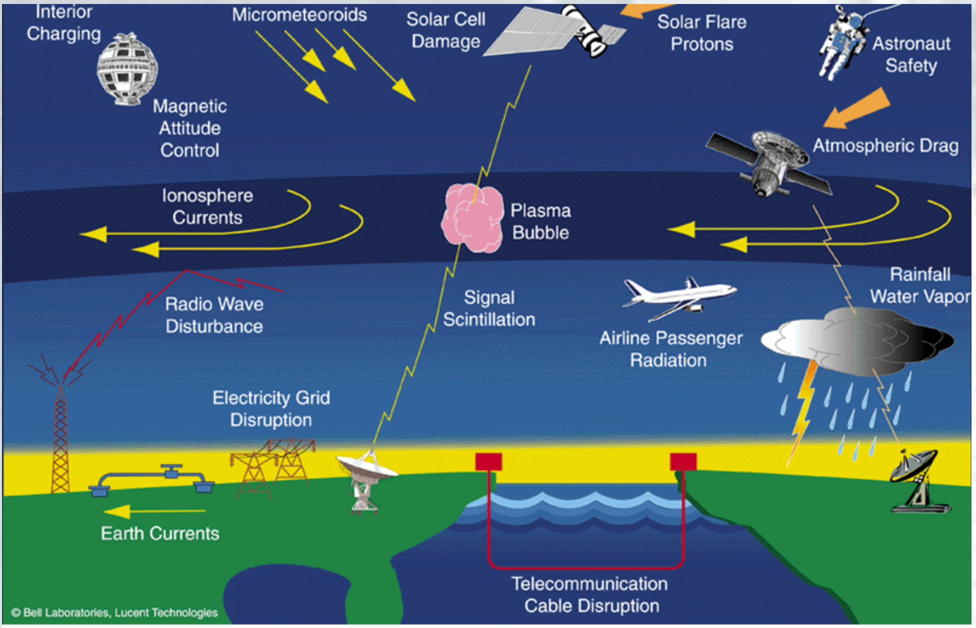




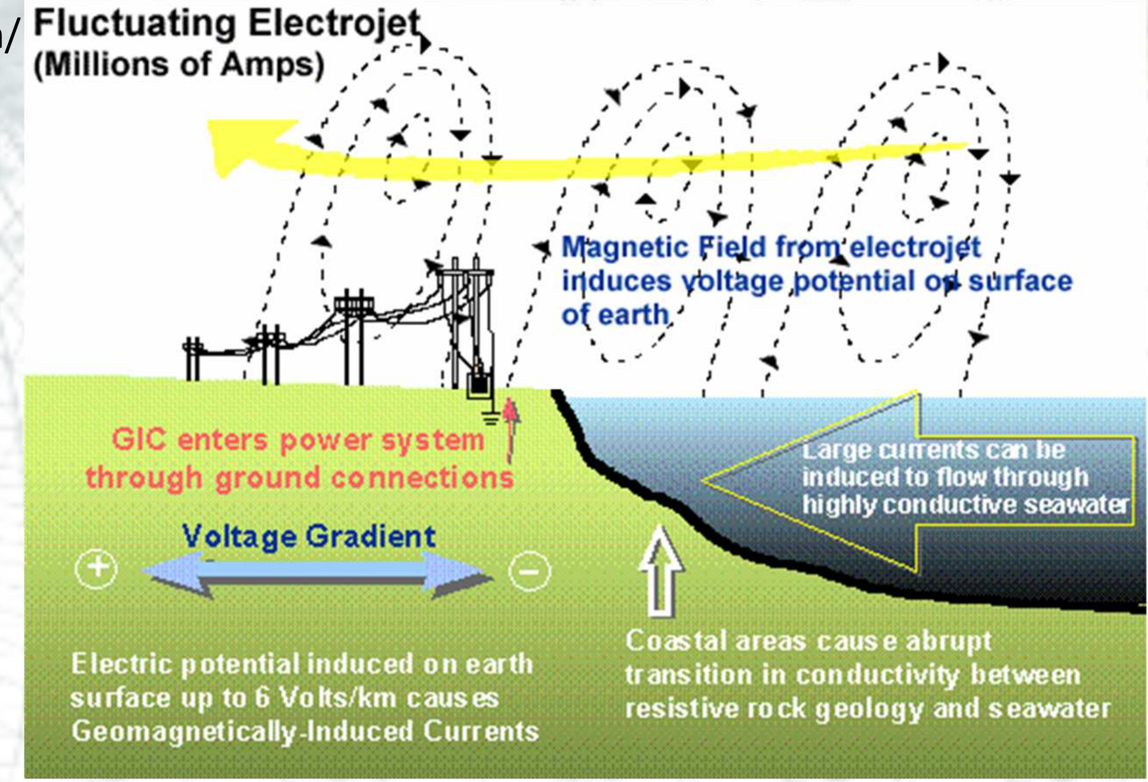
Antti

istp.gsfc.nasa.gov

http://www.metatechcorp.com/



The effects of magnetic storms - what scientists call space weather - extend from the ground to geostationary orbit and beyond.



Torta et al., 2012: *attempt to study and measure GICs in southern European* (Spain) *power grids, a region considered to have low GIC-risk up to the present*

Zois, 2013: *Contrary to common belief in PPC Greece, we see that there are considerable both short term (immediate) and long term effects of solar activity onto large transformers in a mid-latitude country like Greece*

Bailey et al., 2017: *We demonstrate that the Austrian power grid is susceptible to large GICs in the range of tens of amperes, particularly from strong geomagnetic variations in the east-west direction.*

Tozzi et al., 2019: *Results show that during periods of high magnetic activity, potentially detrimental GICs could flow through the power network, especially at the highest Italian latitudes that are characterized by a low conductivity lithosphere.*

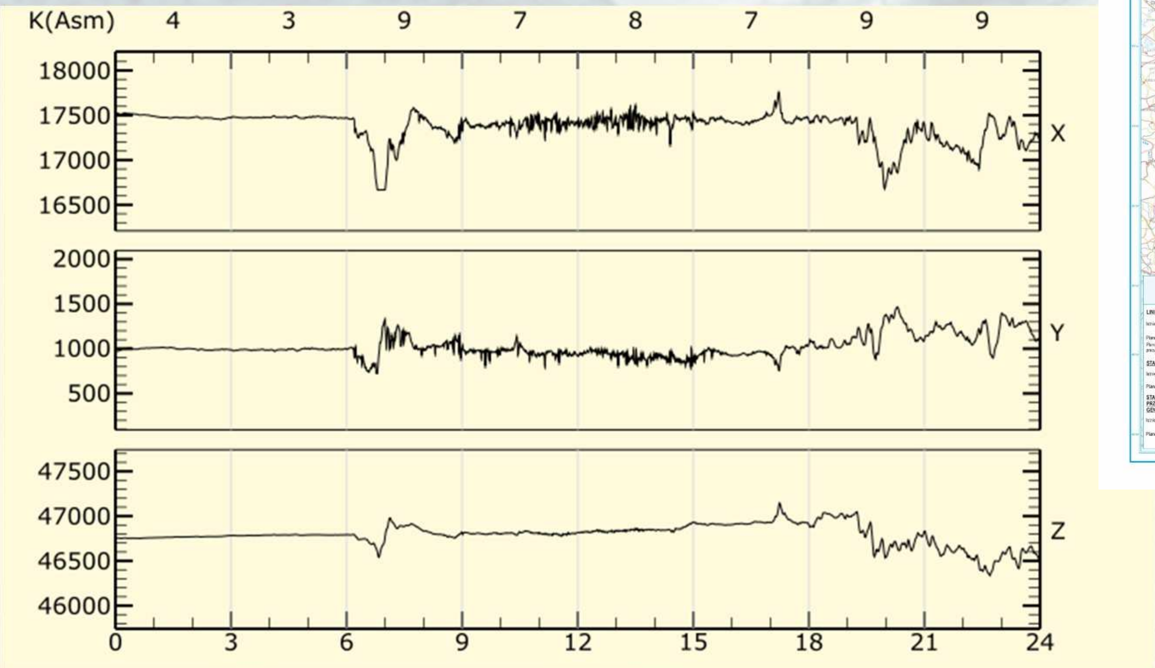
Švanda et al., 2020: *We show that in the 5-day period following the commencement of geomagnetic activity there is an approximately 5-10% increase in the recorded anomalies in the Czech power grid and thus this fraction of anomalies is probably related to an exposure to GICs.*

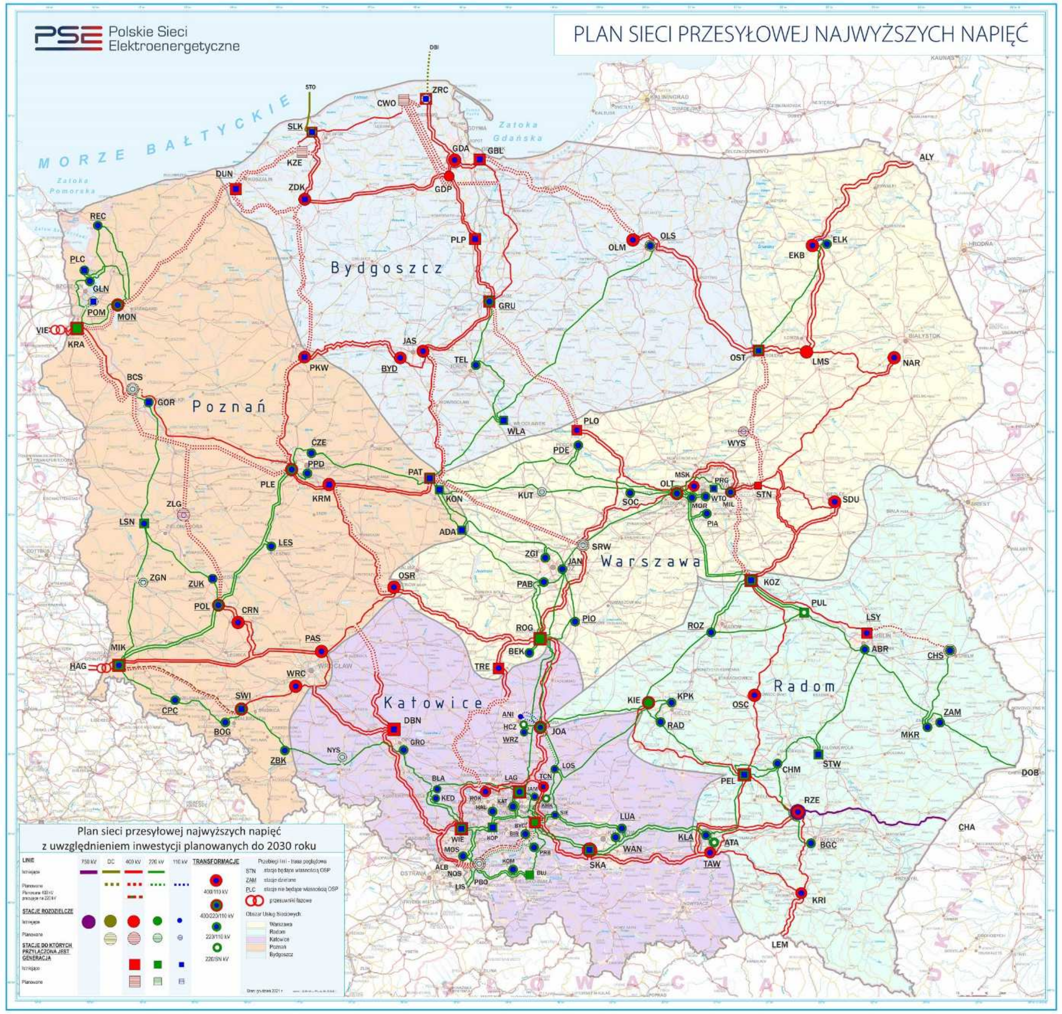
…

Malmo blackout, 30.10.2003 by GIC

29.10.2003, 07:46 interrupted import from Poland to Sweden, 300 MW, SwePol Link

Pulkkinen et al., 2005



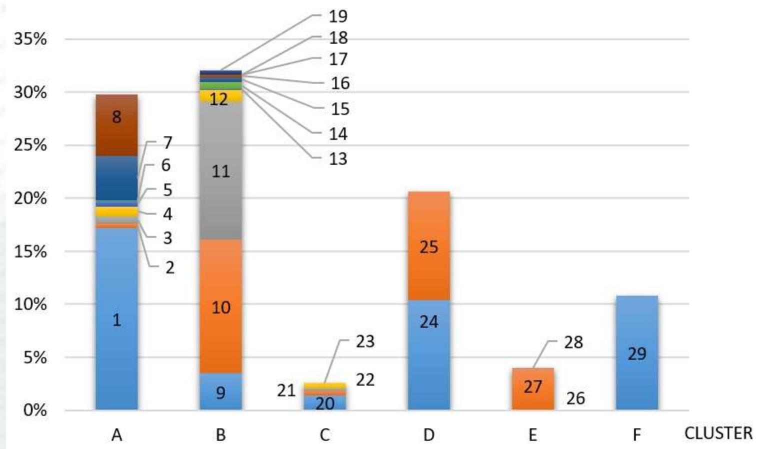


www.pse.pl/

INTERMAGNET: Magnetogram, Hel, 29.10.2003

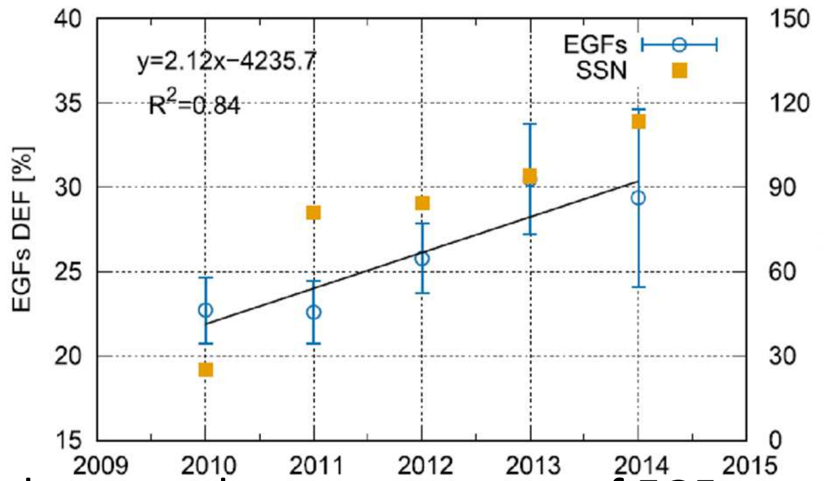
no.	reasons in 2014	main groups	number	%
1	storm		5195	17.2
2	ice& snow & rime		124	0.4
3	rime		197	0.7
4	rime& tree& branch		271	0.9
5	snow		154	0.5
6	snow& tree& branch		30	0.1
7	wind		1272	4.2
8	wind& tree& branch	A: meteorological effects	1761	5.8
		Total A	**9004**	**29.8**
9	protection devices		1065	3.5
10	switching		3800	12.6
11	planned breaks		3924	13.0
12	another operator		337	1.1
13	works of own brigades		38	0.1
14	open object		193	0.6
15	closed object		160	0.5
16	at the recipient		69	0.2
17	in order to save people		1	0.0
18	switching activities		6	0.0
19	assembly defects	B: operational shutdowns	110	0.4
		Total B	**9703**	**32.0**
20	charges, theft, disassembly		410	1.4
21	cutting down trees by other parties		132	0.4
22	fire		105	0.3
23	digging	C: vandalism	145	0.5
		Total C	**792**	**2.6**
24	aging		3135	10.4
25	local impairment of insulation	D: aging	3074	10.2
		Total D	**6209**	**20.6**
26	fuse		1	0.0
27	power system protection automation and telemechanics		1178	3.9
28	secondary circuits and power system protection automation	E: electronics devices	2	0.0
		Total E	**1181**	**3.91**
29	unidentified	**F: unidentified**	**3266**	**10.8**
		TOTAL	30155	100.0

Gil et al., 2019a, doi: 10.1186/s13362-019-0064-9



Groups (numbers as in the left column of the Table) and six general clusters of the EGF causes in 2014

Gil et al., 2021a, doi: 10.1051/swsc/2021013



Linear regression of the annual percentage rate of EGFs from D-F groups in 01.2010–07.2014 (circles, left axis) and yearly changes of SSN (squares, right axis).

Geoelectric Field Computation, Transfer Function - 1D model

Earth conductivity varies in all directions, but the greatest variation is with depth

$$B(t)$$

↓

$$F\{B(t)\}$$

↓

$$K(f)$$

↓

$$E(t) = F^{-1}\left[K(f)\,F\{B(t)\}\right]$$

Layered Conductivity Model

N layers, each specified by conductivity (σ_n) and thickness (l_n)

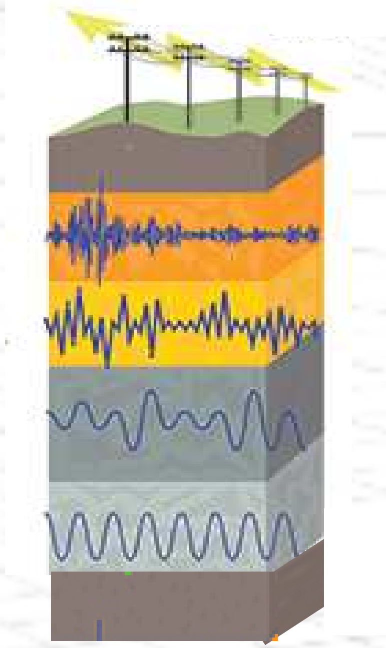
$$K_n = \eta_n \frac{K_{n+1}(1 + e^{-2k_n l_n}) + \eta_n(1 - e^{-2k_n l_n})}{K_{n+1}(1 - e^{-2k_n l_n}) + \eta_n(1 + e^{-2k_n l_n})}$$

$$\eta_n = \frac{i2\pi f}{k_n}$$

$$k_n = \sqrt{i2\pi f \mu_0 \sigma_n}$$

$$\mu_0 = 4\pi 10^{-7} \mathrm{H}^{-1}\mathrm{m}$$

$$K_N = \sqrt{\frac{i2\pi f}{\mu_0 \sigma_N}}$$



Boteler, 1994; Boteler, 2012;
Boteler and Pirjola, 2019

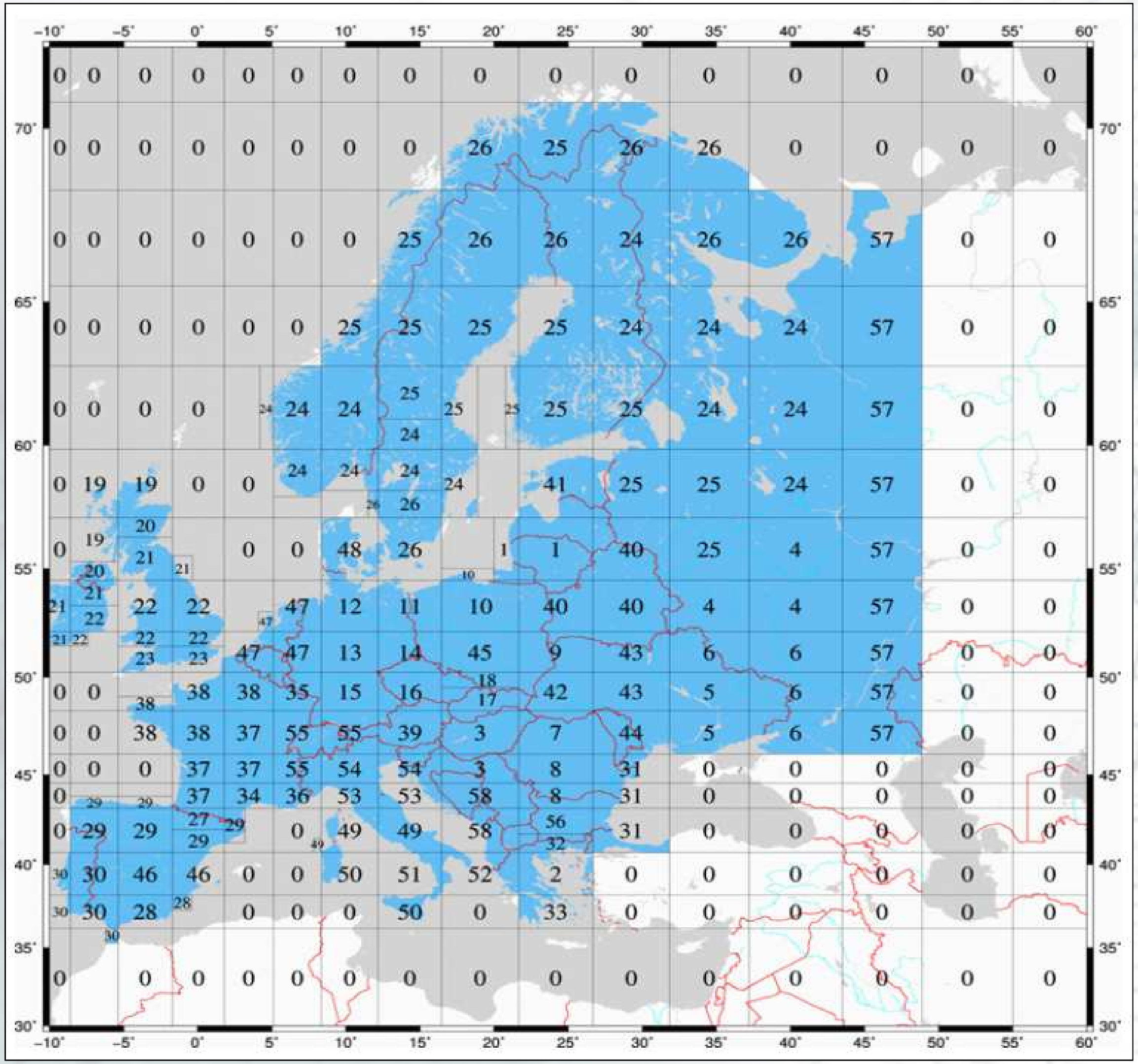


Figure: 1D resistivity models in Europe

Number of layers

Conductivity (σ=1/ρ)

Thickness (l=d)

Layer	ρ Ωm	d km	ϱ Ωm	d km
	Model 1		Model 2	
1	40.00	0.40	20.00	0.10
2	3.00	1.30	170.00	4.00
3	2000.00	140.00	65.00	11.90
4	118.00	170.00	17.00	50.00
5	15.00		0.20	
	Model 3		Model 12	
1	5.00	3.00	1.00	4.00
2	1000.00	57.00	200.00	4.00
3	10.00		0.50	1.50
4			200.00	2.00
5			1000.00	100.00
6			10.00	

Adam et al., EURISGIC, FP7, 2012

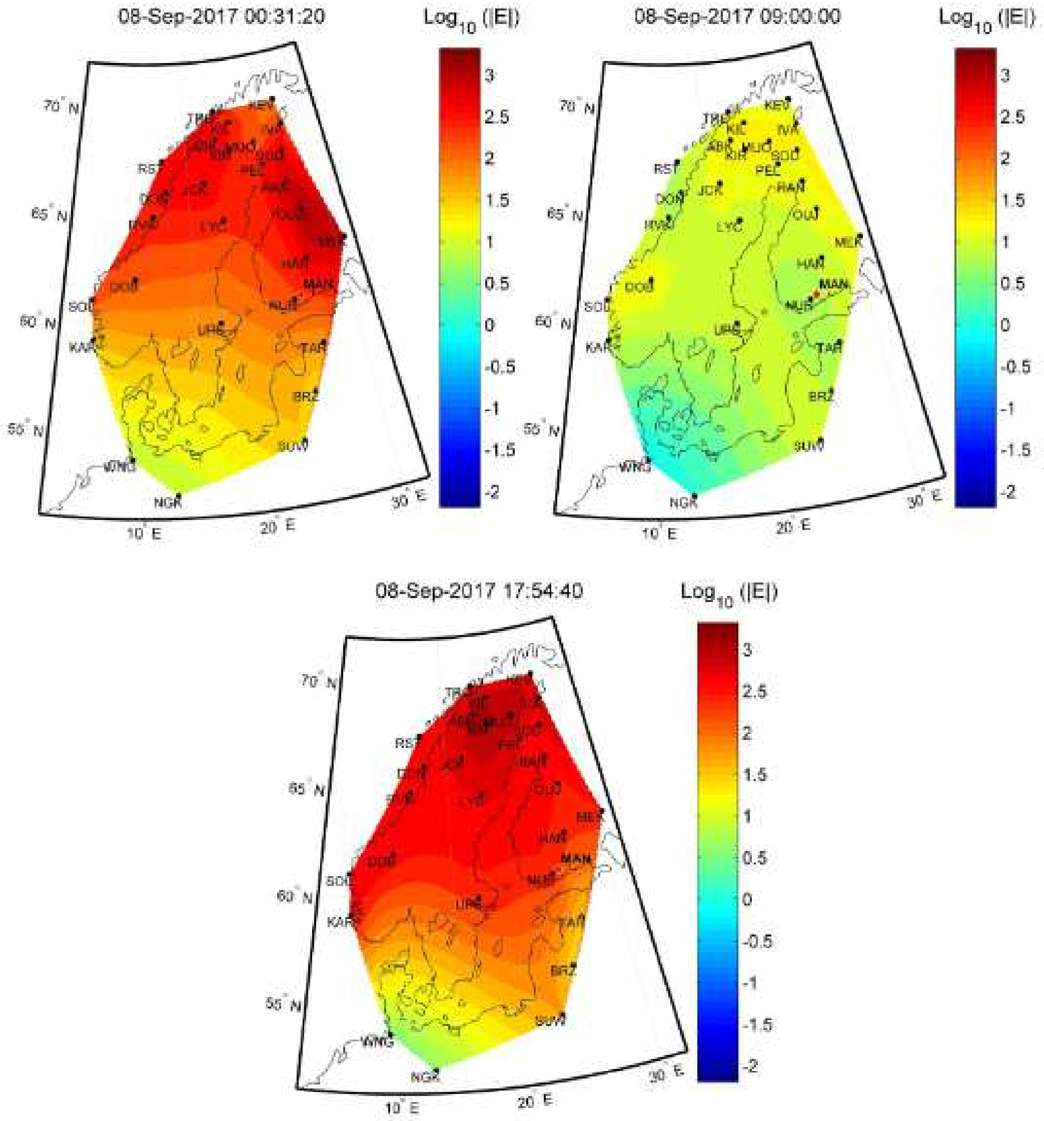


Figure 6. The 2-D spatial structure of geoelectric fields E at 00:31:20 UT, 09:00:00 UT, 17:54:40 UT, on 8 September 2017, reconstructed from the IMAGE magnetometers using the 1-D conductivity model. Color coding indicates $\log_{10}(|E|)$ [mV/km].

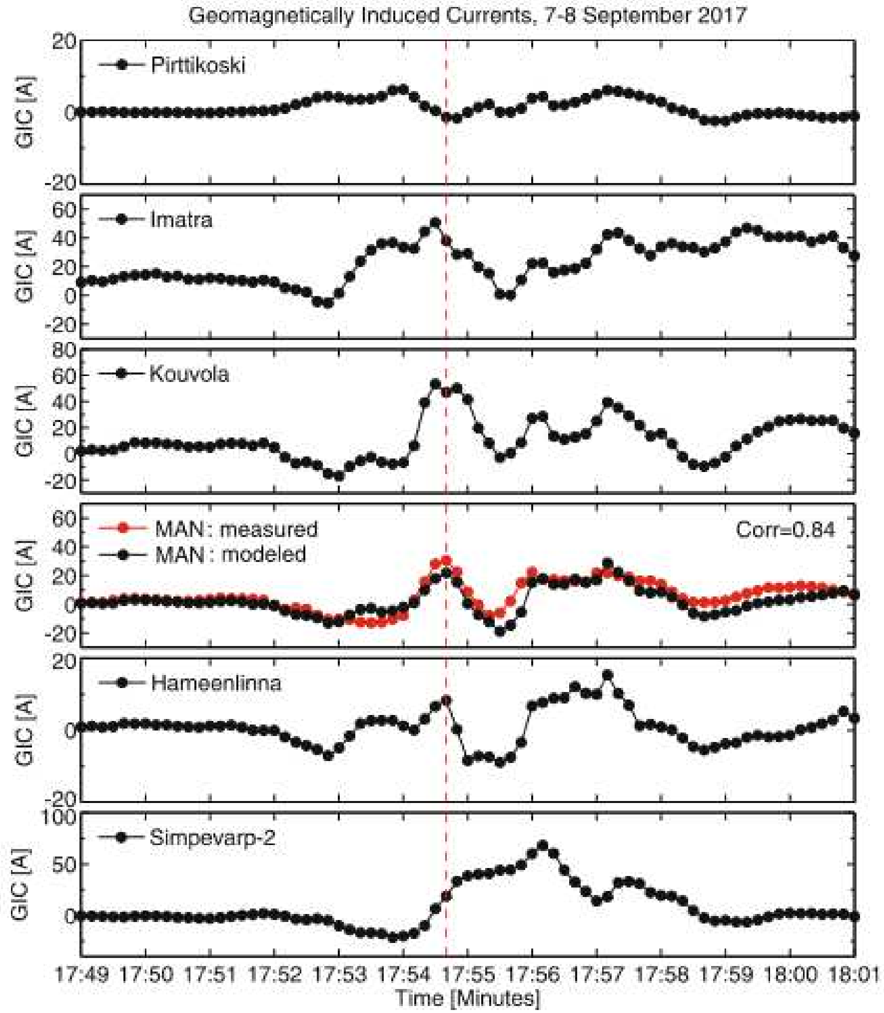


Figure 9. Time variation of geomagnetically induced currents values, determined for period between 17:49 UT and 18:01 UT on 8 September 2017. Results for six selected power substations: Pirttikoski, Imatra, Kouvola, Mäntsälä (MAN), Hämeenlinna and Simpevarp-2, listed in Table 2 have been shown.

Wawrzaszek et al., 2023, doi: 10.1029/2022SW003383

List of the intense geomagnetic storms in January 2010–July 2014.

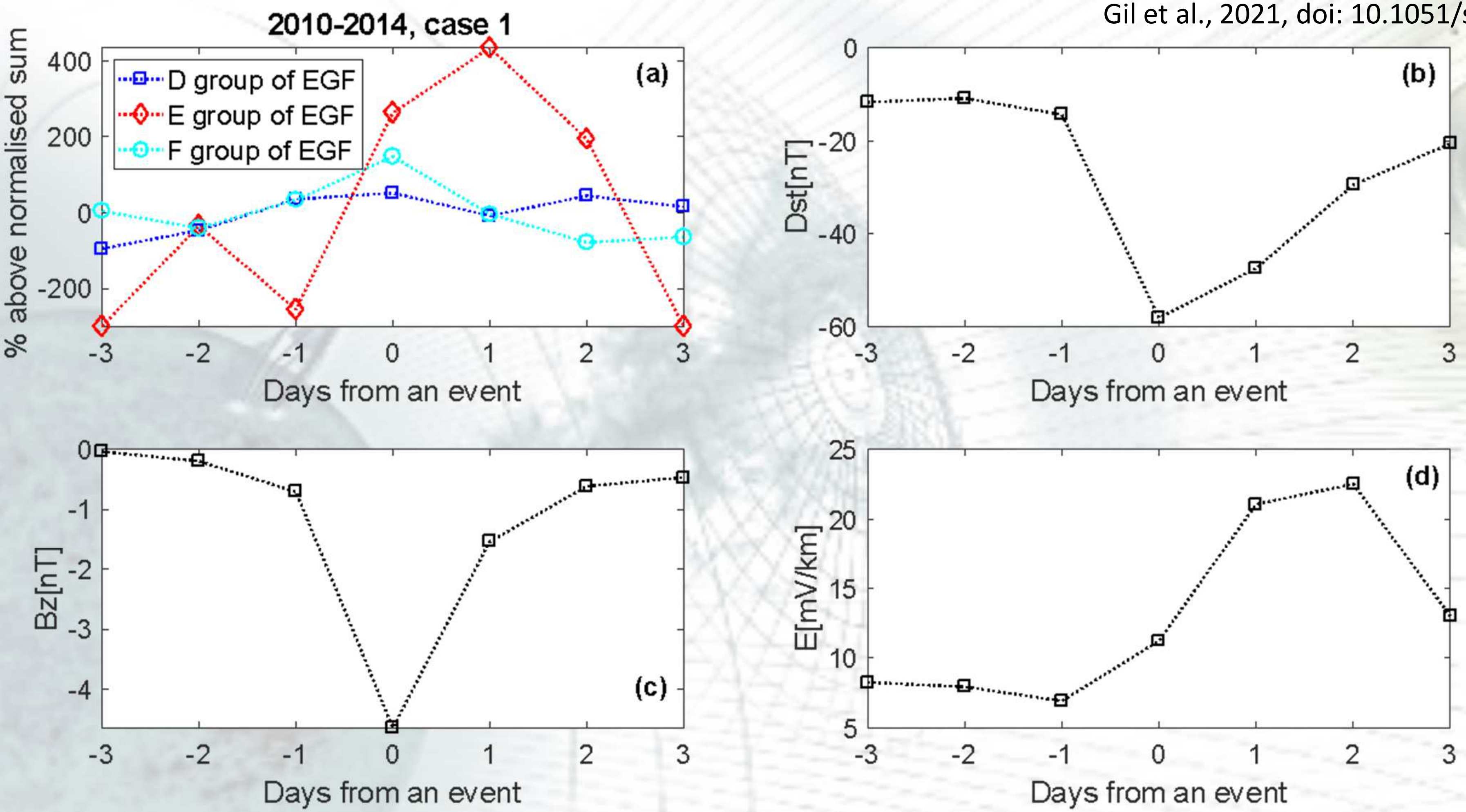
Gil et al., 2021, doi: 10.1051/swsc/2021013

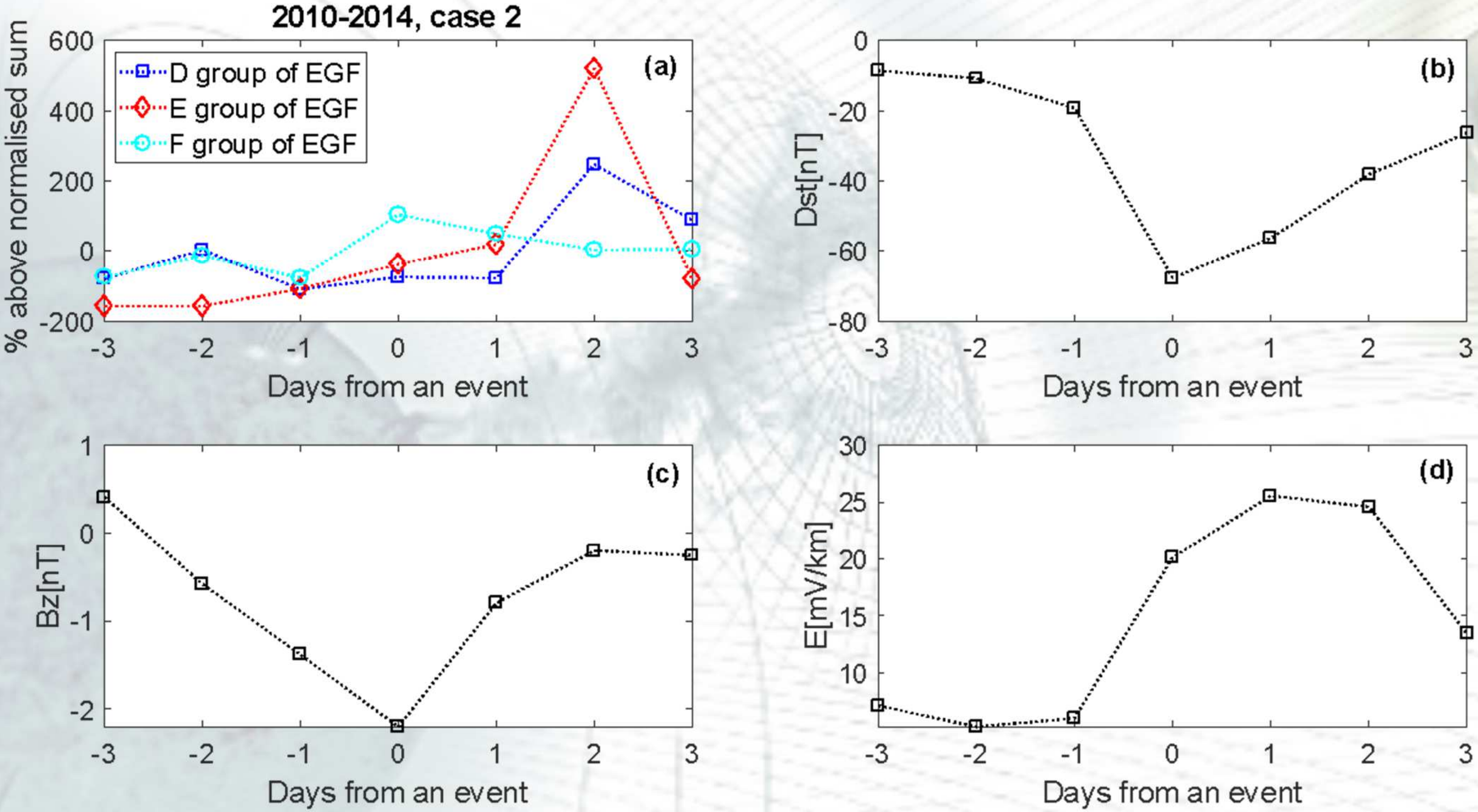
Date	DOY	Duration in [h] of: $B_Z <$ −10/*Dst* < −100	*Bz* min [nT]*	*Dst* min [nT]**	*AE* max [nT]	*B* max [nT]	*SWd* max [N/cm^3]	*SWs* max [km/s]	*ap* max [nT]	*K* max	Fast halo CME appearance
29.05.2010	149	12/0	**−13.8**	−80	1293	14.4	18.1	362	56	4	−
26–27.09.2011	269–270	1+2/4	−24.1	**−118**	1842	34.2	27	688	94	6	+
25.10.2011	298	1/8	−12.8	**−147**	1042	24	23.4	534	154	7	+
09.03.2012	69	6/11	**−16.4**	**−145**	1785	22.3	7.1	741	207	6	+
23–24.04.2012	114–115	10/2+4	**−15.4**	**−120**	1383	15.5	38.8	600	111	6	−
17.06.2012	169	6/0	**−16.5**	−86	1292	40.1	38.6	515	80	5	+
09.07.2012	191	4/0	**−11.4**	−78	1259	12.3	13.3	441	111	6	+
15–16.07.2012	197–198	29/26	**−18.7**	**−139**	1368	27.3	20.7	665	132	7	+
01.10.2012	275	4/6	**−19.2**	**−122**	987	21	23	411	111	6	+
08–09.10.2012	282–283	5+13/1+2+2	**−15.1**	−105	1000	16.3	20.7	527	111	6	−
01.11.2012	306	6/0	**−11.7**	−65	1270	15.8	26.2	373	39	4	−
14.11.2012	319	9/3	**−17.4**	−108	1009	22.3	14.8	467	94	6	−
17.01.2013	17	4/0	**−12.3**	−52	669	14.7	44.4	418	27	5	−
17.03.2013	76	1+1/5	−14.4	**−132**	1822	17.8	14	721	111	6	+
01.06.2013	152	7/7	**−17.4**	**−124**	1217	19.6	26.7	683	132	6	−
06–07.06.2013	157–158	7/0	**−11.7**	−78	1181	13.4	11.2	512	67	5	−
28–29.06.2013	179–180	12/1+1	**−11.9**	−102	1317	13.0	27.3	462	94	5	+
06.07.2013	187	10/0	**−12.5**	−87	1303	12.8	8.7	369	39	4	−
19.02.2014	50	4/2	**−12.9**	−119	1198	18.6	20.6	534	94	6	+

* Values for which *Bz* < −10 nT lasted for more than 3 h are shown in bold.

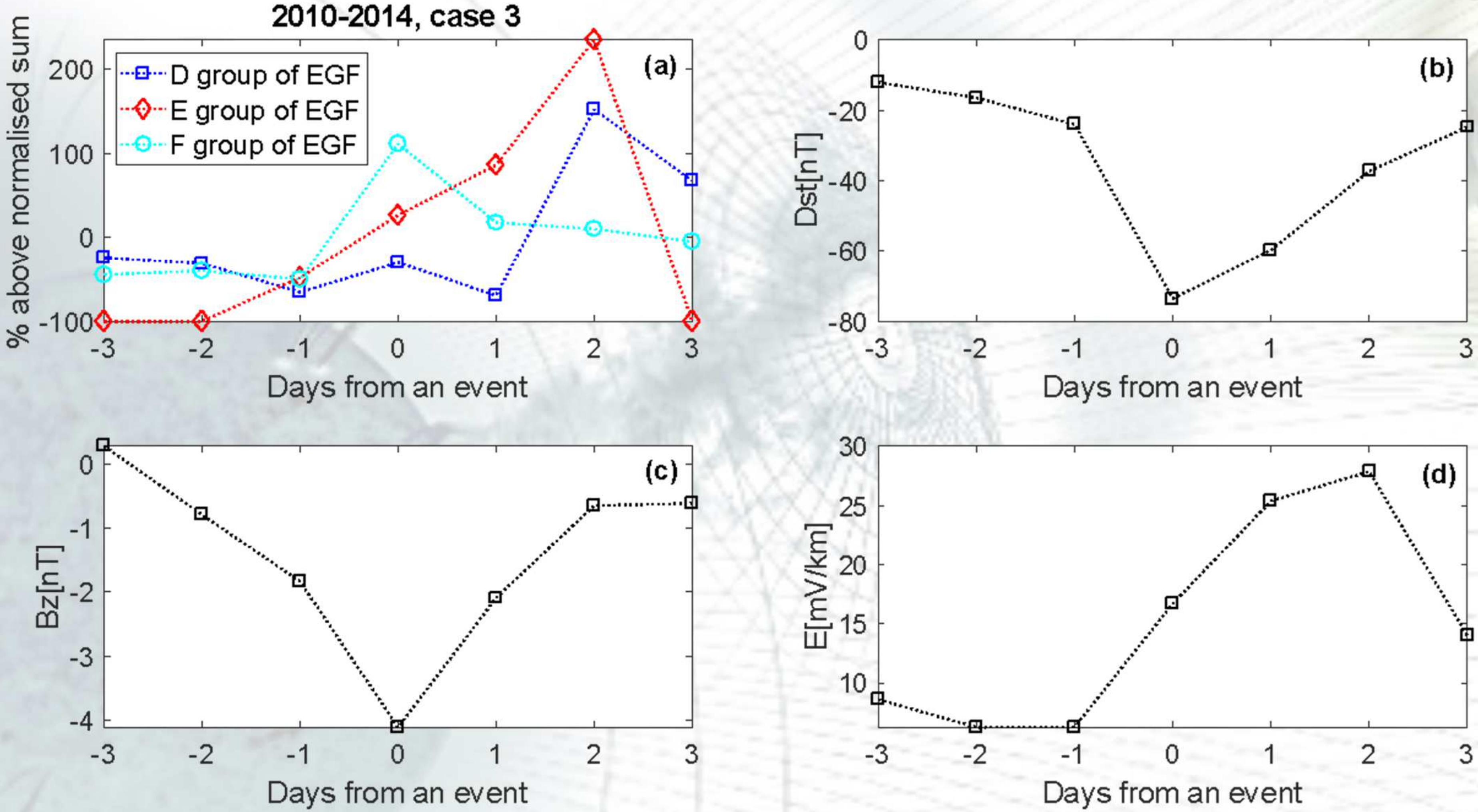
** Values for which *Dst* < −100 nT lasted for more than 3 h are shown in bold.

Gil et al., 2021, doi: 10.1051/swsc/2021013

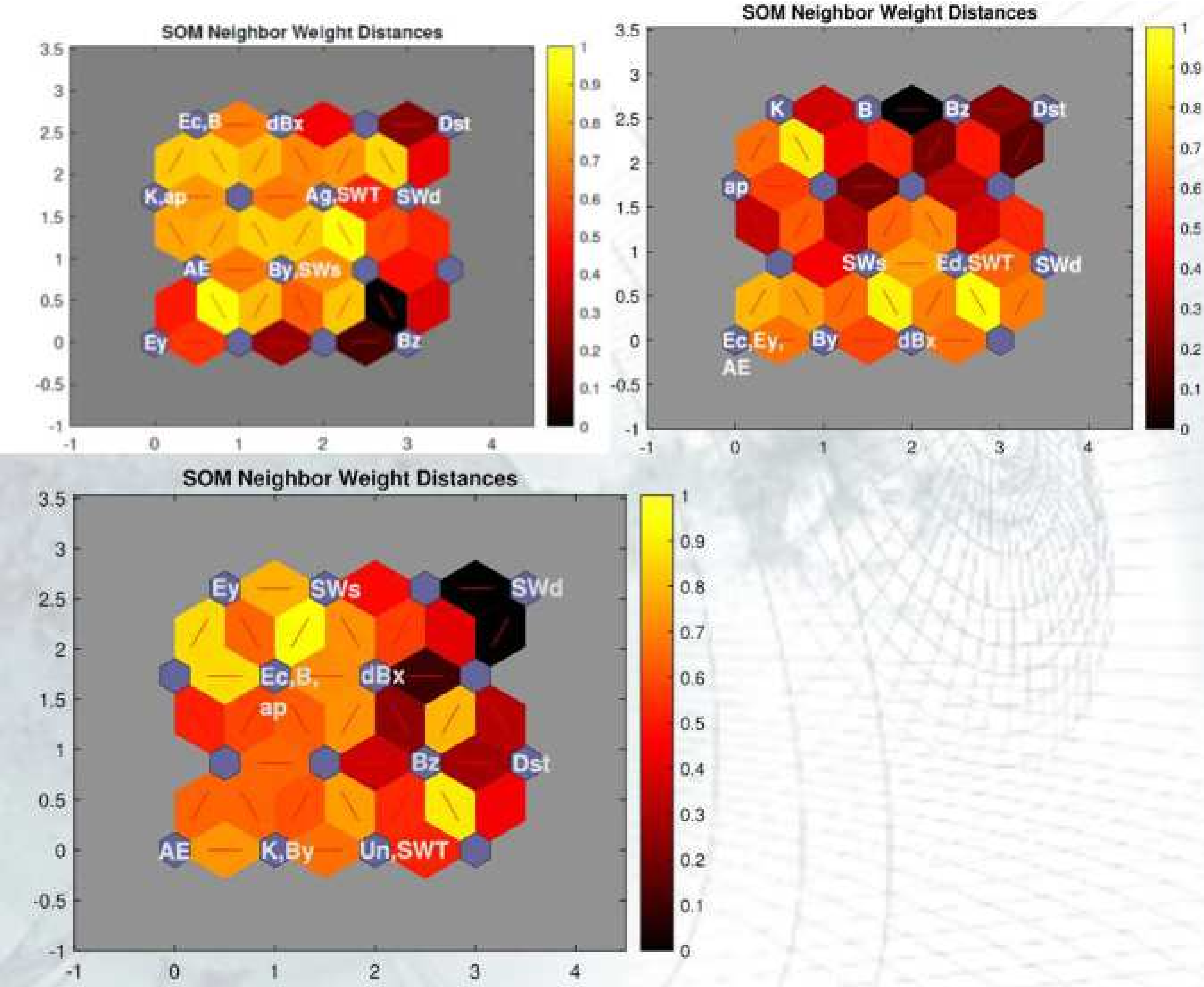




Gil et al., 2021, doi: 10.1051/swsc/2021013

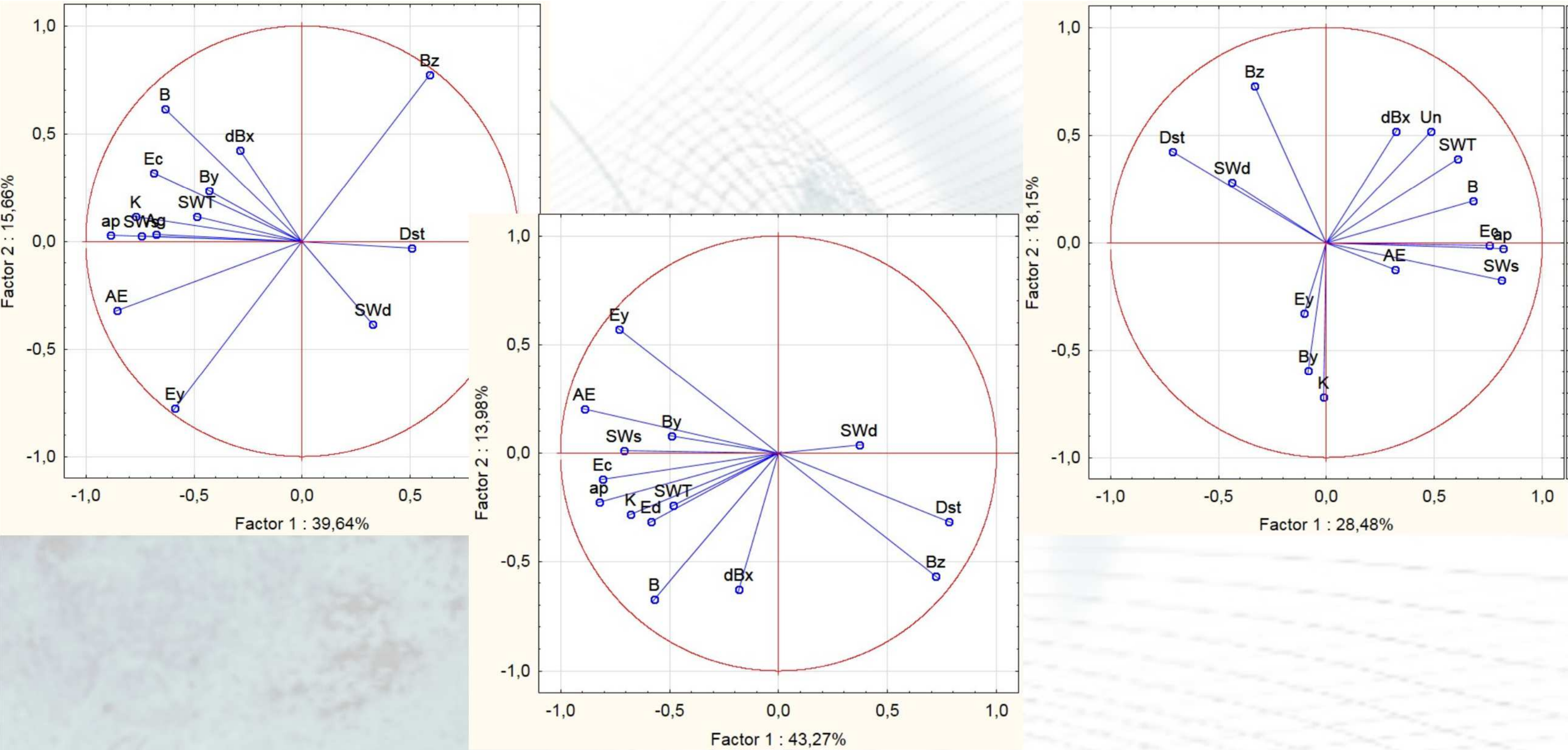


Gil et al., 2021, doi: 10.1051/swsc/2021013



SOM neighbour weight distances with weight values of connections between neighboring neurons for the intense geomagnetic storm 19.02.2014. The blue hexagons represent neurons, and the red lines show which particular neurons are connected. Colors from black to yellow display the weight values of the connection between neighboring neurons

Gil et al., 2023, doi: 10.1007/s11207-023-02119-4



PCA biplot around the intense geomagnetic storm on 19 February 2014

Gil et al., 2023, doi: 10.1007/s11207-023-02119-4

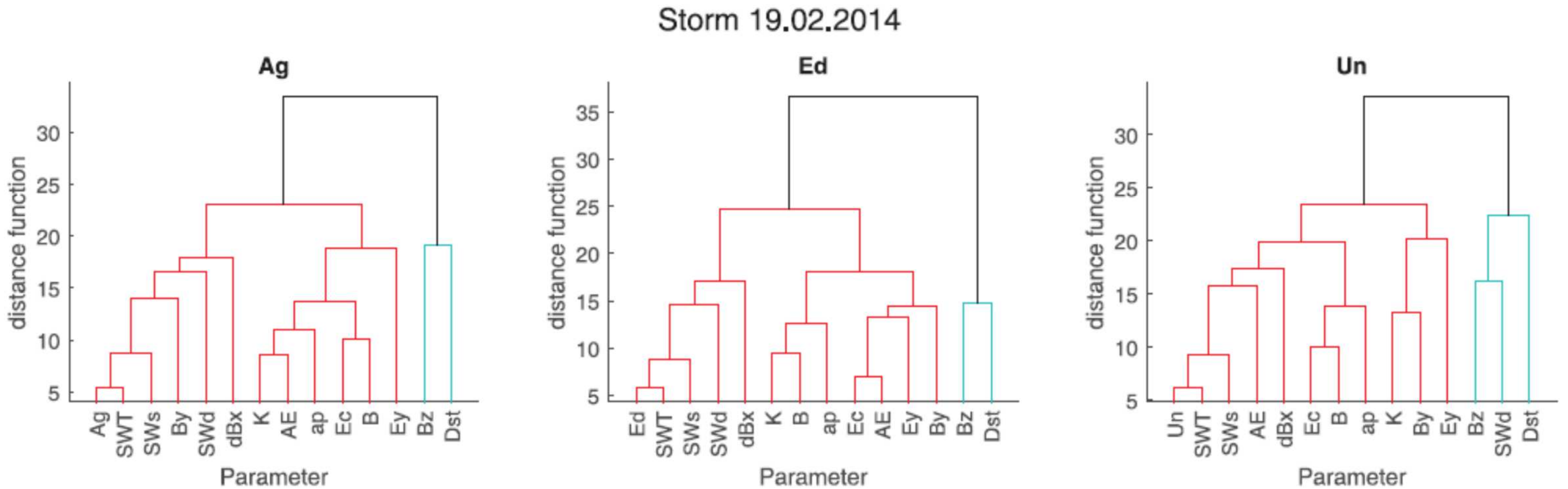


Figure 11. Dendrograms presenting the Ward's linkage of the solar activity parameters and three types of failure (Ag, Ed, Un) during the geomagnetic storm on 19.02.2014

Gil et al., 2023, doi: 10.1007/s11207-023-02119-4

Summary

- We find that the yearly average number of transmission lines failures (which might be of solar origin, i.e. from clusters D-F) in the South Poland show a rising trend from 2010 (near SA min) to 2014 (SA max). Thus, it can be an indication of solar cycle phase dependency.
- The presented rapid growth of the number of electrical grids failures coincides in time (mostly with some delay) with an increase of geomagnetic activity mirrored in the increase of geoelectric field disturbances reflected in GICs. This suggests a link to the space weather effects. The mentioned delay in EGFs emergence may be connected to some cumulative effect due to the result of transient states and their propagation in the distribution network.
- SOM, PCA and HAC analysis showed that the solar-wind parameters have the most substantial connections with all the considered types of electric–grid failures in southern Poland in all the storms under study. These parameters are usually grouped in the same cluster with failures in more than 80% of the results.

Thank you!

Thank you!

Acknowledgements

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References:

- Analysis of Geoeffective Impulsive Events on the Sun During the First Half of Solar Cycle 24/ Gil A, Berendt-Marchel M, Modzelewska R,Siluszyk A, Siluszyk M., Wawrzaszek A., Wawrzynczak A. //Solar Physics 298(2), (2023)
- Analysis of Large Geomagnetically Induced Currents During the 7–8 September 2017 Storm: Geoelectric Field Mapping, A. Wawrzaszek, A. Gil, R. Modzelewska, B. Tsurutani, R. Wawrzaszek// Space Weather 21(3), (2023)
- Fractal Dimension Analysis of Earth Magnetic Field during 26 August 2018 Geomagnetic Storm/ Wawrzaszek A., Modzelewska R, Krasinska A, Gil A, Glavan V//Entropy 24(5):699 (2022)
- Evaluating the relationship between strong geomagnetic storms and electric grid failures in Poland using the geoelectric field as a GIC proxy/ Gil A, Berendt-Marchel M, Modzelewska R, Moskwa S, Siluszyk A, Siluszyk M., Tomasik L., Wawrzaszek A., Wawrzynczak A. //Journal of Space Weather and Space Climate 11, 30 (2021)
- Solar Rotation Multiples in Space-Weather Effects/ Gil A, Modzelewska R, Wawrzaszek A., Piekart B., Milosz T. //Solar Physics 296, 128 (2021)
- Katz Fractal Dimension of Geoelectric Field during Severe Geomagnetic Storms/ Gil A, Glavan V, Wawrzaszek A., Modzelewska R, Tomasik L //Entropy 23(11), 1531 (2021)
- Signs of geoeffective space weather events in cosmic rays during the first half of the solar cycle 24/ Gil A, Modzelewska R, Moskwa Sz, Siluszyk A, Siluszyk M, Wawrzaszek A, Wawrzynczak A //In: NMDB@Home 2020: Proceedings of the 1st virtual symposium on cosmic ray studies with neutron detectors. Kiel: Universitätsverlag Kiel | Kiel University Publishing. S. 119–124 (2021)
- Transmission Lines in Poland and Space Weather Effects / Agnieszka Gil, Renata Modzelewska, Szczepan Moskwa, Agnieszka Siluszyk, Marek Siluszyk, Anna Wawrzynczak, Mariusz Pozoga, Sebastian Domijanski. // Energies. - Vol. 13, nr 9 (2020), s. 1-13
- The solar event of 14 – 15 July 2012 and its geoeffectiveness / Agnieszka Gil, Renata Modzelewska, Szczepan Moskwa, Agnieszka Siłuszyk, Marek Siłuszyk, Anna Wawrzyńczak, Mariusz Pozoga, Łukasz Tomasik. // SOLAR PHYSICS. - Vol. 295, no 10 (2020), art. no 135, s. 1-16.
- Struktura wiekowa polskiej infrastruktury energetycznej / Sylwia Zakrzewska, Agnieszka Gil-Świderska, Paweł Szmitkowski. // Rynek Energii. - 2 (147) (2020), s. 8-23.
- Does time series analysis confirms the relationship between space weather effects and the failures of electrical grids in South Poland? / A. Gil, R. Modzelewska, Sz. Moskwa, A. Siłuszyk, M. Siłuszyk, A. Wawrzyńczak, S. Zakrzewska. // Journal of mathematics in industry. - 2019, Vol. 9, art no 7, s. 1-16.
- Neural net clustering in the study of electrical grids failures in relation to geomagnetic storms / Agnieszka Siłuszyk, Agnieszka Gil, Renata Modzelewska, Szczepan Moskwa, Marek Siłuszyk, Agnieszka Wawrzyńczak. // Journal of Physics. Conference Series. - Vol. 1391 (2019), art. no 012107, s. 1-15.
- Capabilities of Polish power plants - advantages and threats / P. Szmitkowski, S. Zakrzewska, A. Gil, P. Świderski. // Przegląd Elektrotechniczny. - R. 95, nr 5 (2019)
- Electrical energy infrastructure in Poland and its sensitivity to failures as part of the energy security system / P. Szmitkowski, A. Gil, S. Zakrzewska. // Energy Policy J.. 22, 1 (2019)