Grant Agreement Period 5 (GAPG1, Deliverable D3.2 of the MoU, COST Action CA15211, http://www.cost.eu/COST_Actions/ca/CA15211)

D. 3.2: "Report on studies on AEF, aerosol ionization and cloud microphysics performed during the Action“

Working Group 3 – Atmospheric electricity and climate

Report coordinated by WG3 co-leader Eugene Rozanov with contributions from all participants named in the following.

This report contains the cross-disciplinary studies performed within the COST Action 15211 regarding the following:

1. **Science of the Total Environment – Virtual Special Issue ‘Atmospheric Electricity’:** A special issue in the journal *Science of the Total Environment* (Impact Factor 5.59) was initiated by ElectroNet participants. Here we report on the main findings of the accepted papers contributed from WG3 participants and related to energetic electron precipitation, atmospheric ionization rates, ionospheric potential calculations.
2. **Report on the atmospheric electricity and climate response to natural and solar forcing:** investigation the atmospheric electricity connection to natural (radon emissions, climate changes) and solar forcing (solar proton events and interplanetary magnetic field disturbances).
3. **Other aspects of atmospheric electricity:** accumulation of the electricity from the atmosphere.

1. Atmospheric ionization influence on Atmospheric electricity field (AEF)

1.1 Ionization by energetic electrons

The atmospheric electricity features are sensitive to the local condition in the atmosphere including the local ionization rate. High and relativistic energy electron precipitation (HEEP) from the outer radiation belt at the polar high-latitudes causes an increase in the ionization rates down to about

20 km altitudes. The bremsstrahlung from HEEP measured with balloon-based instruments provides information on energy spectra of the precipitating energetic electrons allowing calculations of the atmospheric ionization. For the first time the changes of atmospheric ionization rates on an hourly and minute time scales at different altitudes were retrieved from balloon observations. Substantial changes in precipitating electron fluxes can occur both during one balloon flight and during two balloon flights performed on the same day. On the other hand, in the case of two balloon launches per day, as a rule, HEEP was observed only in one of them, that proves the existence of strong changes in ionization rate on the time scale of 6 hours and longer. The calculated energy spectra and resulting ionization rates for some events are presented in Figure 1.
Whereas the present knowledge about temporal and spatial variations of HEEP is not complete enough the balloon observations shed some light on the variability of ionization rates induced by HEEP. Knowledge about atmospheric ion concentration or other words ionization rates is important for multidisciplinary topics which includes the various processes of atmosphere as well as total environment. Atmospheric ion concentration/ionization is coupled atmospheric electricity and chemistry, ozone layer, climate, and biological systems.

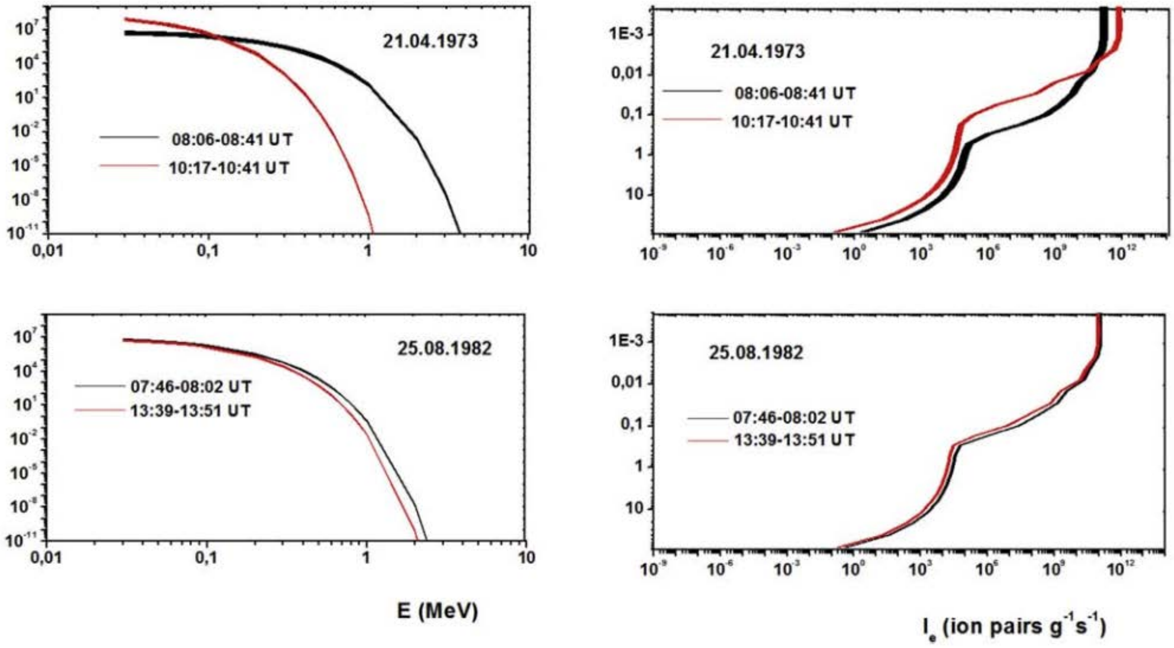

Figure 1. *Precipitating electron energy spectra (left panels) and of atmospheric ionization rates (right panels) caused by HEEP events observed in two balloon flights performed on the same day. The morning data are black lines, and the afternoon data, red lines. Observation time is shown on the figure. Adapted from Mironova et al., (2019).*

These new highlights are important for atmospheric electricity that is sensitive to the local condition in the atmosphere including the local ionization rate. The work was benefited from the discussions with Electronet COST action participants and published with acknowledgement to the Electronet COST action support (Mironova et al., 2019).

The results have been published in:
Mironova, I.A., Bazilevskaya, G. A., Kovaltsov, G. A. Artamonov, A. A., Rozanov E. V., Mishev, A., Makhmutov, V. S., Karagodin, A. V., Golubenko, K. S., Spectra of high energy electron precipitation

and atmospheric ionization rates retrieval from balloon measurements, Science of The Total Environment, 693, 133-242, 2019, doi:10.1016/j.scitotenv.2019.07.048

1.2 Ionospheric potential calculations

The first results of the ionospheric potential (IP) calculations with the chemistry-climate model (CCM) SOCOL (Solar Climate Ozone Links) is presented. For the study, we exploit a parameterization of the difference in electric potential between Earth's surface and lower boundary of the ionosphere as a function of thunderstorm and electrified cloud properties. The model shows a good agreement with the IP obtained by balloon soundings. The simulated UT variation of IP shown in Figure 2 exhibits a maximum at 20 Universal time (UT) and minimum at about 2 UT which agree with the UT cycle of the lightning activity.

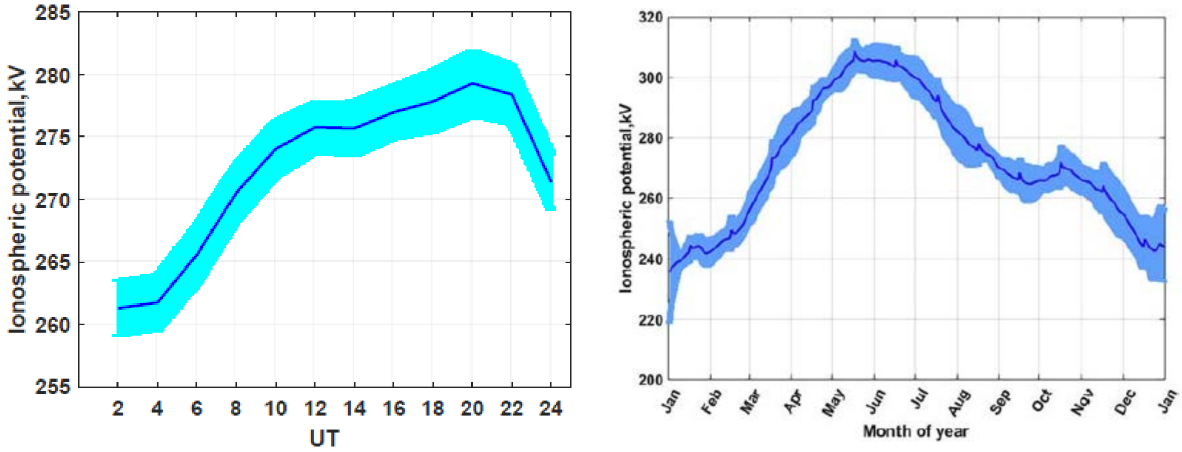

Figure 2. Simulated with the CCM SOCOL diurnal (left) and seasonal (right)cycles of the Ionospheric Potential. Adapted from Karagodin et al.,2019.

The obtained results allow understanding of IP variability pattern at diurnal, seasonal and annual timescales. The simulated seasonal IP cycle is shown in Figure 3. Model shows pronounced maximum of IP in boral summer in general agreement with available estimates.

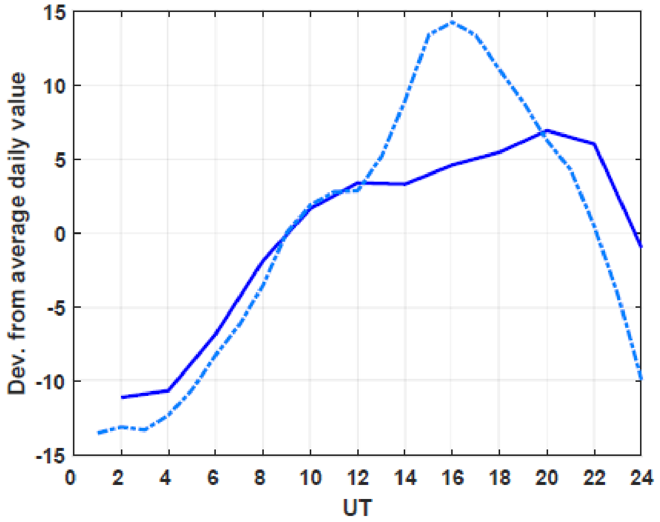

Figure 3. Diurnal cycle of the Ionospheric Potential simulated with Simulated with the CCM SOCOL (solid line) and the INM (dashed line) models. Adapted from Karagodin et al.,2019.

We also compare our results with the IP simulated with the climate model INMCM4 using similar IP parameterization. The comparison (see Figure 3) shows a good agreement of UT cycles especially before 12 UT. Simulated IP annual cycle reaches its maximum in late spring in both models. However, the comparison also reveals some differences in amplitudes of IP variability on different time scales. The large deviations occur after 12 UT for all seasons except summer where the maximum of both results happens before 12 UT. The UT cycle of IP simulated with CCM SOCOL is in a better agreement with observations after 12 UT in terms of phase with similar timing of maximum values. The calculation of IP using climate models can help to fill up the gaps when the observed IP is not available. The interactive calculation of IP is also a step forward in coupling atmospheric and ionospheric processes.

The results have been published in:
Karagodin A., Rozanov E., Mareev E., Mironova I., Volodin E., Golubenko, K., The representation of ionospheric potential in the global chemistry-climate model SOCOL, Science of The Total Environment, 693, 133242, 2019, doi:10.1016/j.scitotenv.2019.134172.

2. Report on the atmospheric electricity and climate response to natural and solar forcing

2.1 AEF response to the ionization by galactic cosmic rays and ^{222}Radon

For the study of AEF response to natural ionizations sources we have extended the chemistry-climate model (CCM) SOCOLv2 (Schraner et al., 2008) to include production, advective and convective transport of Rn-222. The obtained distribution of the ^{222}Rn mixing ratio is shown in Figure 4 and illustrates that the locations of the maxima and minima agree well with observational estimates.

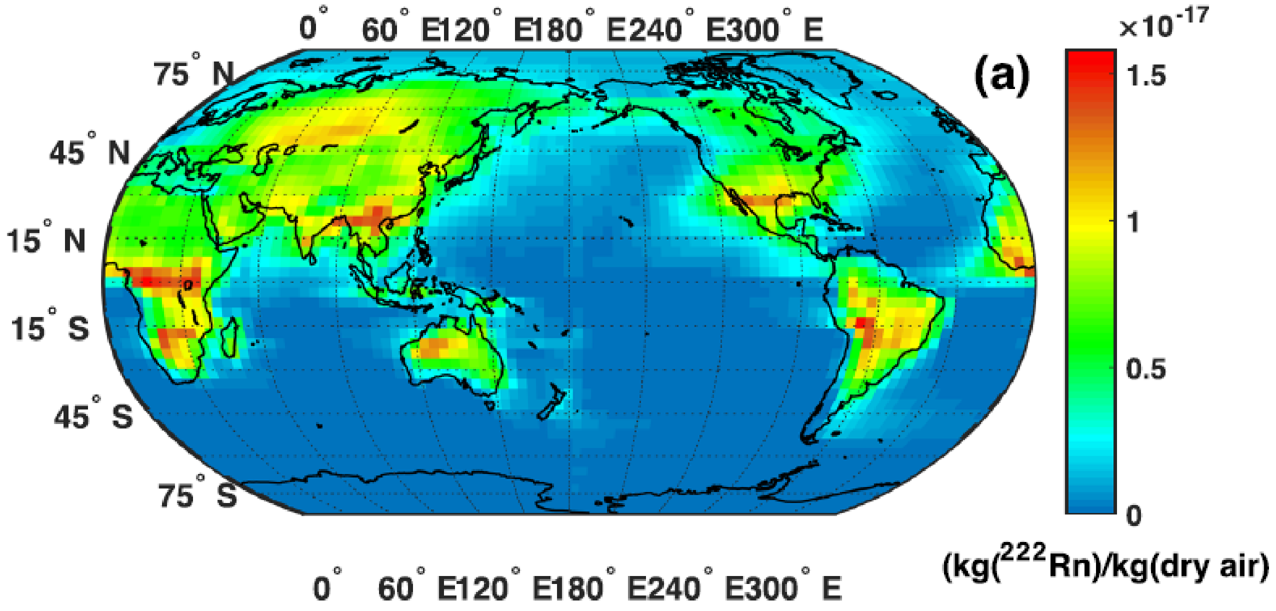

Figure 4. Global map of the modeled Rn-222 mass mixing ratio in the surface air for June 2005. *Adapted from Golubenko et al.,2019.*

The latest model version can simulate Rn-222 and galactic cosmic rays induced ionization rates as well as can calculate several AEF parameters such as ionospheric potential, conductivity, potential gradients, and downward currents in the fair-weather regions. Geographical distribution of the vertical current density (picoA/m^2) for the quiet case (GCR + ^{222}Rn-222 only) is illustrated in Figure 5. The distribution is mostly defined by orography, geographical distributions of the ^{222}Rn mixing ratio and geomagnetic field strength. The maxima are observed at high elevation sites (e.g., Tibetan Plato, Antarctida) and regions with high the ^{222}Rn mixing ratio. Low ionization by GCR in the tropical regions is responsible for the weak current density there. Figure 5 also illustrates global distribution of the fair-weather downward currents for the case of strong solar proton event (SPE) when the ionization rate is formed by extremely energetic solar protons. In this case the radon contribution is not visible because it is masked out by dramatically enhanced ionization in the troposphere by solar protons and the distribution is shaped by orography and geomagnetic field configuration.

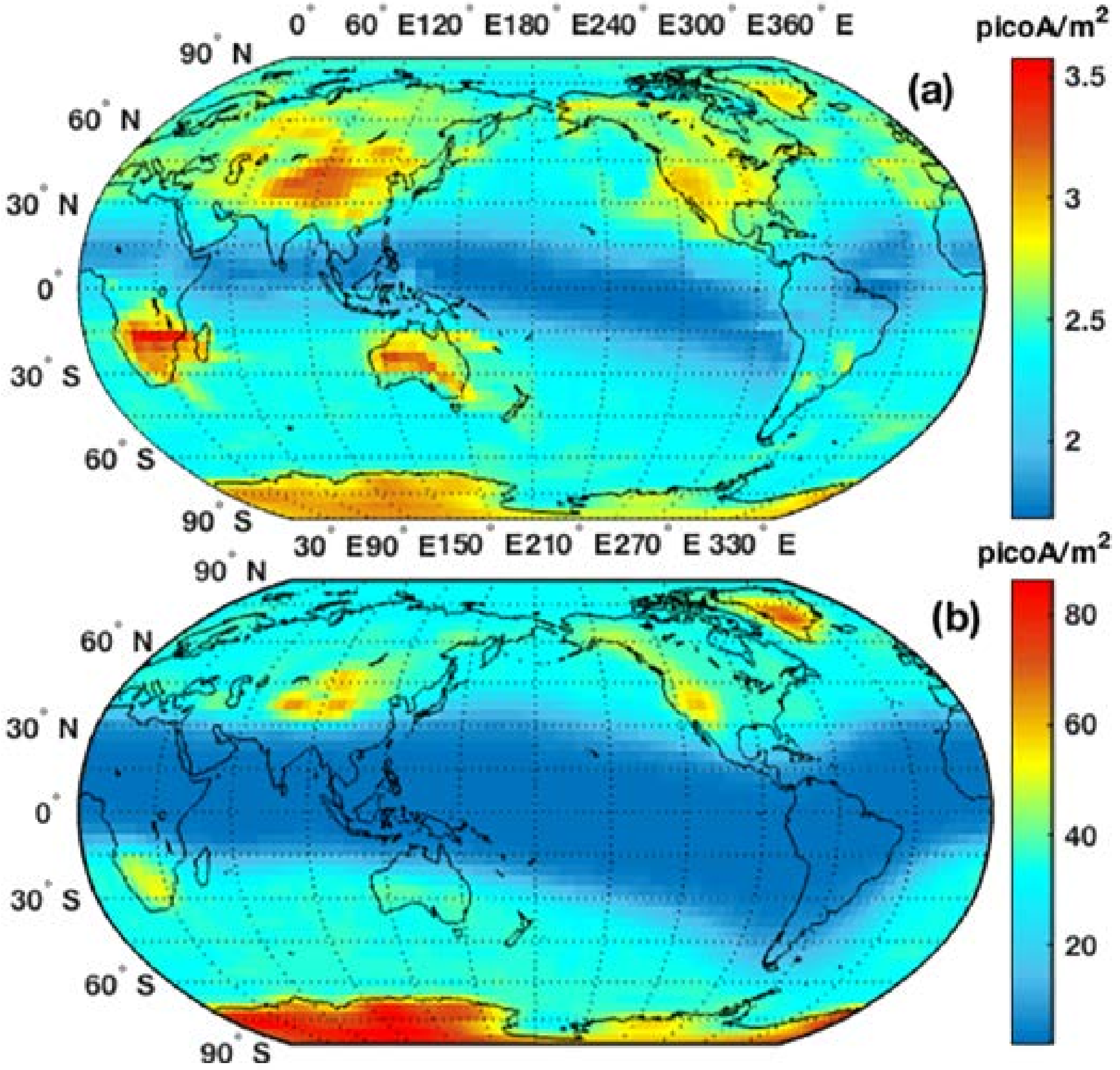

Figure 5. *Map of the vertical current density distribution (picoA/m^2) for the quiet (GCR + ^{222}Rn only, panel a) and extreme scenario 2 (GCR + ^{222}Rn + SPE—panel b).*

The work was performed during K.Golubenko's and I. Usoskin's STSM. The model for the ionospheric potential calculations was developed during A.Karagodin's STSM and published with acknowledgement to the Electronet COST action support (Karagodin et all., 2019).

The results have been published in:
Golubenko, K., Rozanov, E., Mironova, I., Karagodin, A., Usoskin, I., Natural sources of ionization and their impact on atmospheric electricity, Geophysical Research Letters, 47, e2020GL088619, doi:10.1029/2020GL088619, 2020.

2.2 The climate response to cloud properties changes caused by AEF and its climate relevance.

The potential impact of global electric fields on climate variability has been under discussion for many years (Harrison, 2004; Tinsley et al., 2007). The suggested processes include the effects of atmospheric electricity on precipitation efficiency, ion-induced aerosol nucleation, electro-scavenging of ice forming nuclei and some others. In the framework of our COST action, we studied the influence of the enhancement auto-conversion rate from stratiform clouds caused by atmospheric electricity (Harrison et al., 2015) on surface pressure. During STSM mission of A. Karagodin to Switzerland the CCM SOCOL was applied to simulate the atmospheric response to the enhancement of the auto-conversion rate for the clouds over the high latitude regions. In these experiments the auto-conversion rate (and therefore precipitation intensity) was linked to the variability of the By component of the interplanetary magnetic field. The surface pressure response is demonstrated in Figure 6. The obtained results show surface pressure increase over the Antarctic and intensification of negative NAO phase in the Northern hemisphere. The response over the Antarctic can explain observed Mansurov's effect (Lam et al., 2016) if the variability of the interplanetary magnetic field (By component) is able to enhance atmospheric electrical currents and cloud charges. For the Northern hemisphere, the obtained redistribution resembles negative phase of the North Atlantic oscillation with possible strong impact on the temperature and hydrology of Europe and Central Asia. Some results of this study have been discussed by Karagodin et al. (2018) in his report on collaboration with the British Antarctic Survey.

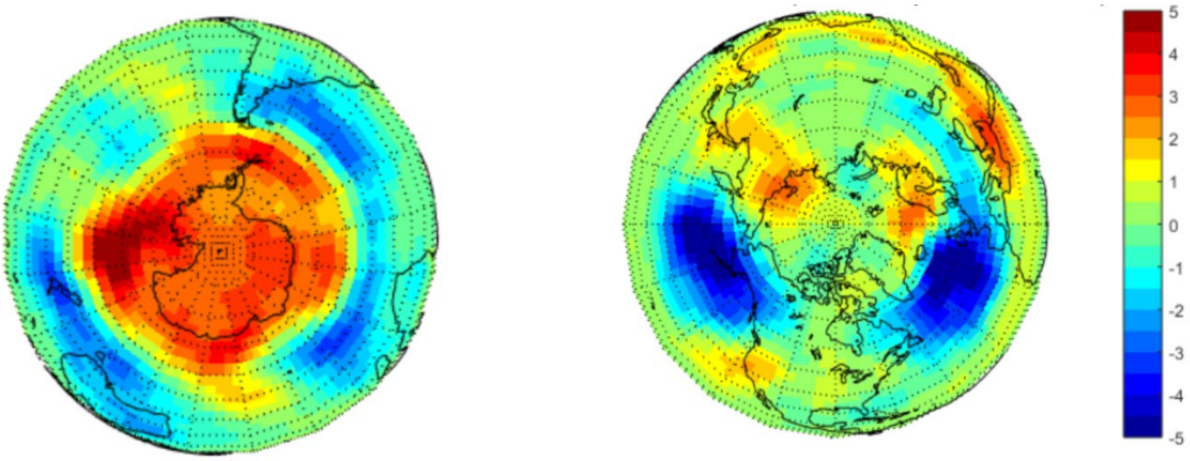

Figure 6. *The response of surface pressure (hPA) in January to the enhancement of the precipitation from high latitudes stratiform clouds. Adapted from Karagodin et al., (2018).*

The plausibility of this mechanism was presented during WG3 meetings by Prof. Harrison. New details of the mechanism have been recently discussed by Harrison and Lockwood. Their explanation of the possible link between energetic particles forcing and climate is presented in Figure 7. We showed earlier (see section 2.1) that strong SPE event can substantially increase the conductivity of the atmosphere and electrical current. According to Harrison RG, Lockwood (2020) it can additionally electrify low level clouds leading to more intensive coagulation of the cloud droplets and precipitation followed by shorter lifetime of the clouds with implications for the circulation and temperature of the troposphere. It is known that some past climate changes like Early Twenties Century Warming (Egorova et al., 2018) or intensive warming during the recovery of the Sun activity after Maunder minimum can be explained by very large solar irradiance changes, which have not commonly accepted by the solar physics community. The discussed here mechanism can represent a missing link between highly energetic particles of solar/galactic origin and climate state. Further progress in this direction would be very desirable, but it requires additional funds to support climate modeling groups because for the understanding of this connection it is necessary to develop and apply a new global climate model which covers the atmosphere from the ground to at least 500 km, include ionosphere, global electric circuit, and improved treatment of the cloud microphysics.

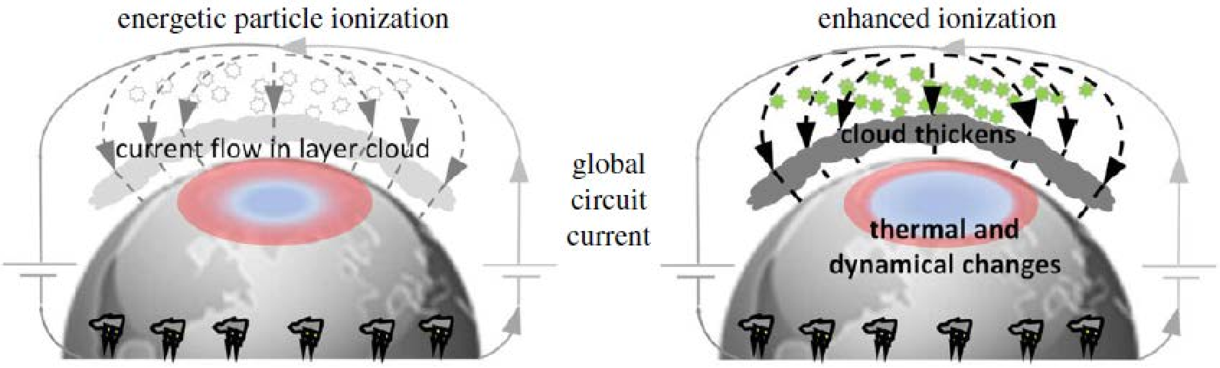

Figure 7. *Proposed causal linkage of solar energetic particles effects into the troposphere. (Left) Current flow in the global atmospheric electric circuit. This is driven principally by charge separation in equatorial regions, flowing through the conductive upper atmosphere and returning through the vertical conduction current density, some of which passes through extensive layer clouds in the lower troposphere. (Right) During enhanced ionization from solar energetic particles, the upper atmosphere becomes more electrically conductive at high latitudes and the current passing through layer clouds increases. Thickened low level clouds modify the local thermal structure of the troposphere, with dynamical changes influencing wind directions. Adapted from Harrison RG, Lockwood, 2020.*

The used version of the CCM SOCOL was developed during A.Karagodin's STSM and published with acknowledgement to the Electronet COST action support (Karagodin et al., 2019). The work was supported by the Electronet COST action network.

2.3 AEF influence on atmospheric ionization

Atmospheric electricity can have impact on atmospheric ionization via lightning induced Gamma Ray bursts. Natural Gamma Radiation (NGR) is linked to cloud charge, lightning initiation and depends on the electron acceleration in the thunderclouds. In the framework of our COST action, we proposed a model (Figure 8) of the enhanced radiation on the earth's surface during thunderstorms, which explains not only short-term spikes of high-energy electrons caused by relativistic electron avalanches but also the long-term isotropic flux of low energy gamma rays from the Rn-222 progenies. During the performed experiments, we also register the fluorescence due to the development of electron-gamma ray cascade in the atmosphere and found its robust correlation with high-energy electron flux. The gammy ray fluxes obtained from the developed model can be used to calculate ionization rates and evaluate possible effects of this ionization sources on atmospheric chemistry. The work was benefited from the discussions with Electronet COST action participants.

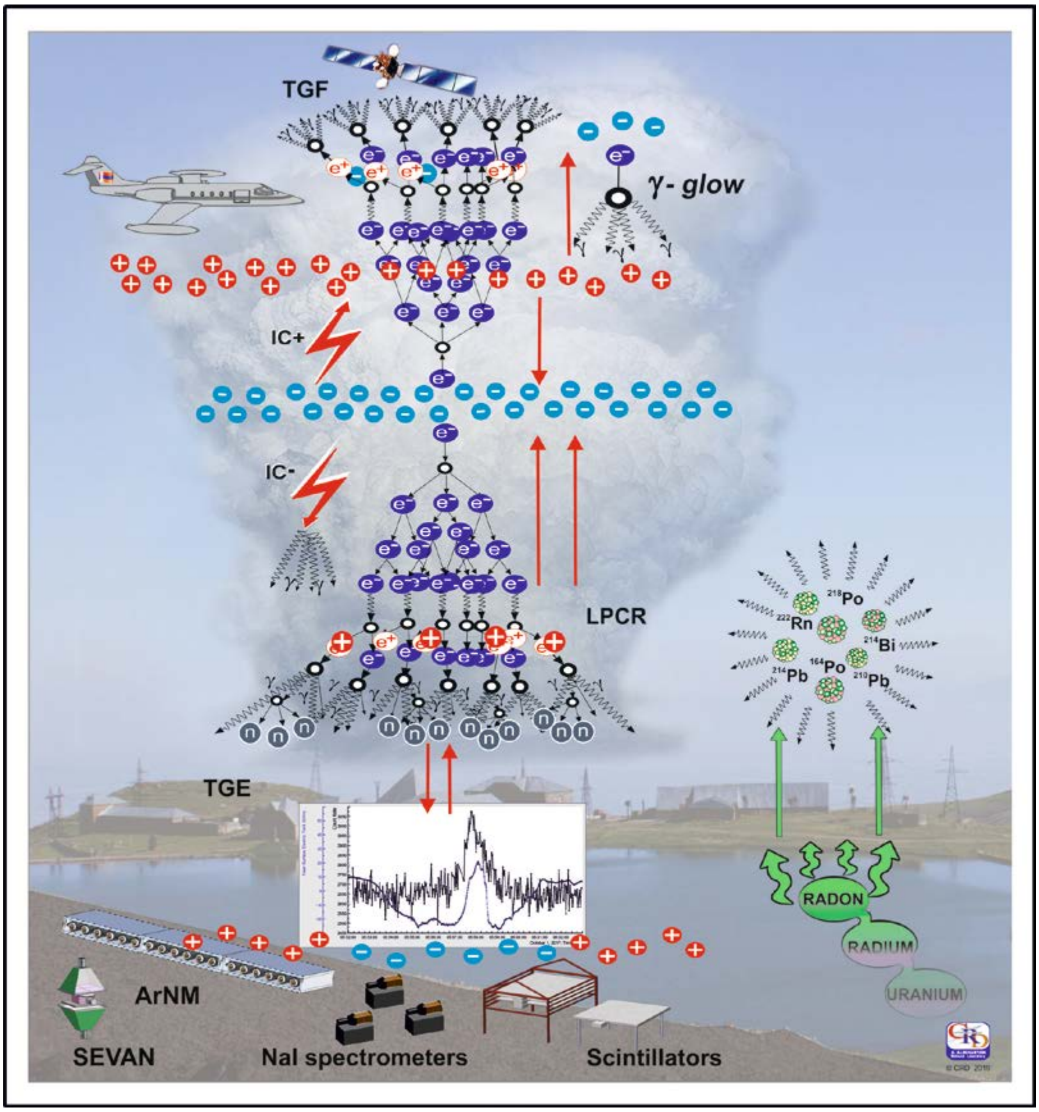

Figure 8. *A schematic view of the NGR enhancement during thunderstorms. Lower dipole consists of the uniform and widely horizontally distributed main negative charge and much smaller compact lower positively charged layer. The figure is adapted from Chilingarian et al. (2019).*

2.4 Thunderstorm evolution dependence on climate

One of the interesting questions discussed during our workshop is related to the connection between climate and lightning activities. Prof. Price discussed possible influence of climate on the thunderstorm activity over Africa using lightning time series and several climate parameters. He found out that the lightning activity correlates better with specific humidity and lifted index, which characterize stratification stability. The discovered correlation allows to estimate lightning activity in the past using reanalysis data and future using the output from models simulating future climate evolution. The analysis of the past revealed an increase of the thunderstorm clusters number during the last decades and this increase is most pronounced since the mid-1990s. it was also shown that surface temperature is a good proxy on annual mean scale, and it gives 40% increase in the number of thunderstorm clusters for every 1 K warming in Africa. Figure 9 illustrates past evolution of the thunderstorm cluster number, surface temperature, lift index and specific humidity.

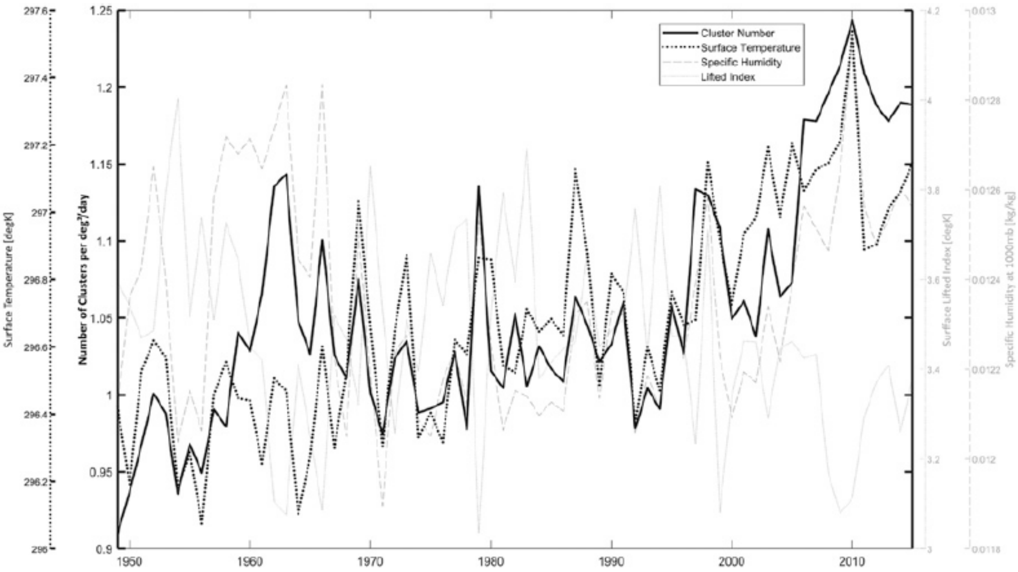

Figure 9. Annual means for 1948–2016 in the African region: cluster number as calculated by the random selector (solid black), surface temperature (dotted black), LI (gray), and specific humidity (gray dashed). A 2-yr smoothing filter (moving average) was applied. Adopted from Harel and Price (2020).

3. Other aspects of atmospheric electricity

3.1 Electricity production from charged clouds.

Cloud's electrification (lightning) occurs by the interaction of water molecules - ice crystals, hail pellets & supercooled water droplets (Takahashi, 1978; Saunders and Peck, 1998). In other words, the electricity is derived from water in its different phases.

Figure 10. *Prof. C. Price and Dr. J. Lax performing the experiment.*

More recently, Ducati et.al. (2010) have shown that metals spontaneously acquire charge when the relative humidity (RH) increases above 50%, as the result of the start of condensation of droplets on the metal surface, with different amounts and polarity of charging occurring for different metals. They used different metals as an asymmetric capacitor, acting as a battery. This charging is assigned to the selective adsorption of OH-/H+ ions, respectively. When exposed to high RH, a potential difference builds up on these metal surfaces. Experiments showed potentials of up to 0.8V, half of an AA battery voltage. In the framework of our COST action we have successfully duplicated the experiments of Ducati et.al. (see Figure 10), and now investigate how to increase the efficiency of the battery. Our experiments confirm charge is being built up on metal surfaces only when the relative humidity is high. Furthermore, while exploring Stainless Steel (SS), our initial results show potentials of -0.9V, while a different type of SS acquired +0.7V. Outdoors experiments under ambient conditions also confirm voltage accumulation when the RH is high. The acquired voltage maintains as long as the RH is high. The knowledge of thunderstorm charging might lead the way to developing a new innovative renewable source of energy. If this idea works, the consumption of fossil fuel can be reduced slowing down the climate warming.

4. General conclusion

This study addresses the question how the solar and natural forcing can affect ionization rates, atmospheric electricity field and climate. The WG3 activity resulted in

1. Development of the climate model with elements of global electric circuit,
2. Evaluation of the electric current response to extreme solar proton events,
3. Suggestion of new solar-climate link mechanism,
4. Three published papers with COST acknowledgement,
5. Two published papers steamed from the discussion during COST workshops,
6. Several presentations and technical reports.

Promising results were obtained in the subproject related to the influence of ionization rates on the cloud life cycle. It would be useful to continue this study in the (or beyond) COST Action framework. Below the participants of this study are presented:

List of WG3 participants

	Participant	**Institution**	**E-Mail**
BG	Boryana Tsenova	National Institute of Meteorology and Hydrology	boryana.tsenova@meteo.bg
DK	Jans Olaf Pedersen	Danish Technical University DTU Space	jopp@space.dtu.dk
FI	Antti Makela	FMI	Antti.Makela@fmi.fi
FI	Tuukka Petaja	Univ. of Helsinki	tuukka.petaja@helsinki.fi
FYROM	Snezana Savoska	University St. Kliment Ohridski	savoskasnezana@gmail.com
DE	Reik Donner	Potsdam Inst. for Clim. Impact Res.	redonner@pik-potsdam.de
EL	Konstantinos Kourtidis	RC ATHENA	kourtidi@env.duth.gr
HU	Jozsef Bor	Hungarian Academy of Sciences	jbor@ggki.hu
HU	Gabriella Satori	MTA CSFK	gsatori@ggki.hu
ISR	Yoav Yair	Interdisciplinary Center Herzliya (IDC)	yoav.yair@idc.ac.il
ISR	Colin Price	Tel Aviv University	cprice@flash.tau.ac.il
PL	Anna Odzimek	Polish Academy of Sciences, Institute of Geophysics	aodzimek@igf.edu.pl
PT	Susana Barbosa	INESC TEC	susana.a.barbosa@inesctec.pt
RO	Marius-Victor Birsan	Meteo Romania	marius.birsan@gmail.com
RO	Mirela Voiculescu	Universitatea Dunarea de Jos Galati	mirela.Voiculescu@ugal.ro
CH	Eugene Rozanov	PMOD/WRC	eugene.rozanov@pmodwrc.ch
UK	Keri Nicoll	University of Reading	k.a.nicoll@reading.ac.uk
RU	Irina A. Mironova	St. Petersburg State University, Institute of Physics	irini.mironova@gmail.com
RU	Evgeny Mareev,	Institute of Applied Physics, Rus. Acad. Sci.	mareev@appl.sci-nnov.ru
RU **CH**	Arseniy Karagodin	St. Petersburg State University, PMOD/WRC	Arseniy.Karagodin@pmodwrc.ch
ARM	Ashot Chilingarian	Yerevan physics Institute	chili987@gmail.com
ARM	Hripsime Mkrtchyan	Yerevan physics Institute	hripsi.mkrtchyan@gmail.com
BG	Boryana Markova	National Institute of Meteorology and Hydrology	boryana.markova@meteo.bg
FI	Ilya Usoskin	University of Oulu	ilya.usoskin@oulu.fi

HU	Veronica Barta	Hungarian Academy of Sciences	bartav@ggki.hu
UK	J. Matthews	Bristol University	J.C.Matthews@bristol.ac.uk
UK	Karen Aplin	Univ. of Oxford	karen.aplin@bristol.ac.uk
UK	Gilles Harrison	Univ. of Reading	r.g.harrison@reading.ac.uk
	Kleareti Tourpali	Physics Dept., AUTH	tourpali@auth.gr
RO	Daniel Carbunaru	Meteo Romania	carbunaru.daniel@gmail.com
UK	Mai Mai Lam	British Antarctic Survey	mml@bas.ac.uk

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