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POLAR REGIONS IN GLOBAL ATMOSPHERIC ELECTRICAL CIRCUIT RESEARCH

Introduction

The Global Atmospheric Electrical Circuit (GAEC) or Global Electric Circuit (GEC) is the concept of the flow of electrical current in the Earth's atmosphere, and was formulated to explain the existence of an electrical field that is ubiquitous in the Earth's lower atmosphere and decreasing with altitude. The GEC is a key and relatively difficult subject of atmospheric electricity research, because of the related concepts and problems – and thus other fields of physical and Earth sciences – that it brings together. By definition, it refers to the entire planet, but polar areas are special zones in it, where the electrical circuit of the lower atmosphere meets the system of the currents in the Earth's ionosphere and magnetosphere. Polar areas are also considered to be important in GEC monitoring.

While preparing the relevant bibliography, we have mainly relied on works on atmospheric electricity regarding observations in polar regions, while trying to present the main currents of foreign and domestic research. General knowledge on the subject of atmospheric electricity and detailed information on the GEC and other issues presented in this work can be found in textbooks by Chalmers (1976), Israëł (1970, 1973) and MacGorman and Rust (1998), and, additionally to the items listed in the literature herein, in the materials of the International Commission on Atmospheric Electricity (ICAE) that is held every four years. The ICAE is currently the commission of the International Association of Meteorology and Atmospheric Sciences (IAMAS) at the International Union of Geodesy and Geophysics (IUGG).

The article discusses, in turn: the GEC concept, and basic concepts and physical quantities used in research on atmospheric electricity; the importance of polar

areas in the GEC; the history of atmospheric electricity measurements in polar regions up until 2015; and national research on atmospheric electricity in polar regions and its prospects.

The lower-atmosphere electrical circuit

The Global Atmospheric Electric Circuit is assumed to be driven by cloud generators – storm clouds with electrical discharges and convective clouds with rain showers, referred to respectively as thunder clouds and shower clouds (Wilson 1921). The global distribution of these clouds concentrates at low and moderate latitudes, especially in the global storm centres (Brooks 1925; Christian et al. 2003) near equatorial parts of Indonesia, Asia, Africa and South America. However, atmospheric discharges are not an indicator of high activity of the GEC centre (e.g. Williams 2009). Circuit charging and current flow occur due to the separation of electrical charge in electrified convective clouds, in the approximate form of a vertical positive dipole (excess positive charge at the top, negative at the bottom) (e.g. Michnowski 1968) and due to current being able to flow in a sufficiently ionised environment. The potential difference of ~ 10 MV arising in clouds forces the electric current upwards (known as “Wilson’s currents”) to the sphere that is heavily ionised by solar radiation (the electrosphere) where this current spreads and returns to fair-weather regions – more precisely in this case, to the lower atmosphere everywhere on Earth away from its electrical generators. The circuit is completed by the current flowing into the highly conductive (compared to the air and the ionosphere) surface of the Earth (Fig. 1). The current flowing in the atmosphere is called the air-Earth current, and its main component is conduction current. The current in the lower atmosphere is carried by positive and negative ions created by cosmic radiation and radioactivity in the air and ground (Swider 1985). The electrical conductivity of the air (or conductivity for short) close to the Earth’s surface is expressed in fS/m (10^{-15} units), and the conductivity of soil in mS/m (10^{-3} units) and water in S/m. A simple diagram of the GEC is shown in Figure 1.

Strongly ionised layers of the atmosphere above ~ 50 - 60 km (ionosphere with a conductivity exceeding several ground conductivity by several orders of magnitude) attain an electrical potential (V_i) of $+250$ kV in relation to the Earth’s surface (Markson 2007). Assuming atmospheric resistance to be ~ 200 W (Tinsley, Zhou 2006), the total electric current flowing in the atmospheric circuit is 1.25 kA. Both the electrical potential of the ionosphere and the resistance of the atmosphere fluctuate due to changes in the intensity of cloud generators, ionising radiation, and the level and type of aerosol pollution. The electrical resistance of a 1 m² column of atmosphere is known

as the “columnar resistance” (R_c). Its value depends, by definition, on the local vertical profile of air conductivity and altitude above sea level. The electrical conductivity of air is a function of several variable altitude factors, such as: ion production by cosmic rays; ion production by soil and air radioactivity (ion sources); ion recombination coefficients; aerosol concentration; concentration of cloud condensation nuclei (CCN); and the ion attachment coefficients (ion losses) corresponding to the types of aerosol and CCN. As a consequence, the distribution of columnar resistance values in geographical coordinates and in time is complicated – this is also true of the electrical field and atmospheric current density. About ~90% of columnar resistance occurs in the atmosphere column’s first few kilometres above ground level, and here the strongest electrical fields occur.

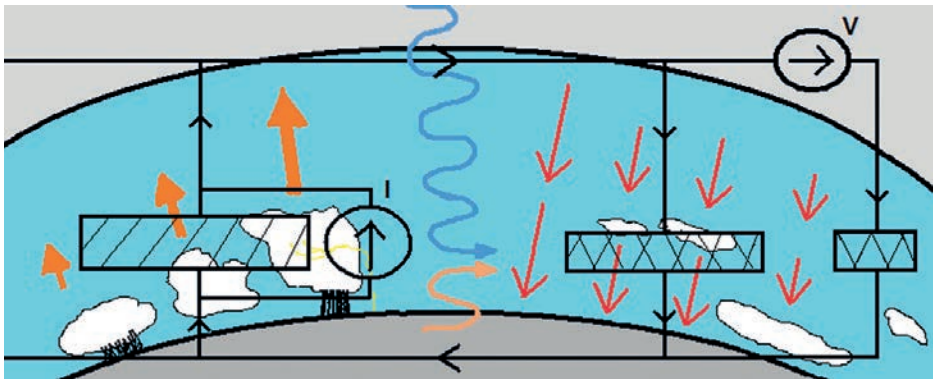


Fig. 1. Diagram of the global atmospheric electrical circuit of the Earth’s lower atmosphere (one hemisphere)¹; main currents in the circuit shown with arrows: Wilson’s currents and air-Earth current, as well as the ionising effects of cosmic rays and radioactivity²; a diagram of the circuit with cloud current generator resistances and fair-weather resistances, the cloud current generator (I) and main directions of the flow are shown; the branch of the fair-weather area in polar regions contains a variable (including directionally variable) voltage source (V) representing the magnetospheric generator

¹ An analogous fair-weather part of the circuit may be drawn in the Earth’s other hemisphere over its temperate and polar latitudes (not featured on the diagram).

² Cosmic rays and radioactivity (wavy arrows) only slightly ionise the air, but sufficiently to support current flow. Electrical voltages in the atmosphere are generated by electrified convective clouds, such as thunderstorm and shower clouds, inducing Wilson’s currents (orange arrows) flowing upward towards the conductive ionosphere (light grey area). These currents return to fair-weather regions (the air-Earth current) and complete the circuit in the conductive surface of the ground (dark grey).

Fair-weather electrical fields

According to Ohm's law, electric current density, J_z (as they dominate, we consider only the vertical components, i.e. along the z axis), for a given part of the globe is expressed by the ratio of ionospheric potential and columnar resistance (1). However, a given location's electrical field (E_z) is expressed as the ratio of the location's current density and air conductivity (2). Due to its dependence on electrical conductivity, the electrical field also varies with altitude.

$$J_z = \frac{V_l}{R_c} \quad (1)$$

$$E_z = \frac{J_z}{\lambda} = \frac{V_l}{\lambda R_c} \quad (2)$$

where: J_z – electric current density (z – vertical component); E_z – electrical field; l – electrical conductivity of the air; R_c – columnar resistance; V_l – electrical potential of the ionosphere. The fair-weather field is directed downwards and by convention considered positive, i.e. of the same sign as potential gradient.

The values of electric current density in the GEC reach the order of several to a dozen or so pA/m², and the electrical field at the Earth's surface ranges, in fair-weather conditions, from several tens to several hundred V/m. The use of Ohm's law assumes that only conduction current – the movement of charges in an electrical field – is considered. This type of electric current flow in the atmosphere is its main part, although other types of electric charge transfer occur in the planetary layer, such as: convection current, precipitation current, corona current, and electric discharges (MacGorman, Rust 1998), which as separate components of total current are often associated with the area of cloud generators (although convective current and other dynamic disturbances to the distribution of particles and charges in the planetary layer, e.g. wind, air mass exchange, also apply to other areas). The appearance of pollutants and other aerosols affect the E_z field via conductivity, causing it to vary even for the same J_z . The atmospheric electrical field near the Earth's surface is therefore dependent on meteorological and atmospheric factors that affect the local formation, accumulation or outflow of electric charge – so the local field often differs from its global nature (which depends on the GEC). This should be borne in mind when analysing ground measurements of electrical parameters. Incidentally, criteria describing the conditions determined by atmospheric electricity as “fair weather” (*fw*) have been established, i.e. when the electrical field of the atmosphere depends on local meteorological conditions to only a small extent, which is likely in the absence of cloudiness, precipitation, fog, dust and strong wind (Imyanitov, Chubarina 1965). Technically, they are determined by the following

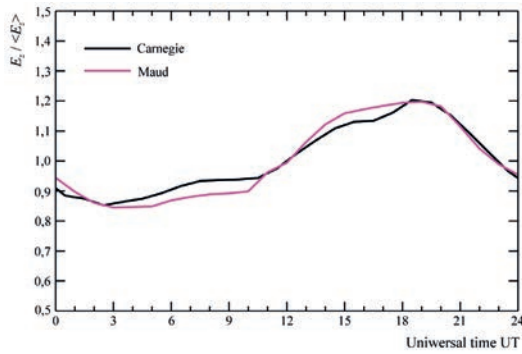


Fig. 2. Relative diurnal variation of the atmospheric electrical field, E_z , based on Carnegie Institution of Washington measurements on research cruises of the sailing ships “Carnegie” (oceans) and “Maud” (Arctic); values based on the curve plots in Whipple and Scrase (1936)

criteria (e.g. Kubicki et al. 2016a): at most, low-level cloudiness ($<4/8$); no precipitation, fog, dews or frosts; low wind speed (<6 m/s). Sometimes, additional criteria are used, such as minimum and maximum field values, and the effect of aerosol concentrations and types. In order to obtain reliable GEC observations, it is essential to monitor compliance with fw criteria. Only in such weather conditions can the field be expected to reflect the global GEC signal. Therefore, measurements of atmospheric electricity are best carried out in places where weather conditions are stable and aerosol concentrations are low.

Diurnal variability of GEC

Measurements of the atmospheric electrical field in clean air in the Pacific, Indian and Atlantic Oceans, which are extremely important for the study of the GEC, were carried out during four cruises of the sailing ship *Carnegie* organised by the Carnegie Institution of Washington (CIW) in 1915-1929 (Mauchly 1926; Gish et al. 1946). Average diurnal fluctuations of E_z in fair weather conditions, calculated from measurements on the Carnegie, show field variation in universal time, with a minimum of around 03-04 UT and a maximum of around 18-21 UT, known as the “Carnegie curve” (Parkinson, Torreson 1931) (Fig. 2). The similarity between diurnal E_z variation at different places as a function of Universal Time had previously been noted thanks to observations from polar stations (Hoffmann 1924; Israël 1953). It is believed that diurnal E_z field changes have such a nature primarily due to the regular, daily fluctuations in the convective and electrical activity of the clouds concentrated in the aforementioned centres in Indonesia and Asia, Africa and America (Whipple 1929), and the Carnegie curve is considered to be the pattern of diurnal changes

in the GEC. Due to the impact of local effects, observations of the atmospheric electrical field around the world confirm this result to varying degrees, depending on whether a station is terrestrial or marine and depending on its global location (latitude, altitude) and the level of pollution (Israël 1966), and even distance from storm centres, e.g. CIW measurements in Huancayo (Torreson, Wait 1948) may record the impact of an American storm centre on diurnal E_z variability.

Magnetosphere–ionosphere current coupling

The lower-atmosphere electrical circuit is bounded in the upper atmospheric layers, at the altitude of the ionosphere's lower layers, and may therefore be affected by the impact of changing space weather that it is subject to (Michnowski 1998) due to its coupling with the magnetosphere, which interacts with the solar wind and the Interplanetary Magnetic Field (IMF). A review of the influencing phenomena of cosmic physics is provided by the works of Wernik (1996), Popielawska (2002) and Kłos et al. (2007), while Milan et al. (2017) provide a thorough review of research results on magnetosphere-solar wind couplings.

The phenomenon of ionospheric convection, which is related to the magnetosphere's interaction with solar wind and the IMF, has a permanent influence on the GEC. It manifests in polar regions as the presence of two or more adjacent areas (bays) of greater and lesser electrical potential that are related to the Earth–Sun axis and dependent on IMF parameters (Dungey 1961). There are areas of differentiated potential in both the northern and southern hemispheres' magnetic polar regions, while convection within hemispheres does not have to be symmetrical. Additional changes in the ionosphere's electric potential, which are caused by coupling with the system of electrical fields and currents of the magnetosphere and lower atmosphere (Park 1976a), will be referred to – as in the literature on atmospheric electricity – as the “magnetospheric generator” or “dynamo”. This is presented diagrammatically in Fig. 1 as an additional voltage source added into the circuit in polar regions. To the observer on Earth, this specific distribution of ionospheric convection potential, also known as the “polar cap potential pattern”, rotates according to the daytime motion of the celestial sphere and generates diurnal changes in the ionospheric potential in the range of ± 20 –100 kV (e.g. Bering et al. 1998; see also Fig. 4).

During magnetic storms and substorms, there is a strengthening of convection-related electrical currents, i.e. field-aligned Birkeland currents closed by currents flowing in the ionosphere, and auroral currents are activated. The potential difference between the bays of positive and negative convection potential, i.e. the polar cap potential (“transpolar voltage” or “dawn-dusk potential”), can then reach up to 250 kV; approaching these values, it reaches

saturation (e.g. Siscoe et al. 2002). During stronger disturbances, the influence of ionospheric convection and auroral currents extends to lower geomagnetic latitudes (e.g. Olson 1971). These are therefore not even approximately steady potential and current distributions, but quite temporally and spatially variable depending on the parameters of magnetosphere-solar wind coupling at the time (i.e. its velocity and density), and on the configuration of the interplanetary magnetic field and the state of the magnetosphere.

As well as the magnetospheric generator, the so-called “ionospheric dynamo” is also important, causing an additional electrical potential difference in the order of ± 10 kV between the northern and southern hemispheres (Roble 1985).

Polar regions in the GEC

Polar regions are of interest to scientists due to the properties of the GEC and the opportunities they afford to study it. These zones are remote from the largest cloud generators, especially storm ones, although storms do occur at these latitudes, too, e.g. Alaska or Spitsbergen (Soroka, Bania 2013). In terms of generating electricity in the atmosphere and in the GEC, snow storms (Anderson 1966) and Nimbostratus clouds, whose role in the circuit has not fully been explored, are more important in polar regions (Odzimek, Lester 2009; Odzimek et al. 2014). In atmospheric electricity observations in polar regions, the presence of the magnetospheric generator is clearly visible due to the proximity of the geomagnetic and geographical poles – especially where these two polar zones overlap (Park 1976a). The significant distance from the centres of cloud generators and the less polluted and more stable atmosphere are additional advantages to making GEC observations from polar regions, where, in areas where *fw* criteria are met, the circuit’s signal should be visible. One key place where fair-weather conditions prevail for most of the year is the Antarctic Plateau; Antarctic coasts have far less favourable weather conditions, as cyclonal systems are constantly in operation there.

The features that distinguish polar regions from other parts of the globe in terms of passive elements of the GEC, i.e. those that increase or reduce conductivity (i.e. atmospheric air resistance) and that consequently affect columnar resistance, include:

- the profile of atmospheric ion production with higher ionisation and without so-called “knee”, that is, a maximum at a height of about a dozen or so kilometres (Israel 1973; Tinsley, Zhou 2006, *ibid* Fig. 4);
- atmospheric ion production being weakened by ground radioactivity due to the presence of ice cover and the occurrence of a so-called “electrode layer” (Ruhnke 1962; Tinsley, Zhou 2006, *ibid* Fig. 5).

- aerosol concentrations and type differing from other regions of the globe (Hess et al. 1998; Tinsley, Zhou 2006, *ibid* Fig. 6).
- the occurrence and altitude a.s.l. of the plateau (Dalrymple 1966).

The aforementioned properties that affect the electrical conductivity of the lower polar atmosphere give polar regions lower columnar resistances and electrical field values, but higher atmospheric current density values.

Below are the results of calculations of the electrical field and current density from the “EGATEC” model of the GEC (Odzimek et al. 2010). The maps (Fig. 3) show model values of the ground electrical field and current density for fair weather in the Arctic and Antarctic in July for a geographical point grid of 5° latitudinal and longitudinal resolution and three-hour time resolution sampled at 0, 3, 6, 9, 12, 15, 18, 21 UT. Minimum GEC activity is observable at 3 UT and maximum at 21 UT (see Fig. 2). Electric field values in the Arctic are $\sim 60\text{--}130$ V/m, current density $\sim 3.0\text{--}6.0$ pA/m². In Antarctica, the current density can be $\sim 3.0\text{--}15.0$ pA/m², and the field $\sim 50\text{--}100$ V/m. The specific conductivity of polar air in fair weather should therefore remain at a few tens or more fS/m, e.g. $\lambda^p = J_z^p / E_z^p \sim (4 \text{ pA/m}^2) / (100 \text{ V/m}) = 40 \text{ fS/m}$, compared to the few or the dozen-or-so fS/m observed in, for example, Świder near Warsaw (Odzimek et al. 2018). The presented model E_z and J_z values are consistent with observation results in the textbook by Israël (1973). A more detailed analysis of measurement and model results is beyond the scope of this article.

To illustrate additional changes in the ionosphere potential in polar regions resulting from ionospheric convection and not included in the current version of the EGATEC model, Fig. 4 presents the nature of diurnal changes in ionospheric convection potential in the northern hemisphere (the Arctic) on the example of July 5, 2005 (a magnetically calm day), developed from the Weimer model (2005) using the same times point grid as in Fig. 3. The input parameters for solar wind and interplanetary magnetic field were taken from OMNI data in the NASA GSFC OMNIWeb database¹. Based on electrical data from Hornsund and a convection model with measurements by the HF SuperD-ARN ground radar network (Ruohoniemi, Baker 1998) a work by Odzimek et al. (2011) estimates that ± 10 kV of convection potential results in a $\pm 10\%$ change in the electrical field value at the Earth’s surface.

GEC observations in polar regions

Because their proximity to the geographical and geomagnetic pole affords them special atmospheric and climatic characteristics and connections with

¹ NASA Goddard Space Flight Center, Space Physics Data Facility, OMNIWeb <http://omniweb.gsfc.nasa.gov>

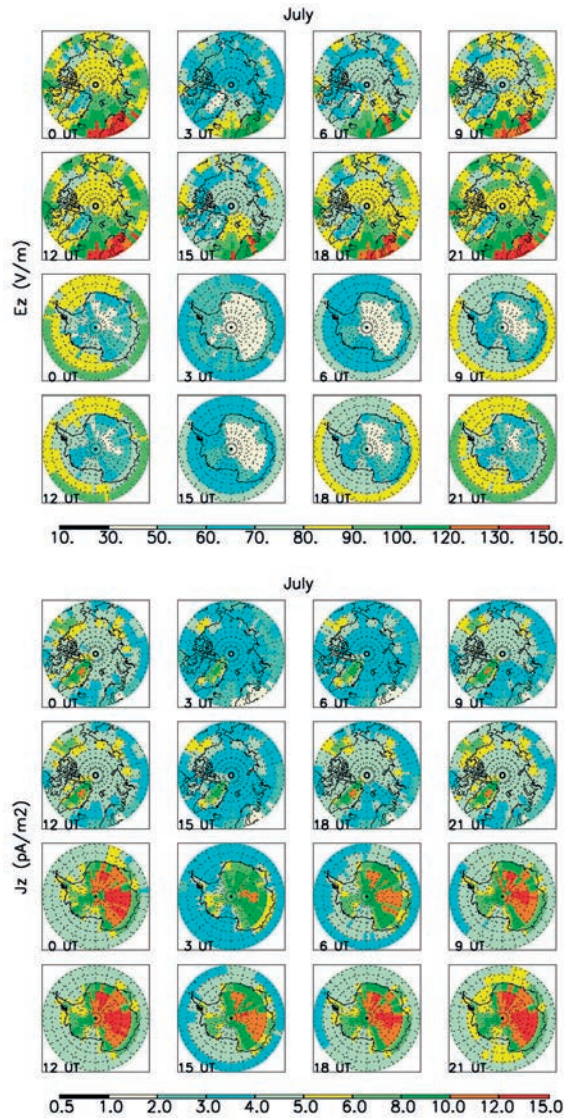


Fig. 3. Diurnal variations and spatial distribution of the fair-weather atmospheric electrical field (E_z ; upper panel) and atmospheric electric current density (J_z ; bottom panel) in the polar regions, for July according to EGATEC model (Odzimek et al. 2010), at 0, 3, 6, 9, 12, 15, 18 and 21 UT; Arctic – two upper rows, Antarctica – two lower rows

the Earth's magnetosphere, polar areas are an important platform for atmospheric, geophysical and space research (Lessard et al. 2014) – especially after the period of expeditions to explore these regions in the 18th and 19th centuries. Major international scientific events, such as: the 1st International Polar

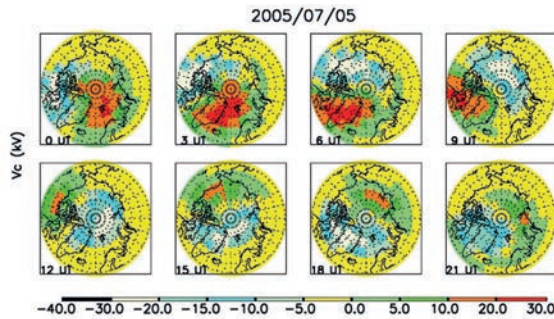


Fig. 4. Diurnal and spatial variations of the ionospheric convection potential (V_c) in the Arctic, for 5 July 2005, according to the Weimer model (Weimer 2005) at 0, 3, 6, 9, 12, 15, 18 and 21 UT

Year (IPY) 1882–83, the International Congress of Physicists in Paris in 1900, the 2nd International Polar Year 1932–1933, the International Geophysical Year (IGY) 1957–1958, and the International Quiet Sun Year (IQSY) 1964–1965 had a huge impact on the development of activities in many research fields. A wide range of scientists from many countries took part, and these projects' plans often included research in the polar regions. Of particular significance in the field of atmospheric electricity were expeditions by the Carnegie Institute of Washington in the first half of the 20th century and programmes by the International Committee for Atmospheric Electricity in the second half of the century, such as the “Ten-Year Program”, i.e. a decade of simultaneous measurements of atmospheric electricity at various locations around the globe (Dolezalek 1991).

Although magnetosphere physics, cosmic weather and other fields studying Earth–Sun relationships are currently treated as separate from atmospheric physics and meteorology, and especially atmospheric electricity, nevertheless, in the 19th and early 20th centuries topics related to natural earthly phenomena related to the influence of the sun were generally called “cosmic physics” (Kragh 2013b) and efforts were made to coordinate research in this scientific field (Kragh 2013a). The aforementioned events such as IPY I and II were based on this concept, allowing scientists to tackle a variety of topics, e.g. the meteorological observations, and research into the aurorae borealis and australis or the Earth's magnetic field, as reported for example by Arctowski (1901) and in other volumes of results from the Belgian Antarctic Expedition on the sailing ship *Belgica* 1897–1899, or notebooks of the results of the Polish expedition of the Second International Polar Year to Bear Island (Lugeon et al. 1936).

As Kasemir (1972) emphasises, observations in the polar climate were initiated, among other reasons, to eliminate undesirable effects such as *Austausch*, which is associated with vertical air mass exchange caused by heating of the land, and which interferes with the detection of the daily variation of the GEC at land stations at low and moderate latitudes. Early measurements

were intended to describe the GEC phenomenon by characterising the diurnal changes in the E_z field from polar regions (Israël 1953; Cobb 1976). In the 1970s and later, publications concerning, among others, the Vostok and Davis stations, were already focussing on studying the impact of the magnetospheric generator, analysing courses of the field after subtracting GEC changes predicted by the Carnegie curve, as well as studying how changes in the ground electrical field depended on interplanetary magnetic field parameters (Park 1976b; Burns et al. 1995; Tinsley et al. 1998; Frank-Kamenetsky et al. 1999, 2001). Other works attempted to eliminate the magnetospheric generator effect from GEC observations (Corney et al. 2003; Reddel et al. 2004, Burns et al. 2005). These two research directions based on activity in polar areas are still being conducted (Kumar et al. 2008; Burns et al. 2012; Kleimenova et al. 2013), while simultaneous measurements from several stations are increasingly being analysed (Frank-Kamenetsky et al. 2012; Kubicki et al. 2014; Victor et al. 2016, Burns et al. 2017), provided that *fw* conditions are met.

Observations at Arctic stations

Soon after mastering the technique of electrical field measurements, such observations were being carried out not only at moderate latitudes, but also in subpolar and polar regions. Systematic measurements of the electrical field were carried out in the Arctic during IPY I, during the Swedish expedition to Spitsbergen (Cape Thordsen) (Andrée 1887; Heathcote, Armitage 1959). Subsequent measurements of the ground-level electrical field were made in Svalbard by J. Elster (1902) at the shores of Virgin Bay (Virgohamna) during the German expedition 1900-1901. During another German expedition in 1913-1914, field measurements were carried out at the Ebeltofhafen Geophysical Observatory on the Mitra Peninsula in Spitsbergen (Hoffmann 1924).

Longer measurements of atmospheric electricity had previously been carried out in the Arctic by G. Simpson at the Norwegian Karasjok observatory (Simpson 1906), thanks to a special research grant from the Royal Commission of the Great Exhibition of 1851. A campaign of measurements that included many atmospheric electricity parameters was carried out in Iceland during the passage of Halley's comet in 1910 (Ansel 1912). The achievements of Scandinavian researchers from the beginning of the last century also include more-than-year-long Swedish observations in Vassijaure (Norinder 1916). In turn, Barlindhaug (1935) describes the results of E_z measurements taken in Tromso in 1932-1933 (IPY II), but also mentions earlier short measurement episodes – both in the Tromso observatory and in Hallde.

During IPY II, there were several atmospheric electricity measurement campaigns. These included observations during the British expedition to Fort Rae

in Canada (Sheppard 1937), the French expedition to Scoresby Sund in Greenland (Dauvillier 1938) and American observations in College (Fairbanks), Alaska (Gish, Sherman 1940). In the 1930s and 1940s, measurements were carried out at various times: at Cape Chelyuskin, in Yakutsk, northern Russia; on Hayes Island in Franz-Joseph Land (Lobodin, Paramonov 1972); and at the Silent Bay (Tikhaya Bay) station on Hooker Island in Franz-Joseph Land.

After the end of World War II, systematic observations were made only during the International Geophysical Year of 1957-1958. In the Arctic, electrical field measurements were carried out: on the glacier in Thule, Greenland (Kasemir 1972); at the Swedish-Finnish-Swiss Kinnvika station in Murchison Bay on Spitsbergen (Lugeon et al. 1959); and in Murmansk (Popov et al. 2008). Earlier, in the 1950s, American researchers conducted measurements in the Greenland region on a special aircraft - an airborne atmospheric electricity laboratory (Clark 1957). In the 1970s, when the Ten-Year Program was in force, electrical field measurements were taken at College in Alaska (Shaw, Hunsucker 1976).

At the turn of 1980s, the electrical field was also measured at many Arctic and subarctic stations of the Soviet Union, and their main purpose was to more thoroughly examine the effects of polar auroras and other magnetospheric effects, as well as the impact of magnetospheric (ionospheric) convection and auroral currents on the atmospheric electrical field (Bandilet et al. 1986; Apsen et al. 1988; Sheftel 1991). These were both ground-based measurements at stations, and aerial measurements using balloons launched from Esrange in Sweden in "SAMBO" measurement campaigns (Russian: *Sinchronnnye Aworralnyje Mnozestwiennyje Balonnye Observatorii*) in 1976, 1979 and 1982. In 1974, current density was measured using balloon probes released from the Norwegian Andenes (Andoya) station towards Greenland (e.g. D'Angelo et al. 1976). Rocket-borne probe measurements were conducted at this station in the 1980s and '90s, and in 1989 also on Hayes Island (Zadorozhny, Tyutin 1997; listing and literature for other E_z measurements therein). In Esrange, Sweden, balloon measurements of atmospheric current density were carried out from the ground until the late 1990s (Belova, Kirkwood 2001). Since 2001, Russian atmospheric electricity monitoring has been conducted on the Kola Peninsula as continuous measurements of electric field or current density in Apatity and Lovozero (Roldugin et al. 2004; Akhmetov et al. 2010).

Since the 1986/1987 season, measurements of electricity have been included in the research programme at the Stanisław Siedlecki Polish Polar Station on Spitsbergen (Michnowski 1996a). Furthermore, the Hornsund station is currently the only Arctic station that has been conducting continuous research monitoring of such processes for decades. For just a short period in December 1986, electrical field measurements were carried out at the Russian station in Barentsburg on Spitsbergen in parallel with observations at the mid-latitude station in Borok (Zotov et al. 1991).

The locations of Arctic terrestrial sites for ground observations of atmospheric electricity are presented in the map in Fig. 5, which is divided into active, temporary and historical stations. Historical stations are places where measurements or a measurement campaign were carried out in the past, e.g. during a polar year, but that have for many years now not been used for observations. Temporary stations are where measurements have taken place in the last two decades, but it is not known if they are to continue. Meanwhile, active stations are those in which atmospheric electricity monitoring is still being carried out – whether continuously or periodically. These points are listed in Table 1 together with information on measured parameters and period of operation. Stations and measuring sites at latitudes beyond 60°N or 60°S are presented, excluding European observatories such as Helsinki, Saint Petersburg and Uppsala (Israël 1973; Tuomi 1989) located close to the 60th parallel.

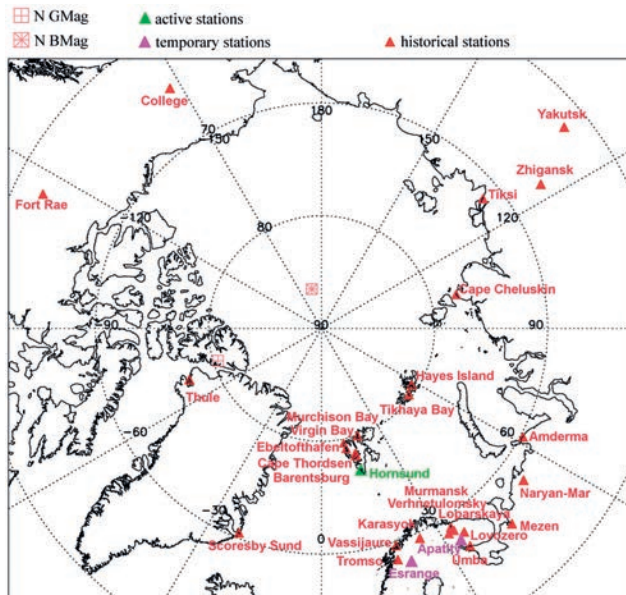


Fig. 5. Arctic atmospheric electricity stations – station locations are marked with triangles; the current position of the magnetic north pole (PMag N) and the projection of the geomagnetic dipole axis (GMag N)¹ is also marked; stations as listed in Table 1. Status of Lovozero station has been corrected

¹ Most of the places indicated are within the Arctic Circle ($66^{\circ}33'39''$). The magnetic axis is at an angle of about 10° to the Earth's axis, but the exact location of the magnetic poles deviates from this axis' intersection with the Earth's surface and undergoes centuries-long changes. The current locations of the magnetic poles and intersections with the model magnetic axis were taken from the World Data Center for Geomagnetism in Kyoto, <http://wdc.kugi.kyoto-u.ac.jp>

Antarctic stations

Antarctic expeditions in the early 20th century produced measurement series from the area of Petermann Island (Rouch 1911) and Cape Evans (Simpson 1919). The end of the 1950s and the following decade, including the International Geophysical Year and the International Quiet Sun Year, saw the birth of systematic stationary and campaign observations of electricity in the Antarctic (Kasemir 1972). Since then, they have been a permanent feature of the Antarctic science programme. As part of the IGY, measurements were carried out at the Belgian Base Roi Baudouin station (van der Schueren, Koenigsfeld 1963; Buis 1968) and the then-Soviet Mirny station (Gordiuk 1984). Soon, similar programmes were launched at the South Geographic Pole, including at the American R. Amundsen and R. Scott South Pole station, where multi-year observations of atmospheric electricity were conducted to measure not just the field but also current density, including using balloons (e.g. Cobb 1976; Burke, Few 1978; Muir, Smart 1981; Bering et al. 1991; Byrne et al. 1993). The Americans also carried out balloon measurements of electrical parameters from the Siple station (Bering et al. 1998). Aerial measurements of atmospheric electricity parameters were also carried out up to a height of several dozen kilometres by Soviet researchers using rockets launched from the Antarctic Molodyozhnaya station (Bragin et al. 1980).

In the 1970s, a Soviet–Australian–American project of ground-based atmospheric electrical field measurements was begun at the Vostok station (Park 1976b; Frank-Kamenetsky 1983; Frank-Kamenetsky, Kalita 1986; Frank-Kamenetsky et al. 1999, 2001). At that time, observations also began at the Japanese Syowa station (Kikuchi 1970), then at the end of the 1980s at the Australian Davis Observatory (Burns et al. 1995; Tinsley et al. 1998), and in the 1990s at the Indian Maitri station (Deshpande, Kamra 2001). In recent decades, measurements have been carried out periodically, e.g. in Syowa (Minamoto, Kadokura 2011) or sporadically in other places – in 2015, a series of measurements of the electrical field was carried out in Halley (Nicoll, Harrison 2016). Continuous measurements were taken at South Pole and Vostok stations.

IPY 2007–2009 was also used for campaign and multi-point observations of atmospheric electricity. Special automatic stations for measuring electrical field and current density, with additional meteorological measurements, were developed in the British Antarctic Survey based on Australian and American experiments (Junyent et al. 2006) and measurement series were carried out at the Sky Blu station and two distant points on the Antarctic plateau – from the Weddell Sea side (M. Jarvis, British Antarctic Survey, own information; places not marked on the map in Fig. 6). In December 2012, continuous measurements of the electrical field began at the Arctowski Polish Antarctic Station (Kubicki et al. 2016b).

The locations of ground-based atmospheric electricity observations in Antarctica are shown in Fig. 6, and the list of stations in Table 2.

The Maud curve

The Carnegie Institution of Washington (CIW), following the example of the Carnegie cruise, provided scientific equipment for Roald Amundsen's expedition across the Arctic Ocean aboard the *Maud* sailing ship (1918-1925), including instruments for measuring atmospheric electricity. The results were published in CIW work by Sverdrup (1927). The expedition's route ran through the ice pack and bays along the northern coasts of Russia. The observation of the electrical field from the deck of the *Maud* produced a diurnal curve of E_z field changes (Whipple, Scrase 1936) analogous to the Carnegie curve, and is presented in Fig. 2 (in pink). The differences between the courses of the two lines can be explained by the influence of the magnetospheric generator, whose influence was not well understood at that time (D'Angelo et al. 1982).

In the late 1970s, measurements of the atmosphere's electricity in the Arctic Sea were also made by the Soviet drifting maritime station North Pole-22 (SP-22) (Guglielmi et al. 1979).

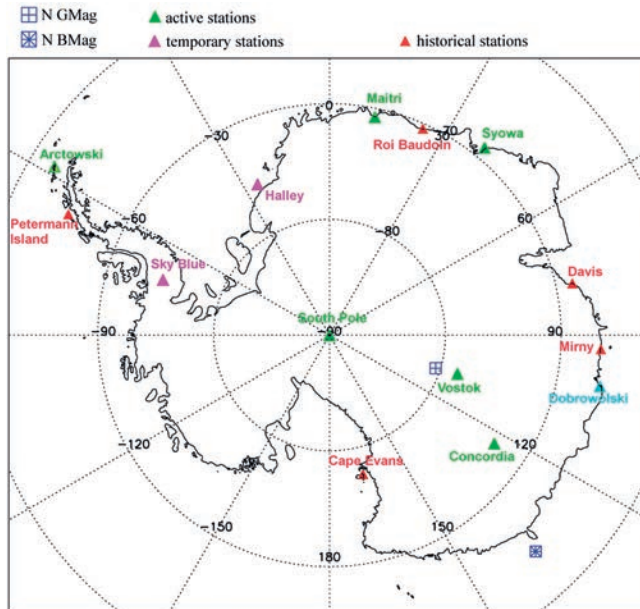


Fig. 6. Antarctic atmospheric electricity stations; the current location of the magnetic south pole (PMag S) and the projection of the geomagnetic dipole axis (GMag S) is also marked; the location of the A.B. Dobrowolski Antarctic Station is marked with a cyan triangle; stations as listed in Table 2. Status of Arctowski station has been corrected

Table 1. Stations and sites of ground-based atmospheric electricity measurements in the Arctic; columns: station name (1 column), measured parameters and physical properties (not always measured simultaneously) (5 columns), country of expedition or station (1 column), presence of measurements per decade, from 1890 to 2010 (13 columns)

Station name or geographical name	Measured size and physical properties				Country organising expedition or owning station	Decades in which atmospheric electricity was measured													
	E_z	J_z	λ	Ions		Aerosol	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Cape Thordsen	X					X													
Virgin Bay	X						X												
Ebeltofhafen	X						X												
Karasjok	X						X												
Vassijaure	X							X											
Tromso	X									X									
College (Fairbanks)	X									X									
Fort Rae	X	X		X	X					X									
Scoresby Sund	X									X									
Tikhaya Bay	X									X									
Hayes Island	X									X									
Cheluskin	X									X									
Yakutsk	X									X									
Murchison Bay	X	X		X							X								
Murmansk	X											X	X						
Thule	X	X	X	X									X						
Amderma	X													X					
Mezen	X													X					
Lovozero	X	X												X	X				X
Naryan-Mar	X													X	X				

Station name or geographical name	Measured size and physical properties			Country organising expedition or owning station	Decades in which atmospheric electricity was measured															
	E_2	$I_{1/2}$	λ		Ions	Aerosol	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010	
	Tiksi	X				RU											X			
Zhigansk	X			RU											X					
Verhnetulomskiy	X			RU											X					
Umba	X			RU											X					
Loparskaya	X			RU											X					
Apatity	X	X		RU											X				X	
Barentsburg	X			RU											X					
Hornsund	X	X		PL			X								X		X		X	
Estrange	✱	X		SE													X		X	

Research on atmospheric electricity and the GEC in Polish polar stations

Polish research in the field of atmospheric electricity in the polar regions is associated with the geophysical research activity and programme of the Polish Academy of Sciences' (PAS) polar stations, i.e. the PAS Siedlecki Polish Polar Station in the Hornsund fjord on Spitsbergen (Svalbard archipelago, Norway) and the PAS Arctowski Scientific Antarctic Station on Prince George Island (South Shetland Archipelago). Atmospheric electricity measurements in Hornsund and at the Arctowski station, together with an atmospheric electricity station at the Geophysical Observatory of the Institute of Geophysics of the Polish Academy of Sciences in Świdler currently constitute the Polish network for observing atmospheric electricity (Kubicki et al. 2016b).

Observations in Hornsund focussed from the very beginning on studying the impact of solar wind through its interaction with the Earth's magnetosphere and on the electrical fields and currents at the Earth's surface, using additional geomagnetic and ionospheric measurements, both domestic, foreign and international (Michnowski 1996a, b). Other than the electrical field's vertical component (Michnowski 1996c; Berlinski et al. 2007), current density was also measured (Łosakiewicz, Drzewiecki 1991). For many years, research has been carried out in bilateral cooperation between the Polish and the Russian Academy of Sciences. For three decades, dozens of cases of atmospheric electrical field behaviour during increased solar wind activity, sub-storms and magnetic storms have been analysed in cooperation with the Russian Academy of Sciences' Institute of Earth Physics in Moscow. Characteristic electrical field disturbances during morning and evening magnetic substorms, during daytime auroral activity and due to the action of the NBZ current system were identified (Michnowski et al. 1991, 1996, 2003; Michnowski, Nikiforova 1996; Kleimenova et al. 1998, 2008, 2011, 2012, 2017; Nikiforova et al. 2003; Kozyreva et al. 2007), as were electrical field disturbances in Świdler during a magnetic storm (Nikiforova et al. 2005; Kleimenova et al. 2008; Michnowski et al. 2014). Other studies have investigated geomagnetic pulsations (Kleimenova et al. 1998), the impact of high-energy particle precipitation on the electrical field (Nikiforova et al. 2003) and the visibility of the GEC signal in measurements from Polish stations (Kubicki et al. 2014). The impact of ionospheric convection on electrical fields during magnetically calm days in Hornsund has also been analysed using the ionospheric convection technique by the SuperDARN (Super Dual Auroral Radar Network) non-coherent radar network, in cooperation with the University of Leicester in Great Britain (Odzimek et al. 2011).

Atmospheric electricity research at the station in Hornsund was also made possible by ionospheric absorption observations using the PAS Space Research Centre's riometer (Kłos et al. 2007) and INTERMAGNET and IMAGE mag-

netometer network measurements fed by geomagnetic data from observations conducted (e.g. in Hornsund) by the Geomagnetic Observation Team in the PAS Institute of Geophysics Department of Magnetism (Reda, Neska 2016)². Since 2004 this team has been measuring the alternating magnetic field in the range of extremely low ELF frequencies, including in Hornsund (Neska, Satori 2006), and this included the Schumann resonance phenomenon, which enabled studies of, among other things, the occurrence of discharges on the globe associated with the location of storms.

Data on air radioactivity in Hornsund was collected using instruments of the Institute for Nuclear Research (now the National Centre for Nuclear Research), allowing analysis of the impact of radioactivity on electrical parameters, e.g. after the failure of the Fukushima nuclear power plant (Myslek-Laurikainen et al. 2006; 2014).

Current Polish research topics within the field of atmospheric electricity (which includes cloud electricity) include analysis of the electrical field during the occurrence of Nimbostratus and Stratus clouds, with the long-term aim of parameterising the electricity of such clouds at medium and high latitudes for GEC models (Odzimek et al. 2014, 2018). As part of a project co-financed by the National Science Centre in 2011–13 (Contract No. 2011/01/B/ST10/07188), the Nimbostratus and Stratus cloud database began to be built from meteorological observations in Hornsund and electricity research into these cloud types.

Atmospheric electricity research have been conducted for many years in Poland mainly as part of the statutory activities of the PAS Institute of Geophysics at the Department of Atmospheric Physics (DAP) – in recent decades as part of the DAP's Laboratory of Atmospheric Electricity. At the Siedlecki Polish Polar Station run by the PAS Institute of Geophysics (and by the Polar Research Department in particular) atmospheric electricity measurements have been conducted – under the supervision of DAP specialists – by many members of scientific expeditions to the Hornsund station. In 2011, supported by the National Science Centre, the PAS Institute of Geophysics began constructing modern atmospheric electricity measuring stations, including for polar stations and for analysing simultaneous measurements of the electrical field and aerosol concentration at the three cited Polish measuring stations (Kubicki et al. 2016b). The initiation in 2012 of new electricity measurements at the Arctowski station run by the PAS Institute of Biochemistry and Biophysics was made possible by cooperation with the PAS Institute of Geophysics and funding from the National Science Centre in 2011–13 (contract no. 2011/01/B/ST10/07118).

² Geomagnetic measurements had also previously been conducted at the Arctowski station for about two decades, starting in 1978 (Szymański 1980, Kubicki et al. 2016b).

The atmospheric electricity measuring infrastructure is financially supported by the PolarPOL (Polish Multidisciplinary Polar Research Laboratory) project at present and in the near future by the CLIMEV project (part of the science and education ministry's Polish Roadmap for Research Infrastructures) (Głowacki 2018). The opportunities in observations of atmospheric electricity that have been created in previous decades or are now emerging should extend Polish national and international cooperation and interdisciplinary scientific research results.

Research directions

After a period of specialisation, there is an increasingly clear need to return to the idea of various scientific fields cooperating within one main stream – “cosmic physics” as it was known at the turn of the 20th century – in order to synthesise and exploit achievements from individual areas. This is particularly evident in the study of polar regions. Atmospheric electricity is in itself an interdisciplinary field that touches on meteorology, atmospheric, ionospheric, and magnetospheric physics, geomagnetism, nuclear physics, gas discharge physics, and others. Scientific cooperation between these diverse fields should bring mutual benefits (e.g. Michnowski 1975).

One interdisciplinary problem in polar areas is the issue of the magnetospheric generator in the GEC and its direct effects on weather, atmospheric pressure and cloud microphysics (Tinsley 1996, 2000; Troshichev et al. 2003; Burns et al. 2007). Furthermore, the aforementioned studies of: the effects of magnetic storms and sub-storms and other cosmic weather phenomena; studies of atmosphere physics regarding aerosols and their impact on atmosphere resistance; cloud physics in polar regions, and particularly clouds that can be GEC generators, including ordinary storms and snowstorms; and precipitation, all continue to be current as research topics in atmospheric electricity.

National research and cooperation in these fields would certainly grow if atmospheric electricity observations were extended to other stations. In this respect, progress is possible in both Antarctic and Arctic research. There are currently several national science stations on Spitsbergen, and the PAS Dobrowolski Antarctic Station in the Bunger Oasis (Gregorzczuk 1980) can also be in the network; if refitted for geophysical research, it would significantly increase the research potential in GEC magnetospheric generator analysis due to its distance to the geomagnetic pole, even despite being exposed to sub-optimal f_w conditions.

Polish measuring stations and observations in the polar regions and projects that have for years been conducted there (Szymański 1976; Petelski 2002; Łupikasza 2003; Mysiek-Laurikainen et al. 2006; Neska, Satori 2006; Karasiński

2012; Górski 2014; Gluza, Siwek 2015; Marsz, Styszyńska 2015; Migąła et al. 2015; Niedźwiedz 2015; Przybylak et al. 2015; Rachlewicz, Zwoliński 2015; Ustrnul 2015; Sobota et al. 2017) provide opportunities to develop atmospheric electricity studies in the direction of interdisciplinary research on a regional scale. This could concern identifying local influences, such as weather conditions, distance from the sea and glaciers, and air and ground properties. Of direct relevance to the GEC is research on the properties and role of the cloud generator and magnetospheric generator, which can be monitored and studied regionally – e.g. studies of the effects associated with influence of calm and disturbed ionospheric convection, movements of the auroral oval associated with the magnetic substorm cycle, and the continuation of research into the effects of changes in concentrations and types of aerosol and radioactivity, as well as on the influence of weather parameters. Parallel meteorological measurements are needed, due to the need to monitor that weather criteria are being met, to observe clouds, etc. This may be helped by the development of the testing and digital infrastructure for scientific research in the Arctic that has taken place in recent years (e.g. Sikora et al. 2012) with the support of national and European funds (Głowacki 2018). Modernising the research process will certainly be extremely helpful, because observation in the polar zone continues to be challenging.

Conclusion

This paper presents one of the main research topics in atmospheric electricity, which is the GEC Global Electric Circuit, and presents a cross-section of the problems associated with it in the context of polar areas. The history of research on atmospheric electricity measurements in the polar regions was described, with particular emphasis on national research projects. The author expresses gratitude to Professor Daniel R. Weimer of the Virginia Polytechnic Institute and State University (USA) for providing a model of the electrical potential of ionospheric convection, which allowed the presented potential maps to be drawn up. The data from the EGATEC model that were used are from the author's own work.

This work is a more detailed elaboration of the topic presented at The Bat-sheva de Rothschild Seminar on The Atmospheric Global Electric Circuit (GEC) on February 5-10, 2017 in Mitzpe Ramon (Israel) and at the XXVIII Seminar on Meteorology and Polar Climatology, 11-12 May 2018 in Sosnowiec, at the Faculty of Earth Sciences of the University of Silesia. The work is financed from the statutory resources of the Institute of Geophysics of the Polish Academy of Sciences, grant MNiSW 3841/E-41/S/2018.

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G l o s s a r y o f a b b r e v i a t i o n s

- CCN - Cloud Condensation Nuclei
- CIW - Carnegie Institution of Washington
- DAP - Department of Atmospheric Physics [*Zakład Fizyki Atmosfery (ZFA)*]
- GAEC - Global Atmospheric Electric Circuit = GEC
- GEC - Global Electric Circuit = GAEC
- IMF - Interplanetary Magnetic Field
- IAMAS - International Association of Meteorology and Atmospheric Sciences
- IAMAP - International Association of Meteorology and Atmospheric Physics
- ICAE - International Commission (or Conference) on Atmospheric Electricity
- IGY - International Geophysical Year

IPY - International Polar Year

IQSY - International Quiet Sun Year

IUGG - International Union of Geodesy and Geophysics

PAS - Polish Academy of Sciences [*Polska Akademia Nauk (PAN)*]

fw - fair-weather criteria or conditions, in terms of atmospheric electricity

S u m m a r y

The article presents the main features of the polar regions - the Arctic and Antarctic - from the point of view of the Earth's global atmospheric electric circuit and its connection to the electric current system of the Earth's magnetosphere. The chronology of observations and research studies of atmospheric electricity in polar regions up to 2015 is presented, including main geophysical events such as International Polar Years and the International Geophysical Year. Research studies on atmospheric electricity based on measurements at Polish polar stations (the S. Siedlecki Polar Station in Hornsund, Spitsbergen, and the H. Arctowski Antarctic Station on King George Island), have been reviewed separately. The Article concludes with the possible directions of development of atmospheric electricity research using Polish polar stations, and potential fields of interdisciplinary scientific cooperation.

Key words: atmospheric electricity, global electric circuit, GEC, Arctic, Antarctic, Carnegie curve, Maud curve, International Polar Year