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Modelling the Earth's Global Atmospheric Electric Circuit – Development, Challenges and Directions

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Abstract

In this paper we summarise modelling work to date concerning the Earth's global atmospheric electric circuit. We discuss the development of the models over last decades and some features that require improvements in future models. We consider various atmospheric and ionospheric data sets and models available which can support and improve the current and future modelling of the global electric circuit. We also highlight the new high-resolution model of the global atmospheric electric circuit, EGATEC, currently developed at the University of Leicester.

1. Overview of the global atmospheric electric circuit

The term Global Atmospheric Electric Circuit (GAEC or GEC) is referred to the flow of electric currents in the Earth's atmosphere. According to the "classical picture" of atmospheric electricity these currents are produced by electrically active cloud generators, thunderstorms and non-thunderstorm clouds, e.g., shower clouds, as suggested by Wilson (1920). Charge transfer in the atmosphere, associated with these cloud generators, is provided by conduction, point discharge currents, and currents carried through electrified precipitation, and tropospheric lightning discharges or upper atmosphere lightning discharges. These currents, except discharge current, can also be present in non-thunderstorm electrified clouds. Compendia by MacGorman and Rust (1998) and Rakov and Uman (2003) provide up-to-date information on the cloud electrical activity and associated phenomena. Some important topics in planetary atmospheric electricity, including global electric circuits, have been also reviewed recently in Leblanc *et al*. (2009).

According to Wilson, the electric currents are driven by the lower atmosphere cloud generators due to large voltages produced inside the clouds. These currents flow upwards from the cloud tops to the ionosphere and between the ground and the bottom of the clouds. They also flow freely through the conducting ionosphere and are closed by downward currents in the less conducting fair-weather area of the atmosphere (as the so called air-Earth current) and currents in the well conducting ground. Due to continuous operation of the cloud generators over the globe, the potential of the ionosphere remains high (200-300 kV) with respect to the Earth at all times but exhibits diurnal, seasonal and irregular variations, as seen in atmospheric electrical measurements of the potential gradient or the air-Earth current density and the ionospheric potential (Kubicki *et al.* 2007, Markson 2007, Williams 2009, and references therein). The ionospheric potential and the total current flowing in the global circuit are the main GEC variables. Observationally, the density of the air-Earth current and the potential gradient (or the electric field) measured at the ground in various locations over the globe are the main indicators of the existence of the GEC.

Currents from the lower atmosphere are coupled to the magnetosphere-ionosphere current systems, as the ionosphere plays a significant role in both current systems, and the atmospheric circuit becomes part of the geospace global electric circuit GGEC (Michnowski 1998). The magnetospheric generators are due to the interaction of the Earth's magnetosphere with the solar wind and the interplanetary magnetic field. Electric fields produced by this interaction map along magnetic field lines at polar latitudes down to the ionosphere and result in dawn-to-dusk voltages across both polar caps (see e.g. Kelley 2009), and therefore the effect of this coupling is mainly seen at polar latitudes. In addition, there are the ionospheric and disturbance dynamo effects due to the neutral ionospheric winds produced by solar and auroral heating of the thermosphere. These processes and their effect on the potential of the ionosphere are discussed in Roble (1991), Rycroft *et al*. (2000) and Tinsley (2008). Markson (1978), Willett (1979) and Roble (1985) have discussed possible relationships between space weather and atmospheric electricity.

In recent years a number of effects correlated with GEC phenomena have been observed, for example, changes of atmospheric pressure, temperature or cloud cover on a regional or global scale (Tinsley 2008, and references therein). Tinsley divided them into five categories relating to five different GEC agents: global ionospheric potential, polar cap potential, relativistic electron flux, solar proton events, cosmic rays Forbush decreases.

Also, interest has risen in various cloud processes taking place in the troposphere and affected by the air-Earth current density (Tinsley 1996, Tinsley 2000, Harrison 2004, Harrison and Ambaum 2008). These results imply further connections of the Earth's GEC, space weather, atmospheric weather systems and even climate.

2. Global circuit models

A model of the global atmospheric circuit must include a model of the electrical properties of the atmospheric medium where electric current flow and a model of the sources that generate these currents, the lower atmosphere current generators (thunderstorms, shower clouds) in the first place. Atmospheric electrical conductivity is the important electrical parameter. In the lower atmosphere the conductivity is due to ions produced by cosmic rays and natural radioactivity. The ions can be lost due to attachment to aerosols and cloud condensation nuclei. The production and loss of the ions and the ion mobilities can be modelled separately to create a complex lower atmosphere conductivity model. At higher altitudes (> 45-50 km) up to ionospheric altitudes electrons play main role and the Earth's magnetic field causes the anisotropy of the conductivity in the Earth's ionosphere. This must be taken into account in the models that consider the effect of magnetospheric-ionospheric generators.

Tinsley and Zhou (2006) have recently developed a sophisticated model of atmospheric resistivity which includes the effects of winter and summer tropospheric aerosols, stratospheric aerosols, and the effects of solar activity on ion production by cosmic rays and volcanic activity on stratospheric aerosols. This model can become an integral part of any modern GEC model, as demonstrated by Tinsley and Zhou (2006) and Odzimek *et al*. (2009).

There are a few analytical and numerical models of the Earth's global atmospheric electric circuit developed over the last few decades (Hays and Roble 1979, Roble and Hays 1979, Makino and Ogawa 1984, 1985, Sapkota and Varshneya 1990, Price *et al*. 1997, Kartalev *et al*. 2004b, Odzimek *et al*. 2009) which contain these two integral part of a GEC model – a model for the electrical properties of the atmospheric medium and a model for current generators. The first high resolution models of the atmospheric circuit were created by Roble and Hays (1979) and Hays and Roble (1979). They are mathematical models, providing a solution for the ionospheric potential as a series of spherical harmonics, at 5 degree resolution in latitude and longitude. Table 1 particularly compares high-resolution GEC models that are able to provide distributions of the main GEC variables over the globe and time variations.

A number of GEC-related thunderstorm generator models have also been developed which are concerned with the flow of the electric current from thunderstorms, playing the role of the sources driving the circuit, and the distribution of the electric potential in the vicinity of the thunderstorms, in the ionosphere above and the conjugate ionosphere, as well as in the cloud-free area of the circuit; for example, Park and Dejnakaritra (1973), Nisbet (1983), Tzur and Roble (1986), Stansbery *et al.* (1993), Kartalev *et al*. (2004a). Rycroft *et al*. (2007) modelled the current contribution from shower clouds for the first time.

Since the 1980s, various satellite measurements started to play role in the development of GEC models. Makino and Ogawa (1984) have used the Defense Meteorological Satellite Programme (DMSP) lightning flash densities in the development of their thunderstorm current generator model. More recently, the Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS) lightning flash rates have served similar purposes (Kartalev *et al*. 2004a, b, Odzimek *et al*. 2009). Price *et al.* (1997) were probably the first to use satellite observations of cloud properties and cloud cover from the International Satellite Cloud Climatology Project (ISCCP) data sets in their GEC cloud generator model, which was a significant step forward in the modelling of the GEC cloud generators.

As far as ionospheric and magnetospheric generators are considered, the ionospheric and magnetospheric dynamo effects have been incorporated in the model of Roble and Hays (1979). Kartalev *et al*. (2004b) considered the effect of the ionospheric

Table 1

Summary of high-resolution GEC models: HR79 (Hays and Roble 1979), RH79 (Roble and Hays 1979), MO84 (Makino and Ogawa 1984), SV90 (Sapkota and Varshneya 1990), EGATEC09 (Odzimek *et al*. 2009). Main features of the models are shown, in terms of the treatment of the atmosphere-ionosphere medium (upper table) and the electric generators considered in each model (bottom table)

Atmosphere-Ionosphere Medium											
Model	SI 1	CR 2	RA 3	AE 4	CCN 5	GMF 6	NEU 7	ION 8	Spatial Variations	Time Variations	Other Data and Models Used
Mathematical											
HR79	+	–	–	–	–	–	–	–	Geo(1)	I(1)	
RH79	+	–	–	–	–	–	–	–	Geo(1)	I(1)	
Engineering											
MO84	+	–	–	–	–	–	–	–	Lat(1)	I(2)	
MO85	–>	+	+	+	+	–	+	–	Geo(2-4,7)	I(2)	
SV90	–>	+	+	+	+	–	+	–	Geo(2-4)	I(2,4)	SA76(7)
EGATEC09	–>	+	+	+	+	+	+	–	Geo(2-7)	DD(5,7), S(4), SC(2)	TZ06(2-6) MSIS-E(7)

Model	THU 1	SHC 2	IDYN 3	ICONV 4	Spatial Variations	Time Variations	Other Data and Models Used
Mathematical							
HR79	+	–	–	–	Geo(1)	D(1)	
RH79	+	–	+	+	Geo(1,4)	D(1), I(3,4)	RC76(3), HE77(4)
Engineering							
MO84	+	–	–	–	Geo(1)	D(1)	DMSP(1)
MO85	+	–	–	–	Geo(1)	D(1)	MO84(1)
SV90	+	–	–	–	Geo(1)	D(1)	MO84(1)
EGATEC09	+	+	–	–	Geo(1-2)	DD, D, S(1)	ISCCP, OTD/LIS, TRMM(1-2)

Description: Sign "+" indicates the presence and "–" absence of an element in the model. The elements of the atmosphere-ionosphere medium include: SI – atmospheric ion conductivity, CR – ion production by cosmic rays, RA – ion production by natural radioactivity, AE – aerosols, CCN – cloud condensation nuclei, GMF – geomagnetic field, NEU – neutral atmosphere, ION – ionospheric conductivities. SI or more advanced model of conductivity derived from CR, RA, AE and CCN could be used – such case is indicated by "–>". The electric generators include: THU – thunderstorms, SHC – shower clouds or non-thunderstorm clouds, IDYN – ionospheric dynamo, ICONV – ionospheric convection. Last two columns inform about spatial and time variation which can be obtained with each model, as well as the model elements which cause these variations, in brackets. "Lat" indicates variations depending on geographical latitude, and "Geo" – variations both in latitude and longitude; the spatial resolution is usually 5 degrees in both longitude and latitude. Time variations are: DD – day-to-day, D – diurnal average, S – seasonal, SC – solar cycle, I – irregular (e.g., due to solar events or cosmic rays Forbush decrease type of events). Other necessary datasets and models used in each of the GEC model are listed in the last column, including the GEC element they refer to, in brackets; these are: DMSP – Defense Meteorological Satellite Programme lightning flash rates (Turner and Edgar 1982), OTD/LIS – Optical Transient Detector/Lightning Imaging Sensor lightning flash rates (Christian *et al*. 1999, 2003), ISCCP – International Satellite Cloud Climatology Project cloud data (Rossow and Schifer 1991), TRMM – Tropical Rainfall Measuring Mission precipitation data (Kummerow *et al*. 1998), MSIS – Mass Spectrometer Incoherent Scatter neutral atmosphere model (Hedin 1991), TZ06 – Tinsley and Zhou (2006) atmospheric conductivity model, RC76 – Richmond (1976) empirical ionospheric dynamo field model, HE77 – Heppner (1977) empirical ionospheric convection model.

convection and Makino and Takeda (1984) and Kartalev *et al*. (2004a) considered the effect of non-equipotential and magnetised ionosphere.

The effects resulting from changes of conductivity during events such as major solar flares or Forbush decreases on natural profiles of the atmospheric conductivity and the global circuit have also been investigated in some of the GEC models mentioned above (e.g., Hays and Roble 1979, Roble and Hays 1979, Makino and Ogawa 1984, 1985, Sapkota and Varshneya 1990).

2.1 High-resolution engineering models

Representation of the GEC in the form of a simple electrical circuit has been used many times ever since the modelling work on GEC started, either as a quantitative illustration of the current flow in the GEC and relationships between the GEC components and agents (Markson 1978, Willett 1979, Ogawa 1985, Tinsley 1996, Rycroft *et al.* 2000) or as the background environment of a single cloud current source which was analysed in more detail (Nisbet 1983, 1985a, 1985b, Rycroft *et al*. 2007, Rycroft and Odzimek 2009a, b).

In some high-resolution models this "engineering" approach has also been exploited. This draws from the possibility of modelling the global atmospheric electric circuit as a network of electrical elements, resistances and current sources, using input from data sets and models, and, if numerical solution is not straightforward simulating the circuit using electrical engineering software.

The model of Makino and Ogawa (1984) is a 5-degree resolution model of GEC with thunderstorm current sources and atmospheric resistance distributed over the globe and represented as a network of branches consisting of 72×36 resistances. The circuit elements were connected in parallel between two circuit nodes representing the ideally conducting ground and the ionosphere. This enabled to solve the circuit analytically relatively straightforward.

Makino and Ogawa (1985) and Sapkota and Varshneya (1990) used the same method and current source distribution but introduced significant improvements in the atmospheric conductivity model, which is an integral part of any GEC model. EGATEC is a new high resolution electrical engineering model which we describe in more detail in Section 4.

3. Some outstanding issues related to GEC and GEC models

Williams (2009) has recently reviewed current state of knowledge about the Earth's global atmospheric circuit. Even though this topic has been present in research for almost one hundred years, some fundamental questions remain unanswered. These questions concern, for example, variations in the GEC on different time scales. In the first place, the dominance of the American tropospheric electric activity centre over that in the African and Asian sectors which is observed in the Carnegie Curve, or diurnal variation, is not well explained, and two very different explanations have been suggested (Williams and Sátori 2004, Kartalev *et al*. 2004a). Also, different trends in the last decades' variation of the GEC have been reported from observations. Williams (2009) discusses this latter problem in detail. Long-term variations of the GEC, on time-scales longer than a decade remain also unknown.

Standard values of the main GEC parameters cited in GEC-related publications broadly agree with various observations but these estimates may be far from accurate on particular days and in particular regions. Realistic modelling of the GEC can provide answers to some of the questions and test various hypotheses, but this requires progress in the modelling of various GEC components, mainly the lower atmosphere as well as magnetosphere and ionosphere current generators. Tinsley and Zhou (2006) describe the situation as follows: "An accurate value for the total upward current supplied to the ionosphere has not been determined; instead, it is estimated at 700-2000 A on the basis of estimates of ionospheric potential (150-600 kV) from tropospheric potential measurements extrapolated through the stratosphere, and estimates of the column resistance of the global ionosphere-Earth return path (200-300 Ω) from conductivity measurements and their extrapolations. These values roughly agree with similarly uncertain estimates of the upward current per thunderstorm and the total number of thunderstorms occurring at any one time. Thus the uncertainties are compatible with additional sources of current from nonthunderstorm shower clouds, and additional sources of column resistance in the stratosphere and troposphere due to aerosol layers, water vapor and clouds, which have not been considered previously". Below we summarise some specific problems that require further consideration and studies in order to improve successful GEC modelling. Many of them are related to the issues mentioned by Williams (2009), which concern the knowledge of the Earth's GEC in general.

3.1 Contribution of particular cloud systems

The charge structure of various thunderstorm systems has been studied recently by Stolzenburg and Marshall and colleagues (Stolzenburg and Marshall 2008, and references therein). These studies have revealed multi-layer charge structures (i.e., more charge layers in addition to the main structure) and that the structure differs in different storms (e.g. small isolated storms, supercells or mesoscale systems), and also varies in different areas of the storm (e.g. convective part, cloud anvil, precipitation region). It was also discovered that the large stratiform areas of Mesoscale Convective Systems (MCSs) may have a discharging effect on the global circuit; early modelling results by Davydenko (2004) have indicated 20 A downward conduction current driven by these systems. Later estimates also give positive values of the same order depending on the charge structure of these stratiform areas. Thus, the total contribution of some thunderstorm system to the GEC may vary from storm to storm.

Mach *et al*. (2009) have recently published a summary of the results of measurements of the conduction currents above thunderstorm systems in the southeastern US, western Atlantic Ocean, the Gulf of Mexico, central America, central Brazil and the

South Pacific north of Australia. These results confirm that in the majority of cases electric currents flow upwards and charge the ionosphere positively. But there are about 7% cases of storms where the current flows downwards, thus discharging the ionosphere. They also note that it was unclear whether this was due to an inverted main charge structure in these storms or perhaps the effect of the charge of the screening layer at the top of the cloud. It is perhaps worth noting that a similar percentage (7-10%) of inverted charge structures have been observed in non-thunderstorm clouds (Imyanitov and Shifrin 1962). It is not clear why some clouds may have those inverted charge structures. What has been usually observed is that the charge and electric field structure depends greatly on the microphysics of the clouds (see, for example, Chalmers 1958, Imyanitov *et al*. 1974, MacGorman and Rust 1998). Our conclusion is that future models of cloud generators should take into account regional characteristics of electrified cloud systems and also incorporate some microphysical cloud parameters.

3.2 Role of electric discharges

It is generally accepted that tropospheric cloud-to-ground (CG) lightning discharges contribute to the dc global atmospheric circuit by transferring the electric charge from the cloud to the ground: negative – negative charge to the ground (i.e., charge the ionosphere positively with respect to the ground), positive – positive charge to the ground (i.e., discharge). Contribution from intra-cloud discharges have not been usually considered with respect to the GEC.

Even though the contribution of lightning current in the total GEC current seems to be less than previously considered (Williams Heckman 1993, Williams and Sátori 2004, Rycroft *et al*. 2007, Maggio *et al*. 2009) the magnitude of this current is still not known very well. Global rates of the lightning discharges are known more accurately, mainly from satellite observations (Turman and Edgar 1982, Christian *et al*. 2003). It is the electric charge transferred by an average lightning discharge (in the sense of the lightning's current amplitude and polarity) that is not very well known, or, alternatively, the charge transferred by negative, positive and intra-cloud discharges separately. This issue is discussed in Odzimek *et al*. (2009).

The discovery of the upper atmosphere lightning discharges (or Transient Luminous Events, TLEs) have brought in the last two decades more attention to the electric activity of particulary active thunderstorm systems, like the MCSs, and positive cloud-to-ground lightning discharges, which are usually associated with sprites, the most commonly observed TLEs (Füllekrug *et al*. 2006). Although the positive CGs discharges are rarer than negative (10-15% of all CGs), and usually have single return stroke, their charge transfer is large due to the long-lasting and strong continuing currents which they often exhibit; these continuing currents seem to play a role particularly in the creation of carrot sprites (Rycroft and Odzimek 2009a, b). Model results by both Price *et al*. (1997) and Rycroft *et al*. (2007) show that globally the net effect of the more frequent negative CGs is larger than the opposite effect of positive CGs, although the magnitude of the total lightning current differs in these two models by factor of ten, mainly due to different value of charge transferred by an average lightning discharge, used in their models. Füllekrug and Rycroft (2006) and Rycroft *et al*. (2007) showed that the effects of a sprite on the circuit was to discharge it but the effect was relatively very small. Cummer *et al*. (2009) have calculated that the charge transfer in some cases of gigantic jets recently observed in the US were of the order of charge transferred by strong CGs but, in the case of these TLEs, the rates of occurrences are rather poorly known (the occurrences rate of sprites has been estimated so far, on the basis of available measurements, Ignaccolo *et al*. 2006), and neither the total contribution can be determined very well. Some recently developed techniques of the analysis of observations of magnetic field generated by lightning discharges, in the extremely low frequency range (Kułak *et al*. 2006, 2009), can be helpful in accurate determination of the current contribution of cloud-to-ground lightning discharges in future.

With regard to intra-cloud lightning discharges, a simulation by Rycroft and Odzimek (2009a) showed that a 10 kA intra-cloud discharge between bottom negative layer and upper positive layer in their model thundercloud discharged the ionosphere by 2 C, indicating that intra-cloud discharges do have some effect and it is to discharge the circuit if the discharge reduces the voltage created by the separation of charges inside a cloud (which normally causes charging of the ionosphere positively). Recent observations also acknowledge the effect of intra-cloud flashes (see e.g. Maggio *et al*. 2009). Taking into account that intra-cloud discharges are the major fraction (~85%) of all lightning discharges this result complicates our understanding of the role of lightning discharges in the circuit.

More importantly, not only the lightning current seems to be an issue. In fact, the relative contribution of conduction, precipitation current and corona (point discharge) current are poorly determined. Measurements provide a wide range of current density values for each of these processes which often are of opposite sign and of the order or comparable to the total current density which can be associated to a cloud system (Imyanitov and Shifrin 1962, MacGorman and Rust 1998). Williams and Heckman (1993) show examples of the diurnal variation of point discharge and precipitation current from single sites concluding that next to conduction currents, they contribute the most to maintaining the high potential of the ionosphere. However, Imyanitov and Shifrin (1962) pointed out that the current budget may be different at different locations. This issues require serious modelling efforts combined with observation campaigns of various cloud systems in different regions of the globe and different time of season, similar to the work of Nisbet (1985b), Michnowski *et al*. (1987), Nisbet *et al*. (1990a, b). Such models are practically nonexistent for non-thunderstorm clouds, except perhaps the model by Chalmers (1958) of the altitude profile of the electric potential in snow and rain Nimbostratus clouds, created on the basis of electric current density and potential gradient measurements under these clouds in the UK.

3.3 Thunderstorm current and non-thunderstorm current

Even though shower clouds have been considered to generate electric current in the GEC, their contribution has not been determined so far. The electric activity of non-thunderstorm clouds has been studied more extensively in the former USSR – see e.g. Imyanitov and Shifrin (1962), Imyanitov *et al*. (1974) and MacGorman and Rust (1998, Chapter 2). The interpretation of these results indicates that the mid-layer clouds such as Nimbostratus may charge the ionosphere positively. Measurements of current density under Nimbostratus in the UK by Harrison and Nicoll (2008) are in broad agreement with the modelled current contribution of shower clouds in Rycroft *et al*. (2007), who estimated the non-thunderstorm current as 40% of the total GEC current. The effect of non-thunderstorm clouds has been also modelled recently with EGATEC model (Odzimek *et al*. 2009, Section 4). Preliminary results from this model are that the thunderstorm contribution is ~80% *versus* ~20% from non-thunderstorm clouds. This requires further investigation. In addition, the uncertainties mentioned in the previous subsection, in relation to the role of MCSs, the role of precipitation, corona and lightning current, further complicate this issue.

3.4 Cloud conductivity

The electric conductivity is critical parameter in any electrical circuit, including GEC. While significant progress has been made to model air conductivity including the effect of aerosols (Sapkota and Varshneya 1990, Tinsley and Zhou 2006) there are less advances in GEC models in the electric conductivity of cloudy air, especially in various types of clouds. Considering that clouds cover ~50% of the Earth and that cloud conductivity can be a few times less than that of free air (Imyanitov and Shifrin 1962, MacGorman and Rust 1998), there must be a significant contribution of clouds to the total atmospheric resistance. This includes the resistance of clouds-current generators (which has been considered in some models, e.g., Makino and Ogawa (1984, 1985), Sapkota and Varshneya (1990), Rycroft *et al.* (2007) and also clouds which are rather passive. The conductivity of thunderclouds is an interesting issue on its own, as discussed in MacGorman and Rust (1998, Chapter 7).

It should also be noted here that the model results mentioned in the previous paragraphs by Davydenko *et al*. (2004) or Rycroft *et al*. (2007), related to the contribution of cloud current to the GEC, are very sensitive to the cloud conductivity which was used in those models. Therefore, it is important to use realistic models of the conductivity.

3.5 Coupling to the magnetosphere-ionosphere current system

The GEC is linked directly with space weather effects of the electrodynamics of the interaction between the solar wind and the Earth's magnetic field. This effect has always been evident particularly at high latitudes where the ionospheric convection affects the electric field at the ground the most (Burns *et al*. 1995, Tinsley 1998, Frank-Kamenetsky *et al*. 1999, Corney *et al*. 2003, Michnowski *et al*. 2007, and references to earlier papers therein) but can also be significant at middle latitudes (Nikiforowa *et al*. 2005, Kleimenowa *et al*. 2008). In the analysis of observations of the potential gradient in Antarctic these effects have been usually subtracted from the effect of lower atmosphere generators using various empirical models of the potential difference caused by the magnetospheric generators, for example, model by Heppner (1977) or more recent Weimer (1996) and IZMEM model by Papitashvili *et al*. (1994). These models calculate the potential difference over a specific location from a statistical potential pattern parametrised by the components of the interplanetary magnetic field; the latter could be obtained from satellite observations. But as far as high-resolution GEC models are concerned, since the model by Roble and Hays (1979) and recent work by Kartalev *et al*. (2004b) there seems to be no significant update on the modelling of the combination of the lower atmosphere and the ionosphere-magnetosphere current systems, although modelling of the latter components has improved over the years (Roble 1991). This can now be improved using new observations of the plasma flow at ionospheric heights with high frequency radar technique. This was established as continuous monitoring in the 1990's, by the radar network SuperDARN, currently run by an international consortium of nine countries. SuperDARN (Chisham *et al*. 2007) currently consists of twenty operational radars in the northern and southern hemispheres which are able to monitor the high latitude electric field on a continuous basis. There are plans to expand the network equatorwards to form StormDARN, which will enable the electric field during highly disturbed intervals, geomagnetic storms, to be measured.

The SuperDARN observations available at present give an opportunity to revise this particular model component using the ionospheric electric potential patterns calculated from the SuperDARN observations (Ruohoniemi and Greenwald 1996). These SuperDARN polar cap potential data, necessary for the evaluation of higher latitude current generators (Chisham *et al*. 2007), are available from 1995 onwards with the best coverage in both hemispheres from 2000 onwards. The developing StormDARN should provide more material for the modelling of such effects at middle latitudes in near future.

As far as the impact of the ionospheric dynamo on the GEC is considered, it is expected that wind models, such as the Horizontal Wind Model (HWM, Hedin 1996) or the Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIE-GCM) (Richmond *et al.* 1992) can provide the necessary input.

4. EGATEC

The Engineering model of the Global Atmospheric Electric Circuit (EGATEC) was proposed to start the development of a novel engineering quasi-3D model of the Earth's DC global atmospheric electric circuit at the University of Leicester. EGATEC is a high-resolution electrical engineering model.

In the current version of EGATEC, the lower atmosphere current generators are modelled with current sources. The coverage of the generators is determined on the basis of the satellite measurement of surface area covered by various types of clouds, available from the ISCCP cloud data (Rossow and Schiffer 1991), and TRMM (Tropical Rainfall Measuring Mission, Kummerow *et al*. 1998) precipitation. Model current densities produced by the cloud generators are used, derived from available observations of the electric activity of such clouds, in particular the satellite OTD/LIS lightning flash rates. The area of the globe where the electric current is generated as well as current source-free area can be estimated with the spatial resolution of 5 degrees in latitude and longitude and 3 hour time resolution, which is mainly limited by the ISCCP D1 data resolution. The resistance load of the atmosphere is calculated using the atmospheric conductivity model by Tinsley and Zhou (2006) which is also spatially dependent and has the same spatial resolution. The current sources and resistance of the cloud generators and resistance of the cloud-free area associated with a latitude and longitude in a model grid create one circuit branch. These branches can be connected in a network and create an electric circuit representing the GEC which can be solved either numerically according to the standard circuit theory or using a circuit simulation software PSpice. A result of such calculation or simulation is the global distribution and diurnal variation of the main GEC variables.

Nisbet (1983) was the first to introduce the idea of using circuit analysis software for simulations of a network representing a thunderstorm and its electrical environment (i.e., GEC) and used the Electrical Circuit Analysis Program (ACAP). Many of these programs are available on different system platforms for today's computers. For example, SPICE, developed at the University of Berkeley, is a general-purpose circuit simulation program for DC, AC and transient analyses (Kielkowski 1995, Dobrowolski 2004). SPICE is currently available in some software packages (as PSpice) and the capability of this simulator is sufficient to create a high-resolution model of the DC global atmospheric electric circuit, with parameters distributed with latitude, longitude and altitude, and including simultaneously the effect of various processes operating in the circuit more realistically.

In EGATEC the air-Earth electric current density due to lower atmosphere current generators and vertical electric field can be calculated with the spatial and time resolution used for the input data. The total GEC current can also be calculated. The circuit can be constructed assuming the ionosphere as equipotential or non-equipotential surface while the ground is always assumed to be an ideally conducting surface. The main advantages of this model are:

- Input to the model is based on currently available satellite observations of clouds and cloud properties and activity, and the model includes a model of atmospheric conductivity. The model treats clouds more realistically by taking into account the role of the cloud conductivity in the global resistance and by assessing of the contribution of clouds as current generators;
- The main GEC parameter can be obtained at 3-hour time resolution and global distributions of the air-Earth current density and electric field at spatial resolution of 5 degrees in geographic coordinates;
- The model can be used for investigations of diurnal and seasonal variations of the GEC;
- The model is a high-resolution representation of the global atmospheric electric circuit created using an equivalent electric network. Standard algorithms and software can used for calculating and solving the model circuit.

The next version of EGATEC is under development and the developments include:

- Modelling of the coupling to the ionosphere-magnetosphere current system;
- Increasing spatial resolution of the model;
- Input from observed aerosol concentrations;
- Improving cloud generator model and cloud conductivity model.

5. Conclusions

The GEC is a global phenomenon and represents all natural static electric forces affecting the environment on both regional and global scales. However, there remain many unresolved questions about the GEC and many GEC-related phenomena and processes are not fully understood or determined. It is necessary to not only continue monitoring the circuit by observations but also to improve our understanding through modelling and simulations of the GEC and its effects.

Developments of new techniques for measuring different electrical parameters and new findings in the area of atmospheric electricity require newer models and re-examination of previous results. Thus, the necessity of the development of such a model that treats realistically the overall processes contributing to the phenomenon. New facilities, measurements and projects that have been established worldwide can support GEC-related research and enable the electrical effects of the global electric circuit in the atmosphere to be established. Such facilities provide various useful data-sets which together with new modelling tools will lead to major improvements in modelling the global atmospheric circuit.

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