EGATEC
Engineering Model of the Global ATmospheric Electric Circuit
Version 1.2

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Abstract

This document describes version 1.2 of EGATEC, an engineering model of the Earth's DC global atmospheric electric circuit, developed at the University of Leicester in a project sponsored by the European Commission. EGATEC can be relevant to atmospheric scientists, meteorologists and climatologists concerned with the atmospheric electricity, atmospheric circulation and climate modelling.

1 Introduction

EGATEC is a new high-resolution, engineering model of the global atmospheric electric circuit *Odzimek and Lester, 2009* [12]. The model version EGATEC 1.2 was developed at the University of Leicester, UK, in a two-year project which started in October 2007.

Any 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, i.e. the lower atmosphere current generators. In EGATEC, the lower atmosphere current generators: thunderstorm and non-thunderstorm clouds, driving the circuit, have been constructed on the basis of satellite measurements of the surface area covered by various types of clouds, available from the International Satellite Cloud Climatology Project data, and model current densities of cloud generators, derived from observations of the electric activity of such clouds, in particular using the satellite Optical Transient Detector/Lightning Detection Sensor lightning flash rates. The areas of the globe where the electric current is generated as well as current source-free areas can be estimated with the spatial resolution of several degrees in latitude and longitude and three hour time resolution. The resistance load of the atmosphere is calculated using the atmospheric conductivity model by Tinsley and Zhou (Journal of Geophysical Research, 2006) which is also spatially dependent and sensitive to the level of solar activity. In addition, representations of the global distributions of aerosol in the summer and winter, available in the conductivity model, allow studies of the seasonal changes of the model global circuit due to the aerosol-related changes of the atmospheric conductivity. The cloud 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 circuit branches connected in an electrical network representing the global atmospheric electric circuit. This electric network can be solved numerically according to standard circuit theory or simulated by engineering software. As a result the global distribution and diurnal variation of the air-Earth electric current density due to lower atmosphere current generators and vertical electric field can be obtained from the calculations, with the spatial and time resolution used for the input data. The circuit can be

Table 1: Models and datasets used in EGATEC.

Acronym	Data sets/Parameters
Data	
ISCCP	D1
OTD/LIS	LRTS, LRADC
TRMM	3B42
Models	
MSIS-E	Neutral composition and temperature
GADS	Aerosol profile parameters

constructed assuming the ionosphere to be either an equipotential or non-equipotential surface, and the ground assumed to be an ideally conducting surface. First results from this model have been published in *Odzimek et al., 2010* [13].

2 Representation by electrical circuit

The circuit is a network of branches consisting of electric elements (resistors and current sources) fixed between a discrete number of nodes at chosen points (locations) covering the whole globe and altitudes up to the ionosphere. The ionosphere in this version of the model is assumed to be an equipotential surface at 60 km altitude.

The circuit nodes are enumerated subsequently as the geographic (geodetic) longitude λ and colatitude θ increases. The number of nodes depends on the resolution of the circuit − in the direction of increasing λ (X direction) there are ResX = 360°/ResXD nodes enumerated by index $i = 1 \ldots$ ResX. Similarly, in the direction of increasing θ (Y direction) there are ResY = 180°/ResYD nodes enumerated by index $j = 1 \ldots$ ResY. ResXD and ResYD are circuit resolutions in degrees in x and y direction - currently ResXD, ResYD = 5° or 10° are used creating 36×18 nodes or 72×36 nodes in one horizontal layer (i, j). In the vertical direction the number of nodes is either smaller and attributed to characteristic layers of the Earth's atmosphere and ionosphere, where atmospheric or ionospheric properties are similar. the circuit elements are all connected to node "0" representing the potential of conducting ground - assumed to be ideally conducting in this model version.

The EGATEC circuit is a network of branches consisting of electric elements (resistors and current sources) fixed between a discrete number of nodes representing chosen locations in the Earth's atmosphere or ionosphere, covering the whole globe and altitudes up to ionospheric; in this model version the ionosphere is at 60 km (Figure 1). The circuit nodes are enumerated subsequently as the geographic longitude λ, colatitude θ, and altitude z increase. The number of nodes depends on the resolution of the circuit − in the direction of increasing λ there are $N_{lon} = 360°/D_{lon}$ nodes enumerated by index $i = 0...N_{lon} - 1$. Similarly, in the direction of increasing θ there are $N_{lat} = 180°/D_{lat}$ nodes enumerated by index $j = 0...N_{lat} - 1$; D_{lon} and D_{lat} are the circuit resolutions in degrees in longitude and latitude, respectively. This creates $N_{lon} \times N_{lat}$ circuit branches centred at geographical longitudes $\lambda_i = D_{lon}(i + 0.5)$ and colatitudes $\theta_j = D_{lat}(j + 0.5)$. In the current model version $D_{lon} = D_{lat} = 5°$, as in the models of [11, 18, 20]. All the branches are connected to node "0" representing the ground at potential zero (i.e. assumed to be ideally conducting) and node "1" representing an equipotential (ideally conducting) ionosphere, at a constant potential in relation to the ground V_I which has to be found.

Figure 1: The main structure of the EGATEC circuit. The circuit is oriented geographically. $N_{lon} \times N_{lat}$ atmospheric branches (AB) are arranged with increasing geographic latitude and colatitude, 72 × 36 branches are created at 5° resolution in geographic longitude and latitude. In this model the ionosphere is considered to be an equipotential surface so all branches are connected to the same node representing the ionosphere and the node representing the ideally conducting ground.

The surface area of a branch at a longitude λ_i and colatitude θ_j decreases with increasing geographic latitude $\varphi_j = 90° - \theta_j$

$$A^{ij} = \frac{2\pi R_E^2}{N_{lon}}(\sin\varphi_j - \sin\varphi_{j+1}) \tag{1}$$

where R_E is the Earth's average radius of 6371.2 km. In the case of 5° resolution in latitude and longitude the branches' surface area ranges from 13,500 km^2 at polar regions to 309,000 km^2 near the equator. This is usually too large area compared even to very large convective systems. Therefore it is allowed in the model that a single circuit branch has up to seven sub-branches, each representing an area covered by the cloud types 1-7, introduced in the next section. Within each area the variations in the lateral dimensions are suppressed and all model variables are reduced to their vertical components. Area types 1,2,3,6,7 are represented by one resistor. The resistance of the resistors are calculated using model columnar resistances (see subsection 2.1 below), calculated from the atmospheric conductivity profiles described in Section 3. Area types 4 and 5 are represented by a series of three resistors and a current source in parallel with the middle resistor, as shown in Figure 2. The current sources are described in Section 4.

Figure 2: The atmospheric branch of the EGATEC circuit. Each circuit branch consists of 1-7 sub-branches representing area covered by cloud generator type 4 and 5, and covered by passive cloud type 1,2,3,6, and cloud-free area 7. Passive areas are represented by one resistor, and generator areas are modelled by a series of three resistors and a current source in parallel with the middle resistor. The electric current flowing in a sub-branch is described by Eq. (29).

2.1 Columnar resistances

Columnar resistances, i.e. the resistances of the portion of the atmosphere of a unit surface area, at a branch (i, j) and cloud area type $a = 1..7$, from height z_1 to z_2 can be calculated by integration of $1/\sigma(z)$ over a height interval $z_1 \leq z \geq z_2$

$$\tilde{R}_a^{ij}(z1, z2) = \int_{z_1}^{z_2} \frac{dz}{\sigma_a^{ij}(z)} \tag{2}$$

where $\sigma(z)$ is the atmospheric conductivity profile at a branch (i, j). The conductivity model is described in Section 3.

The resistance of the sub-branch from height z_1 to z_2 equals the columnar resistance $\tilde{R}_a^{ij}(z_1, z_2)$ divided by the sub-branch surface area S_a^{ij} can be a fraction of $A^{i,j}$, obtained from the ISCCP data.

$$R_a^{ij}(z1, z2) = \frac{\tilde{R}_a^{ij}(z1, z2)}{S_a^{ij}} \tag{3}$$

In the following sections R_a^{ij} or $\tilde{R}_a^{ij}$ denote the resistance or columnar resistance, respectively, over the total altitude range in the branch from ground level z_g to the ionosphere height $z_{ion} = 60$ km.

3 Lower atmosphere conductivity

Atmospheric electrical conductivity is the important electrical parameter in each global circuit model. In the lower atmosphere the conductivity is due to ions produced by cosmic rays and natural radioactivity. The ions can be lost due to the 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 [20] developed a novel atmospheric conductivity model which can be conveniently applied in EGATEC. The model includes: 1) ion production rates due to cosmic rays, 2) ion production rates due to radioactive radon ^{222}Rn, ^{220}Rn and particle radiation coming from the Earth, 3) the Global Aerosol Data Set (GADS), which provide tropospheric aerosol concentration distribution and altitude profiles [5], and 4) a stratospheric aerosols geographic distribution and altitude profile model. The conductivity model is sensitive to the level of solar activity as the model ion production rates by cosmic rays are parametrised by low and high solar activity (at solar minimum and solar maximum conditions). Also, the concentration of stratospheric aerosols can be enhanced at higher volcanic activity in this model. In addition, two different tropospheric aerosol concentration distributions are taken from the GADS data to recreate the aerosol distribution over the globe for summer and winter (July and December).

The conductivity is calculated according to the standard formula

$$\sigma = e(\mu_- n_- + \mu_+ n_+) = 2e\mu n \tag{4}$$

where e is one elementary electric charge, μ is the ion mobility, and n is the ion concentration, assuming that throughout the atmosphere positive (+) and negative (−) ions having equal concentrations and mobility.

3.1 Ion mobility at STP

[19] gives values of the atmospheric positive and negative ion mobility at standard temperature and pressure (STP) in four altitude ranges, 0-15 km, 15-35 km, 35-50 km, 50-70 km (15-45 km and 45-70 km for the negative ion mobility). As up to 35 km, which includes the most resistant portion of the atmosphere, these positive and negative mobilities are equal we take an average ion mobility of the positive and negative mobilities in three altitude ranges, the same for positive and negative ions.

$$\mu_-(z) = \mu_+(z) = \mu(z) = 10^{-2} \times \begin{cases} 1.70 & 0 \le z < 15 \quad \text{km} \\ 1.70 & 15 \le z < 45 \quad \text{km} \\ 2.10 & 45 \le z \le 60 \quad \text{km} \end{cases} \quad \frac{cm^2}{V \cdot s} \tag{5}$$

3.2 Ion concentration

The calculations of ion concentration follows the procedure described in [20]. The ion concentration is found from a steady state condition $dn/dt = 0$, from which the following equation follows

$$n = \frac{2q}{\beta N + \sqrt{(\beta N)^2 + 4\alpha q}} \quad (cm^{-3}) \tag{6}$$

where n is the ion concentration, β is the effective attachment coefficient, N is the concentration of condensation nuclei (aerosol particles and droplets), α is the ion recombination coefficient and q is the ion production rate.

3.2.1 Ion production at STP

The ion production in the atmosphere is due to corpuscular radiation in the form of 1) cosmic rays, 2) "direct α, β, and γ radiation from the surface layers and dust aerosol, and radiation from radioactive gases (principally ^{222}Rn but also ^{220}Rn) and daughter products that are carried up into the troposphere by vertical convection" [20]. In the model each of the contributions to the ion production is described by an analytical expression q_{cr} and q_r. The total ion production rate is

$$q(z) = q_{cr}(z) + q_r(z) \qquad \frac{cm^3}{s} \tag{7}$$

Ion production due to cosmic rays The ion production due to cosmic rays is set to be a function of magnetic colatitude θ_M and the profile is assumed to be constant for geomagnetic latitudes higher than 60°, i.e. if $\theta_M < 30°$ and $\theta_M > 150°$. The geomagnetic latitude is obtained in a dipole field approximation.

The cosmic ray ion production depends on solar activity; *Tinsley and Zhou (2006)* [**?**,]Table 2]TinZho06 distinguish two models of the cosmic ray ion production: for high solar activity (solar maximum) and low solar activity (solar minimum).

$$f_s = \begin{cases} 1 & \text{for solar maximum} \\ 0 & \text{for solar minimum} \end{cases} \tag{8}$$

The profile of the ion production is determined according to equations from Table 2 in *Tinsley and Zhou, 2006* [20]

$$q(z) = \begin{cases} q_a \exp((z - z_a)/s_s) & 0 \le z < z_a \\ q_b \exp((z - z_b)/s_a) & z_a \le z < z_b \\ q_c \exp((z - z_c)/s_b) & z_b \le z < z_c \\ q_m \exp(-((z - z_m)/s_c)^2) & z_c \le z < z_m \\ q_d + (q_m - q_d)\exp(-((z - z_m)/s_c)^2) & z \ge z_m \end{cases} \tag{9}$$

where

$$\begin{aligned} s_s &= (z_a - z_s)/\ln(q_a/q_s) \\ s_a &= (z_b - z_a)/\ln(q_b/q_a) \\ s_b &= (z_c - z_b)/\ln(q_c/q_b) \\ s_c &= (z_m - z_c)/\sqrt{\ln(q_m/q_c)} \end{aligned} \tag{10}$$

and, according to Table 1 from *Tinsley and Zhou, 2006* [20],

Level	z_{eq}	z_{kn}	φ_{kn}	q_{eq}	q_{kn}	Type
z_s	0.0	0.0	$50 + (49 - 50)f_s$	$1.40(1 - 0.040f_s)$	$2.2(1 - 0.01f_s)$	q_s
z_a	6.5	9.8	$52 + (50 - 52)f_s$	$13.5(1 - 0.042f_s)$	$145(1 - 0.20f_s)$	q_a
z_b	9.0	16.0	$58 + (55 - 58)f_s$	$34.0(1 - 0.044f_s)$	$325(1 - 0.30f_s)$	q_b
z_c	11.0	21.0	$60 + (56 - 60)f_s$	$64.0(1 - 0.047f_s)$	$435(1 - 0.45f_s)$	q_c
z_m	16.0	32.0	$63 + (56 - 63)f_s$	$98.0(1 - 0.050f_s)$	$500(1 - 0.50f_s)$	q_m
	asymptote		$63 + (56 - 63)f_s$	$45.0(1 - 0.060f_s)$	$550(1 - 0.60f_s)$	q_d

(11)

The production type has the form

$$q^{s,a,b,c,m,d} = q_{eq}^{s,a,b,c,m,d} + (q_{kn}^{s,a,b,c,m,d} - q_{eq}^{s,a,b,c,m,d})\frac{\cos^4\theta_M}{\cos^4\theta_{kn}} \qquad \frac{cm^3}{s} \tag{12}$$

where q_{eq} is the production at equator, q_{eq} is the production at knee, θ_M is the magnetic colatitude of the location for which the profile is calculated and $\theta_{kn} = 90 - \varphi_{kn}$ is the magnetic colatitude of the knee.

Ion production due to Earth's radioactivity Tinsley and Zhou [20] divide this component of ion production into two parts q_{rd} and q_{r0} with different scale heights. The ion production q_{r0} caused by direct α, β, and γ and gaseous ^{2}20Rn is set uniform at $10/cm^3$ at the land surface, and $5/cm^3$ for land between 60°N and 70°N, both with the scale height 0.2 km. For the oceans and Greenland and the regions poleward of 70°N and 60°S q_{rd} is zero. The second source q_{r0} due to the radioactive ^{222}Rn is described by two components of different scale heights s_R and $2s_R$, and s_R changes with season: during local summer $s_R = 3$ km and during local winter $s_R = 2$ km. The geographic distribution of q_{r0} for July and December at the ground level is shown in [20] in Figure 5. The total ion production q_r (also at standard temperature and pressure) is given by

$$q_r(z) = q_{rd}\exp((z_g - z)/0.2) + 0.8q_{r0}\exp((z_g - z)/s_R) + 0.2q_{rd}\exp((z_g - z)/2s_R) \qquad \frac{cm^3}{s} \quad (13)$$

3.2.2 Scaling of mobility and ion production

Equations (5) and (7) describe the mobility and ion production rates at standard temperature and pressure (STP). They are converted to numbers at height, z, by scaling with the neutral concentration N at height z

$$\mu(z) = q^{STP}(z)\frac{N_L}{N(z)} \qquad q(z) = q^{STP}\frac{N(z)}{N_L} \quad (14)$$

N_L being the Loschmidt constant $N_L = 2.6867775 \times 10^{19} cm^{-3}$. [22] point out that this type of conversion may not be appropriate for the whole range of atmospheric temperatures and pressures, although, using more realistic formula, e.g. their expression $(A9)$, does not lead to very significant differences in our calculations. In the conversion from STP values we use the neutral number concentration $N(z)$ obtained from the International Mass-Spectrometer-Incoherent-Scatter (MSIS-E-90) model [4].

3.2.3 Recombination rate

For the recombination rate α we use the model profile from [19]

$$\alpha(z) = \begin{cases} 6\times10^{-8}\sqrt{\frac{300}{T_n}} + 1.702\times10^{-6}\exp(-1.984\ln(\frac{300}{T_n})\exp(-0.451\ln\frac{N}{N_L}) & z < 10\text{km} \\ 7\times10^{-8} + 2\times10^{-25}N & z \geq 10\text{km} \end{cases} \quad (15)$$

where N is the neutral concentartion, T_n the temperature of the neutrals (from MSIS-E model), N_L is the Loschmidt constant.

3.2.4 Aerosols and attachment rates to aerosol particles

The attachment term βN is considered as $\sum_i\sum_r \beta_r dN(r)/dr\Delta r$ by *Tinsley and Zhou* [20] in more detail "because of the variability of the concentrations, size distributions, and species of the aerosol particle concentrations S_i. The coefficient of attachment, b_r, varies with the radii of the particles" – hence the summation over particles' size and kind. [20] distinguish three main types of aerosol present in the atmosphere: 1) boundary layer aerosol, 2) free troposphere aerosol and 3) stratospheric aerosols. Each of these types may be a mix of various subtypes of aerosol, as described in *Hess et al, 1998* [5]. All concentrations are expresses in cm^{-3}.

Tropospheric aerosols Besides the free troposphere aerosol (Tropos) *Hess et al.* [5] distinguish 4 types of boundary layer aerosols: Continental clean (CnCln), Continental average (CnAve), Desert, Urban, Maritime clean (MrCln), Maritime tropical (MrTro), Continental polluted (CnPol), Maritime polluted (MrPol), Arctic, and Antarctic (Antarc). Each may consist

Table 2:

	Ins	Wats	Soot	Ssacc	Sscoa	Mnnuc	Mnacc	Mncoa	Mntrans	Sulph
CnCln	0.577E-4	1.0	-	-	-	-	-	-	-	-
CnAve	0.261E-4	0.458	0.542	-	-	-	-	-	-	-
Desert	-	0.870	-	-	-	0.117	0.133E-1	0.617E-4	-	-
Urban	0.949E-5	0.177	0.823	-	-	-	-	-	-	-
MrCln	-	0.987	-	0.132E-1	0.211E-5	-	-	-	-	-
MrTro	-	0.983	-	0.167E-1	0.217E-5	-	-	-	-	-
CnPol	0.12E-4	0.314	0.686	-	-	-	-	-	-	-
MrPol	-	0.422	0.576	0.222E-2	0.356E-6	-	-	-	-	-
Arctic	0.152E-5	0.197	0.803	0.288E-3	-	-	-	-	-	-
Antarc	-	-	-	0.109E-2	-	-	-	-	0.123E-3	0.998
Tropos	0.00017	0.6	0.4	-	-	-	-	-	-	-

of up to ten aerosol component: Insoluble (Ins), Water soluble (Water), Soot, (Sacc), (Sscoa), (Mnnuc), (Mnacc), (Mncoa), (Mntrans), and (Sulph), with the mixing ratios as listed in Table 2, according to the Table in *Hess et al.* [5]. At a location the aerosol concentration changes according to

$$N_{tb}(z) = N_{tb_0} \exp(-(z - z_0)/p_t), \qquad (z - z_0) \leq z_t \tag{16}$$

where N_{tb_0} is the aerosol concentration at the ground and p_t is the scale height of the aerosol type and z_t is the upper altitude of the aerosol layer. The free troposphere aerosol is up to 12 km altitude and the boundary layer aerosols are up to 2 km, except for the Desert aerosol up to 6 km above the ground and the Antarctic aerosol up to 10 km. The geographical distributions of the aerosol types, the concentration at the ground N_{t0} and their scale heights p_t can be obtained from software GADS, presented in *Hess et al. (1998)* [5]. The concentration profile of the free troposphere aerosol is set to

$$N_{tf}(z) = 730 \exp(-z/8), \qquad z \leq 12 \quad \text{km} \tag{17}$$

The attachments rates are calculated using the size distributions of the ten aerosol components, described by parameters σ and r_{mod} as well as the minimum and maximum radius of an aerosol particle r_{min} and r_{max}.

$$(\beta N)_t(z) = N_t(z) \sum_{j=1}^{N=10} \int_{r_{min}}^{r_{max}} \frac{dN_j(r)}{dr} \beta(r) dr \qquad s^{-1} \tag{18}$$

and $\beta(r)$ depends on the particle radius according to

$$\beta(r) = \begin{cases} \log \beta_r = 1.243 \log r - 3.978 & r < 0.01 \mu m \\ 4.35 \times 10^{-5} r - 9.2 \times 10^{-5} & r \geq 0.01 \mu m \end{cases} \tag{19}$$

and dN_j/dr are lognormal size distributions, as in Eq. 3d in *Hess et al. (1998)* [5]

$$\frac{dN_j(r)}{dr} = \frac{N_j}{\sqrt{2\pi} r \log \sigma_i \log 10} \exp \left[\frac{1}{2} \left(\frac{\log r - \log r_{modn}}{\log \sigma_i} \right)^2 \right] \tag{20}$$

where N_j are the mixing ratios of each aerosol component from Table 2 and σ_j, r_{modn_j}, r_{min_j} and r_{max_j} are shown in Table 3.

Stratospheric aerosols According to *Tinsley and Zhou* [20] there are three layers of stratospheric aerosols, centred at altitudes 15, 21 and 40 km. The higher layer is present at latitudes higher than 40° and is most intense at poles. The concentration profiles are Gauss functions with half-widths 5 km for both the 15-km and 21-km aerosol and 2.5 km for the 40 km aerosol,

Table 3:

Component	σ	r_{modn} (μm)	r_{min} (μm)	r_{max} (μm)
Insoluble	2.21	0.4710	0.005	20.0
Water-soluble	2.24	0.0212	0.005	20.0
Soot	2.00	0.0118	0.005	20.0
Sea salt, acc mode	2.03	0.2090	0.005	20.0
Sea salt, coa mode	2.03	1.7500	0.005	60.0
Mineral, nuc mode	1.95	0.0700	0.005	20.0
Mineral, acc mode	2.00	0.3900	0.005	20.0
Mineral, coa mode	2.15	1.9000	0.005	60.0
Mineral transported	2.20	0.5000	0.020	5.00
Sulphate	2.03	0.0695	0.005	20.0

Table 4:

Table 5:

Mode	$N_{0_{s_{ij}}}$	σ	r_{modn} (μm)	r_{min} (μm)	r_{max} (μm)
Aerosol 15 km					
Mode 1	9.00	1.75	0.10	0.01	1.5
Aerosol 21 km					
Mode 1	7.15	1.315	0.195	0.01	1.5
Mode 2	1.27	1.26	0.44	0.01	1.5
Aerosol 40 km					
Mode 1	2.0E7	1.2	0.0015	0.001	1.5
Mode 2	1.8E5	1.4	0.02	0.001	1.5
Mode 3	3.8E2	1.45	0.06	0.001	1.5
Mode 4	2.0E1	1.3	0.80	0.001	1.5

and each stratospheric aerosol layer consists of up to four aerosol modes. The concentrations of stratospheric aerosol in these layers can be described according to

$$\begin{array}{l} N_{s_{15}}(z) = \sum_{j=1}^{M=1} N_{0_{s_{15j}}} \exp(-(z-15)/5)^2) \\ N_{s_{21}}(z) = \sum_{j=1}^{M=2} N_{0_{s_{21j}}} \exp(-(z-21)/5)^2) \\ N_{s_{40}}(z) = \sum_{j=1}^{M=4} N_{0_{s_{40j}}} \exp(-(z-40)/2.5)^2 \cdot [1-(90-|\varphi|)/40] \end{array} \qquad (21)$$

where φ is the geographical latitude and z is altitude in kilometres, $N_{0_{s_{ij}}}$ are given in Table 5.

Each mode is described by the size distribution 20 with parameters listed in Table 5 and N replaced by the number of modes.

$$(\beta N)_s(z) = \sum_{i=15,21,40} \sum_{j=1}^{M\leq 4} N_{s_{ij}}(z) \int_{r_{min}}^{r_{max}} \frac{dN_j(r)}{dr}\beta(r)dr \qquad s^{-1} \qquad (22)$$

where $N_j = 1$, and σ_j, r_{modn_j}, r_{min_j} and r_{max_j} shown in Table 5.

3.2.5 Cloud droplets and attachment rates to droplets

In EGATEC we also take into account cloud conductivity which is usually lower than that of free air *MacGorman and Rust (1998)* [8]. For simplicity we assume that the concentration of condensation nuclei in all types of clouds, (as in *Makino and Ogawa (1984)* [11] and *Zhou and Tinsley (2007)* [22]), equals

$$N_{cl} = 2 \times 10^2 \qquad cm^{-3} \qquad (23)$$

and the ion attachment rate is

$$\beta_{cl} = 1.6 \times 10^{-4} \qquad cm^{-3}s^{-1} \qquad (24)$$

This will lead to a reduction of conductivity within clouds by a factor of a few to a few tens, compared to the free air conductivity.

3.2.6 Other factors affecting atmospheric conductivity

Below thunderclouds the conductivity can increase due to the production of ions by corona discharges *(Sapkota and Varshneya, 1990* [18]). In the case of corona discharges the conductivity at the ground will be twice higher than normal conductivity and above the ground it would change with altitude according to Eq.(4) in *Sapkota and Varshneya* [18].

4 Lower atmosphere generators

4.1 Clouds

The International Satellite Cloud Climatology Project (ISCCP, http://isccp.giss.nasa.gov) data sets provide global distributions of cloud radiometric properties and of atmospheric temperature and humidity *Rossow and Shiffer, 1991* [14] and are available from the NASA Langley Research Center Atmospheric Science Data Center, http://eosweb.larc.nasa.gov. The ISCCP cloud data are obtained by satellite measurements of radiance in the infra-red (IR) and near infra-red range. Clouds detected by the IR technique can be divided into three main altitude categories: high-, mid-, and low-level clouds. During daytime the satellite instruments make measurements in the optical range (VIS) and more cloud categories can be resolved by comparing cloud optical thickness versus cloud top pressure, The nine VIS cloud categories are: deep convective, cirrocumulus, cirrus (the high-level), nimbostratus, altostratus, altocumulus (the mid-level), stratus, stratocumulus and cumulus (the low-level), clouds, i.e. three categories within each IR category which is based only on the estimate of the cloud top pressure. Results from the optical measurements are considered to be more reliable than the infra-red *(Rossow, 1996)* [16].

EGATEC uses the ISCCP D1 data series, created following improvements of cloud categorisation algorithms used in the original ISCCP C1 data series *Rossow and Shiffer, 1999* [15]. Each ISCCP D1 data set provides 202 cloud and atmospheric variables at 3-hour resolution in the 5969-cell ISCCP grid (of 2.5° resolution in geographic latitude and variable number of cells at each latitude at 280 km resolution: from 3 equal-area cells at geographic poles, each ∼80,000 km^2 to 144 equal-area cells at the equator, each ∼77,000 km^2). At 0, 3, 6, ..., 21 UT the IR cloud data are available for ∼85-98% fraction of the globe, and the VIS-adjusted data for ∼40% of the globe.

In the current EGATEC model version the following ISCCP D1 variables are used: 1) percentage of clear sky area 2) percentage of area covered by clouds (for the three "level" categories and the nine "optical" categories if VIS-adjusted data are determined), 3) cloud top height, and 4) precipitable water for high, middle, and low altitude-pressure level – per an ISCCP cell. The percentage of area covered by the clouds are in fact sums of the percentages determined for each cloud subcategories, stored in subsequent bytes of the ISCCP cell record (Table 2.2.5 "D1 Data Map Grid Cell Layout" in *Rossow, 1996* [16]). A computer software D1READ which is provided with the ISCCP data calculates some additional variables; the cloud amounts (% by IR and VIS) and cloud top height (in meters) are used in EGATEC. In total there are twenty one EGATEC-ISCCP variables calculated from an ISCCP record. The variables and the range of ISCCP record bytes the variables are calculated from are listed in Table 6.

Since the ISCCP cannot provide the distribution of clouds over the whole globe, as required for a complete GEC model, an algorithm is applied to interpolate the ISCCP variables to those cells where no data or only part of data are available and, partly, to interpolate the VIS-adjusted results over the larger area of the globe. This algorithm is described in Appendix A. Furthermore, ISCCP grid elements are tagged with a mean topographic altitude, land cover fraction

Table 6: EGATEC ISCCP variables.

Variable	Name	Range of bytes in ISCCP record/additional variable	IR/VIS
0	number of pixels	1/additional	IR/VIS
1	IR cloud amount	additional	IR
2	IR clear sky amount	additional	IR
3	cloud top	additional	IR
4	high-level prec	201	IR
5	mid-level prec	199-200	IR
6	low-level prec	197-198	IR
7	high-level clouds	23-25	IR
8	mid-level clouds	26-27	IR
9	low-level clouds	28-29	IR
10	convective	34-35, 40-41, 46-47	VIS
11	cirrostratus	32-22, 38-39, 44-45	VIS
12	cirrus	30-31, 36-37, 42-43	VIS
13	nimbostratus	52-53, 58-59	VIS
14	altostratus	50-51, 56-57	VIS
15	altocumulus	48-49, 54-55	VIS
16	stratus	64-65, 70-71	VIS
17	stratocumulus	62-63, 68-69	VIS
18	cumulus	60-61, 66-67	VIS
19	VIS cloud amount	additional 10-18	VIS
20	VIS clear sky amount	additional	VIS

and vegetation type. The mean topographic altitudes are used to calculate the topographic map on the EGATEC grid.

4.2 Lightning and rainfall

Lightning and rainfall can particularly be associated with occurrence of electrified clouds such as thunderstorm or shower clouds. Data obtained by the Optical Transient Detector (OTD) over the 1995-2000 period and the Lightning Imaging Sensor (LIS) from 2003 onwards are the largest source of information on global lightning activity at present *(Christian et al., 2003)* [1]. Geographical distribution of hourly, monthly and yearly rates of lightning flash density for the period 1 April 1995 to 12 December 2006 are available from http://thunder.nsstc.nasa.gov. The OTD/LIS data are provided in a geographical grid of 2.5° resolution in longitude and latitude. In EGATEC 1.2 we use the gridded Low Resolution Time Series (LRTS) and the gridded Low Resolution Annual/Diurnal Climatology (LRADC) datasets. LRTS provides current (daily) lightning flash density and LRADC provides an average 2-hour lightning flash density per cell, on any day of the year. Furthermore, rainfall is obtained from the gridded Tropical Rainfall Measuring Mission *(Kummerow et al., 1998)* [7] 3B42 data (TRMM-Adjusted Merged-Infrared Precipitation). The TRMM data sets are available from the Goddard Distributed Active Archive Center at http://daac.gsfc.nasa.gov. The rainfall estimates are gridded on at 3-hour temporal resolution, similar to the ISCCP data, and 0.25° spatial resolution in a belt extending from 50°N to 50°S latitude (40°N to 40°S prior to February 2000, http://trmm.gsfc.nasa.gov/3b42.html). Both the lightning flash rate and the rainfall level is further used in the model to provide more information for an adequate division of the ISCCP clouds into current generator and non-generator categories and to calculate equivalent DC current generators (Section 4.1).

4.3 Generator and passive clouds

It is considered in the model that deep convective clouds and mid-level nimbostratus clouds can generate electric current and most actively contribute to the global current flowing in the global circuit. Thus the division between the generator and passive (all remaining) clouds is made

Table 7: Categorisation of clouds in EGATEC. Six types of areas covered by clouds are distinguished and a cloud-free area.

Area type	ISCCP VIS Cloud data	ISCCP IR Cloud data	Other conditions
1	Ci, Cs	High-level other than 4	–
2	Ac, As	Mid-level other than 5	–
3	Cu	Low-level other than 6	–
4	Cb	High-level, TRMM> 0 or PWH+PWM+PWL> 0.8	$\mathrm{LRTS}_N > 1$
5	Ns	Mid-level, TRMM> 0 or PWM+PWL> 0.5	–
6	Sc, St	Low-level, PWL> 0.3	–
7	None	None	–

accordingly. By using the input cloud, lightning and rainfall data we divide each circuit cell into seven types: area covered by: 1. High-level clouds such as cirrus (Ci), cirrostratus (Cs), 2. Middle-level altocumulus (Ac) and altostratus clouds (As), 3. Low-level cumulus clouds (Cu), 4. Deep convective clouds such as cumulonimbus (Cb), 5. Middle-level layer clouds such as nimbostratus clouds (Ns), 6. Low-level clouds such as stratocumulus (Sc) and stratus (St), and 7. Cloud-free area, where no clouds are detected.

If the ISCCP optical data are determined for the cell such division is straightforward. If the case when only IR data are determined an auxiliary procedure follows. It is assumed that rainfall or larger magnitude of precipitable water (taken from ISCCP data) may be an indication of the presence of convective or shower clouds. In these cells where TRMM data are determined the presence of rainfall will support the presence of generator clouds and in the absence of rainfall clouds will be categorised as passive. In those cells where the TRMM rainfall is not determined certain thresholds of the ISCCP precipitable water are applied to categorise the IR high-, and mid-level clouds into the generator (4-5) and passive (1-3 and 6) cloud categories: in generator clouds 4 the sum of precipitable water high-, mid- and low- level must exceed 1.0, and in clouds 5 the sum of precipitable water at mid- and low- levels must exceed 0.5; the thresholds have been roughly estimated by analysing the precipitable water levels for VIS-adjusted cloud data. In addition, to ensure that thunderstorms were likely to occur in the area, the number of flashes per day derived from the OTD/LIS LRTS flash rate density, LRTS_N, will have to be larger than 1. Table 7 summarises how the clouds are categorised and what additional conditions and thresholds are used.

Furthermore, the cloud altitude range is estimated as follows: if the cloud top altitude is determined in ISCCP data then this value is associated with clouds of the highest level occurring in the cell, otherwise, and for all the remaining cloud species, the cloud top and base altitude are prescribed. The cloud top z_t is set to be a function of geographic latitude and ranges from larger values at the equator and lower values at polar latitudes. The function is $z_t = z_t^{pl} + (z_t^{eq} - z_t^{pl}) \cos\varphi$, where φ is the geographic latitude, z_t^{eq} – cloud top height at equator, and z_t^{pl} – cloud top at geographic poles. Different z_t^{pl} and z_t^{eq} are assigned to different types of clouds. In addition, for each cloud category, a constant altitude z_b is assigned for the cloud base (Table 8). The cloud altitude range will be used in calculation of the columnar resistance and in the case of generator clouds - to calculate the height of main charge layers in these clouds and determine the altitude of equivalent DC current generators.

4.4 Cloud current generator models

The current generated by generator clouds is modelled in EGATEC by equivalent current generators shown schematically in Figure 2. *Willet (1979)* [21] discusses the representation of the

Table 8: Cloud base and top altitudes. The top cloud altitude, which depends on geographic latitude φ, is used if ISCCP cloud top estimate is not determined.

Area type	Cloud type	Cloud base (km)	Cloud top (km)
1	Ci	$6 + 2\cos\varphi$	$10 + 6\cos\varphi$
	Cs	$4 + 2\cos\varphi$	$6 + 2\cos\varphi$
2	Ac,As	2.0	$4 + 2\cos\varphi$
3	Cu	0.5	$1 + 0.5\cos\varphi$
4	Cb	1.0	$8 + 10\cos\varphi$
5	Ns	0.9	$3 + 3\cos\varphi$
6	St	0.3	0.8
	Sc	1.0	2.0
7	None	–	–

thunderstorm current generators in more detail and argues that a current source is a more appropriate electrical representation for thunderclouds compared to the representation by voltage sources. We apply the same approach to non-thunderstorm current generators but probably the most problematic task in GEC modelling is the accurate prediction of the amplitude of these equivalent current sources. In this model the current source representing a cloud current generator is estimated as follows. The source, for either convective or non-thunderstorm generator (type $a = 4, 5$) will be fixed in parallel with the source's internal resistance between nodes related to the locations of the two main charge layers within the cloud. We will assume the simplest dipolar charge structure in both convective ($a = 4$) and middle-level ($a = 5$) shower clouds, and construct the current source to be a DC equivalent of currents driven by the cloud due to charge separation inside the cloud. For simplicity we assume that the distance between the cloud charge layers will be proportional to the cloud height, and moreover, that both the lower, negative, charge layer height z_n and higher, positive, charge layer height z_p, are in the following relation with the cloud top and base heights: $z_n = z_b + 0.45(z_t - z_b)$ and $z_p = z_b + 0.85(z_t - z_b)$, where z_t is the cloud top altitude and z_b cloud base altitude (Table 8). The real altitude of the bottom charge layer is usually determined by temperature and lies between 0°C and −20°C isotherms, or 5-10 km for thunderclouds. Our estimate based up on the expression for z_n above gives values within this range.

Next, we assume constant current density j_C for cloud generators at a particular geographic latitude (Table 9). We further assume that this amplitude also changes with latitude as $j^{pl} + (j^{eq} - j^{pl})\cos\varphi$; this enforces higher intensities of cloud generators at lower latitudes, related to the cloud height. [9] acknowledge that there is a relation between currents produced by the storms and storm height but it seems to be more complicated. We assume that for deep convective clouds $j^{pl} = 0.25 j^{eq}$ and mid-level generators $j^{pl} = 0.40 j^{eq}$, where j^{eq} is the amplitude at the geographic equator and j^{pl} the amplitude at the geographical poles. We will also assume that the current density in the current sources generating current in clouds are stronger over land by 33% than over the oceans. In addition, for the non-thunderstorm cloud generators we assume that they not produce any lightning and that their equivalent current source amplitudes are at 20% of that for thunderclouds (*Mach et al., (2010)* [10] obtained 25% from their analysis). This magnitude of the current sources produces electric fields inside and below the cloud of the order of 10^2-10^3 V/m, in agreement with values from *Imyanitov and Shifrin (1962)* [6], Tables I, II, Figure 23d. Table 9 shows the current densities associated with deep convective and middle-level cloud generators. These generators' current densities result in upward currents driving the global circuit that agree with the observed values concerning thunderstorms or shower clouds, e.g. *Harrison and Nicoll 2008; Mach et al., 2009* [3, 9].

The contribution by lightning j_L can be estimated from an average charge transferred by a lightning discharge and the rate of lightning flashes. The flash rates can be obtained locally by

Table 9: Equivalent generator current densities for deep convective (land) and nimbostratus clouds at latitude φ. The amplitude of the lightning current density depends on the LIS/OTD LRADC flash density as described in the text.

Cloud type	j_C (pA/m^2)	j_L
Deep Convective	$50 + 150\cos\varphi$	LRADC dependent
Nimbostratus	$12 + 18\cos\varphi$	-

Figure 3: The equivalent circuit of the network shown in Fig. 1 including branches shown in Fig. 2. All sub-branches are connected in parallel between the ground and the ionosphere nodes. Sub-branches can be divided into generator and non-generator group. The current generated in the circuit is calculated according to Eq. (27). The ionospheric potential V_I and the current flowing in the circuit are found from Eq. (28).

lightning detection systems, and global distributions and global rates can nowadays be obtained by optical detectors on satellites, the recent data coming from the OTD and LIS instruments [2, 1]. The charges involved are less well known. In this model we set the charge carried by lightning $Q_L = 2$ C which is equivalent of an assumption that one $-$CG transfers $+18.7$ C (including multiple return strokes), one +CG transfers -46.6 C (taking into account that perhaps $\sim$30% +CGs may not have very strong continuing currents) and one IC transfers -2 C. This is also equivalent to ICs not contributing at all and each $-$CG contributing $+14.5$ C (using the lightning frequency weighting as in *Rycroft et al., 2007* [17] 10 $-$CG, 0.7 +CG and 33 ICs in every $\sim$44 lightning discharges; 44$\pm$5 being the global lightning flash rate by *Christian et al., 2003* [1].

Using the LRADC flash rate from OTD/LIS data, expressed in m^{-2}s^{-1}, the current density due to lightning becomes $Q_L\cdot$ LRADC (A/m^2). This value is next multiplied by the total columnar resistance of the generator area from the ground to the ionosphere divided by the resistance of the portion from z_n to z_p, i.e. $j^{ij}_{L,a} = Q_L \mathrm{LRADC}^{ij} \cdot R^{ij}_a / R^{ij}_{2a}$ (A/m^2) and $a = 4$, to ensure that the contribution of the lightning current is not reduced by the equivalent current source's internal resistance. Finally, for cloud generators of type $a = 4, 5$, the current densities $j^{ij}_{C,a}$, and $j^{ij}_{L,a}$ add up to the total source current density j^{ij}_{0a}. The current source amplitude is found by multiplying the total current density by the surface area S^{ij}_a covered by those clouds in any circuit branch (i, j)

$$j^{ij}_{0a} = j^{ij}_{C,a} + j^{ij}_{L,a}, \qquad I^{ij}_{0a} = j^{ij}_{0a} S^{ij}_a \tag{25}$$

5 Circuit solution

The circuit representing the GEC with an equipotential ionosphere from Figure 1 can be solved analytically. All $N_{lon} \times N_{lat}$ branches with their sub-branches, connected in parallel between nodes "0", where the potential is set to be zero, and node "1" at the ionospheric potential V_I, can be divided into a generator group (all sub-branches with current sources) and passive group (all sub-branches consisting of resistances only), as shown in Figure 3.

The resistance of the passive branches is the resistance R_F and the resistance of all the branches is the total resistance of the atmosphere R_G, and they can be calculated according to Eqs. (26)

$$\frac{1}{R_G} = \sum_{i,j} \sum_{a=1}^{7} \frac{1}{R^{ij}_a}, \qquad \frac{1}{R_F} = \sum_{i,j} \sum_{a=1,2,3,6,7} \frac{1}{R^{ij}_a} \tag{26}$$

The generator branches drive an upward current I_U which equals the sum of the amplitudes of the individual current sources multiplied by the ratio of the internal resistance of the sources and the total resistance of each sub-branch

$$I_U = \sum_{i,j} \sum_{a=4,5} \frac{I_{0a}^{ij} R_{2a}^{ij}}{R_a^{ij}} \tag{27}$$

The potential of node "1", i.e. the ionospheric potential V_I, and the current flowing in the global circuit I_G can be found from R_G, R_F and I_U as follows

$$V_I = \frac{I_U}{R_G}, \qquad I_G = V_I R_F \tag{28}$$

When potential V_I is calculated, the current flowing in each sub-branch can be found from

$$I_a^{ij} = \frac{I_{0a}^{ij} R_{2a}^{ij}}{R_a^{ij}} - \frac{V_I}{R_a^{ij}} \tag{29}$$

In all passive sub-branches $a = 1, 2, 3, 6, 7$ the current equals $-V_I/R_a^{ij}$, i.e. the current there flows downward and discharges the ionosphere. Current flows upward and charges the ionosphere in sub-branches where $V_I/R_a^{ij} > I_{0a}^{ij} R_{2a}^{ij}/R_a^{ij}$, i.e. where the generator current overcomes the current imposed by the ionosphere. Current density j_a^{ij} can be calculated either by using columnar resistances in Eq. (29), instead of resistances, or by dividing the current by the surface area of the sub-branch. Finally, the vertical electric field at height z can be found from

$$E_a^{ij}(z) = \frac{j_a^{ij}}{\sigma(z)} \tag{30}$$

In particular the electric field at the ground can be calculated by dividing the current density by the conductivity at the ground level z_g: $E_{0a}^{ij} = j_a^{ij}/\sigma(z_g)$.

A ISCCP data fit procedure

This procedure is required to interpolate ISCCP cloud data over these ISCPP cells where all or some required ISCCP cloud variables are not determined. This allows to obtain complete distributions of these variables for input to the GEC model.

The interpolation of ISCCP data can be performed in the time and spatial domain and normally starts with the interpolation in the time domain. First, the dataset of interest at t_0 = 0, 3, 6... is read simultaneously with preceding and following datasets at $t_0 - 12$h, $t_0 - 9$h, $t_0 - 6$h, $t_0 - 3$h, $t_0 + 3$h, $t_0 + 6$, $t_0 + 9$h, $t_0 + 12$h; ±12 hours is the furthest we consider the interpolation is reliable. Initially it is assessed in which cells of the t_0 dataset the required ISCCP IR variables (fraction of cloud-free area and area covered by the three IR cloud categories, cloud top altitude and precipitable water at the three levels) and VIS-adjusted variables (percentage of area covered by nine VIS cloud categories and cloud-free area) are not determined. Next, the fraction area of IR or VIS clouds for every cell where either IR or VIS cloud variables are not determined are found by the following procedure:

1. The data in the read datasets are checked whether an IR set of variables is determined in the same cell in any preceding data set at $t < t_0$ and which of them is the nearest one, and the same over the following data sets at $t > t_0$. The relevant IR-variables sets $\{P_j\}(t_1^{IR})$ and $\{P_j\}(t_2^{IR})$, $t_1^{IR} < t_0 < t_2^{IR}$ are stored for use in following fitting procedures. If such t_1^{IR} and t_2^{IR} are found the cell is tagged as "IR-fit-able".

2. The same is checked and determined for VIS variables. If t_1^{VIS} and t_2^{VIS} can be found the cell is tagged as "VIS-fit-able".

3. In case neither IR or VIS variables are determined in the cell at t_0 and if the cell is only "IR-fit-able" a procedure called FitIR2IR follows, and procedure FitVIS2VIS if the cell is "VIS-fit-able".

4. In case only VIS variables are not determined and the cell is "VIS-fit-able" then if $|t_2^{VIS} - t_1^{VIS}| <= |t_2^{IR} - t_1^{IR}|$ the procedure FitVIS2VIS is called otherwise a procedure called FitVIS2VISbyIR applies.

5. In the FitVIS2VIS procedure, if at t_0 IR variables were not determined at the start they are now found from the appropriate newly calculated VIS variables.

Procedures FitIR2IR, FitVIS2VIS and FitVIS2VISbyIR are constructed similarly, except in the latter case only clouds from the levels present in the IR data of cells at t_1^{IR} and t_2^{IR} are allowed in the fitting of VIS variables from t_1^{VIS} and t_2^{VIS} to t_0.

In each case a specified set of variables $P = \{P_i\} : \sum_i P_i = 1$ must be found for the cell. In FitIR2IR P has four elements (fraction area of 3 cloud categories and cloud-free area). In FitVIS2VIS P has ten elements (fraction area of 9 cloud categories and cloud-free area), and in FitVIS2VISbyIR P is a subset of this ten-element set. $\{P_i\}(t_0)$ are found on the basis of $\{P_i\}(t_1)$ and $\{P_i\}(t_2)$ as follows:

1. An index j of the variable P_j occupying the most of the surface area in both $\{P_i\}(t_1)$ and $\{P_i\}(t_1)$ i.e. such as $P_j(t1) + P_j(t2)$ is the largest, is found.

2. A new P_j value at t_0 is found by a linear relation

$$P_j(t_0) = P_j(t_1) + \frac{P_j(t_2) - P_j(t_1)}{t_2 - t_1}(t_0 - t_1) \tag{31}$$

3. The lately calculated variable P_j is removed from P.

4. Instructions 1.,2.,3. are repeated until there is only one variable left in the subset P or the sum of newly calculated values becomes overloaded, i.e. $\sum_j P_j > 1$.

5. If $\sum_j P_j$ is overloaded then $P_j(t0)$ is replaced by $1 - \sum_j P_j$ and all remaining P_i in the set P are set to zero.

6. In case there is only one variable P_i left in the set P the following condition are checked: if after last time $\sum_j P_j$ was overloaded then the last P_j is set to $1 - \sum_j P_j$ and $P_l(t_0) = 0$ (previous case). Otherwise, at first P_l is estimated by Eq. (31). If adding the new value to $\sum_j P_j$ overloads it then P_l is set to $1 - \sum_j P_j$. In case $\sum_j P_j + P_i < 1$ then the remaining fraction $1 - (\sum_j P_j + P_i)$ is added to the cloud-free fraction, or, alternatively, all values are scaled proportionally to make $\sum_i P_i = 1$. The first choice is preferred in the current algorithm version.

If necessary, new values for the cloud top level and three precipitable water levels are fitted separately, according to Eq. (31).

After the procedure in the time domain the whole ISCPP grid is checked once again if IR variables are determined in all cells. If still there are empty cells then the procedure starts in the spatial domain. In the spatial domain analogous procedures WeaveIR2IR and WeaveVIS2VIS follow. The main change in the procedures is that variables are now interpolated by averaging values from adjacent cells over the same ISCCP grid, and Eq. (32) is used instead of Eq. (31).

$$P_j(t_0) = \frac{1}{n}\sum_{k=1}^{n} P_j^k(t_0), \qquad n >= 4, 3 \tag{32}$$

The spatial averaging is performed firstly for IR variables and next for VIS variables. In addition, in the first step, the procedure is applied if at least one adjacent cell from both the north, south, west, and east of the cell can be used for the interpolation (i.e. the set of necessary variables is determined in each of those cells). In the next step if the set of necessary ISCCP data is still not complete it is allowed that adjacent cells from just three directions are used. In practice the interpolation in the time domain is usually sufficient to complete the whole ISCCP data set.

Equations (31) and (32) may underestimate (overestimate) a variable P_i in case the real value was a local maximum (minimum). In future the whole procedure may be developed and more complicated interpolation method found, for example, based on data from more cells in the time domain or by combining interpolation in time and space simultaneously.

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References

[1] H. J. Christian, R. J. Blakeslee, D. J. Boccippio, W. L. Boeck, D. E. Buechler, K. T. Driscoll, S. J. Goodman, J. M. Hall, W. J. Koshak, D. M. Mach, M. F. Steward, E. J. Alderman, and E. R. Williams. Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *J. Geophys. Res.*, 108(D1), 2003.

[2] H. J. Christian, R. J. Blakeslee, S. J. Goodman, D. M. Mach, M. F. Steward, D. E. Buechler, W. J. Koshak, J. M. Hall, K. T. Driscoll, and D. J. Boccippio. The Lightning Imaging Sensor. In *Proceedings of the 11th International Conference on Atmospheric Electricity*, pages 746–749, 1999. Guntersville, Alabama, June 7-11.

[3] R. G. Harrison and K. A. Nicoll. Air-earth current density measurements at Lerwick; implications for seasonality in the global electric circuit. *Atmos. Res.*, 89(5-6):181–193, 2008.

[4] A. E. Hedin. Extension of the msis thermospheric model into the middle and lower atmosphere. *J. Geophys. Res.*, 96(A2):1159–1172, 1991.

[5] M. Hess, P. Koepke, and I. Schult. Optical properties of aerosols and clouds: the software package OPAC. *Bull. Amer. Met. Soc.*, 79(5):831–844, 1998.

[6] I. M. Imyanitov and K. S. Shifrin. Present state of research on atmospheric electricity. *Soviet Physics Uspekhi*, 5(2):292322, 1962. in Russian.

[7] C. Kummerow, W. Barnes, T. Kozu, J. Shiue, and J. Simpson. The Tropical Rainfall Measuring Mission (TRMM) sensor package. *Journal of Atmospheric and Oceanic Technology*, 15:809817, 1998.

[8] D. MacGorman and W. D. Rust. *The electrical nature of storms*. Oxford University Press, New York, 1998.

[9] D. M. Mach, R. J. Blakeslee, M. G. Bateman, and J. C. Bailey. Electric fields, conductivity, and estimated currents from aircraft overflights of electrified clouds. *J. Geophys. Res.*, 114, 2009.

[10] D. M. Mach, R. J. Blakeslee, M. G. Bateman, and J. C. Bailey. Comparisons of total currents based on storm location, polarity, and flash rates derived from high-altitude aircraft overflights. *J. Geophys. Res.*, 115, 2010.

[11] M. Makino and T. Ogawa. Responses of atmospheric electric field and air-earth current to variations of conductivity profiles. *J. Atmos. Terr. Phys.*, 46:431–445, 1984.

[12] A. Odzimek and M. Lester. Modelling the Earth's global atmospheric electric circuit - development, challenges and directions. *Publs. Inst. Geophys. Pol. Acad. Sc.*, D-73(412):37–53, 2009.

[13] A. Odzimek, M. Lester, and M. Kubicki. EGATEC - a new high-resolution engineering model of the global atmospheric electric circuit. 1. currents in the lower atmosphere. *J. Geophys. Res.*, 2010. in press.

[14] W. B. Rossow and R. A. Schiffer. ISCCP cloud data products. *Bull. Amer. Met. Soc.*, 71:2–20, 1991.

[15] W. B. Rossow and R. A. Schiffer. Advances in understanding clouds from ISCCP. *Bull. Amer. Met. Soc.*, 80:2261–2288, 1999.

[16] W. B. Rossow, A. W. Walker, D. E. Beuschel, and M. D. Roiter. International satellite cloud climatology project (ISCCP) documentation of new cloud datasets. *WMO/TD*, (737), 1996. World Climate Research Programme (ICSU and WMO), pp. 115.

[17] M. J. Rycroft, A. Odzimek, N. F. Arnold, M. Fullekrug, A. Kulak, and T. Neubert. New model simulations of the global atmospheric electric circuit driven by thunderstorms and electrified shower clouds: The roles of lightning and sprites. *J. Atmos. Sol.-Terr. Phys.*, 69(17-18):2485–2509, 2007.

[18] B. K. Sapkota and N. C. Varshneya. On the global atmospheric electric circuit. *J. Atmos. Terr. Phys.*, 52(1):1–22, 1990.

[19] W. Swider. Ionic mobility, mean mass, and conductivity in the middle atmosphere from near ground level to 70 km. *Radio Sci.*, 23(3):389–399, 1985.

[20] B. A. Tinsley and L. Zhou. Initial results of a global circuit model with variable stratospheric and tropospheric aerosols. *J. Geophys. Res.*, 111, 2006.

[21] J. C. Willett. Solar modulation of the supply current for atmospheric electricity? *J. Geophys. Res.*, 84(C8):4999–5002, 1979.

[22] L. Zhou and B. A. Tinsley. Production of space charge at the boundaries of layer clouds. *J. Geophys. Res.*, 112, 2007.