Global Electric Circuit Variabillity in a GCM Model

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ABSTRACT: The ionospheric potential (IP) parameterization has been proposed taken into account quasi-stationary currents of electrified clouds (including thunderstorms) as principal contributors into the DC global circuit. A General Circulation Model (GCM) of the atmosphere and ocean is used for modeling the global electric circuit (GEC) short-time variability and long-term evolution. The diurnal, seasonal and annual variability of the GEC were modeled and compared with available data. Numerical simulations suggest the decrease of the ionospheric potential by about 10% for the XXI century if the global warming follows an assumed greenhouse gas emission scenario RCP 8.5. Inter-annual variability of the IP is low and does not exceed 1% from the mean value. It should be emphasized however that it is correlated tightly with the mean SST in the Pacific Ocean (180W-100W, 5S-5N – El-Nigno area). The IP maximum corresponds to the SST minimum. This result can be explained taking into account that during El-Nigno (positive temperature anomaly) precipitations in the equatorial part of the Pacific increase while in other tropic zones including the land areas they decrease. Comparison of simulation results with the observational data on lightning activity on the ENSO time scale is discussed.

INTRODUCTION

The account of electric processes in the General Circulation Models (GCM) of the atmosphere and ocean is impeded by the lack of adequate parameterizations for these processes. The first parameterizations of the mean flash rates for thunderstorm clouds over the land and ocean, as well as the relation of intracloud and cloud-to-ground flashes were suggested and used in a high-resolution climate model by *Price and Rind* [1992; 1993]. Now these parameterizations are still widely used, while a number of new parameterizations for the flash rates were suggested and used [e.g., *Futian and Del Genio*, 2007; *Tost*, 2007; *Grewe*, 2009].

Another important atmospheric electrical parameter is the ionospheric potential (IP) which represents the electric voltage between the Earth's surface and the lower ionosphere and can be measured with a sufficient accuracy using the balloon soundings over the lowest 15-20 km. This parameter can serve as a global index relating the GEC state to the planetary climate [e.g., *Williams*, 2009; *Markson*, 2007; *Mareev*, 2010; *Williams and Mareev*, 2014]. But exploring the GEC as a diagnostic tool for climate studies requires an accurate modeling of the IP stationary state and its dynamics, while a question of secular trend of the IP is still under discussion [*Williams*, 2009; *Markson*, 2007]. The first parameterization of Vi appropriate for the use in climate-model simulations has been developed and discussed in [*Kalinin et al.*, 2011; *Mareeva et al.*, 2011; *Mareev and Volodin*, 2011]. This study uses such a parameterization with a high resolution

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GCM model (NMCM4.0). The diurnal, seasonal and annual variability of the GEC is discussed and compared with available experimental data. The IP calculations performed for XX and XXI centuries are presented. Physical mechanism of the long-term GEC evolution is revealed. We discuss also further development of IP parameterization to be more appropriate for the using in the modern climate/mesoscale models.

GEC PARAMETERIZATION AND ITS VERIFICATION

Vi is an infrequently sampled quantity. Dedicated efforts are needed to monitor this globally representative scalar on a continuous basis. The most reliable measurement of Earth's geoelectric potential that avoids contamination by the various local effects is to make electric field profile soundings and integrate the results from the ground up to the ionosphere [*Clark*, 1958; *Markson*, 1976]. Figure 4 in the paper by [*Markson*, 2007] summarizes the measurements of the three groups conducting reliable Vi measuring programs during the last 50 years (several hundred soundings in total). It is seen from this figure that the sounding series give more or less close results around the mean value 240 kV, and it is difficult to reveal any reliable trends connected with the definite physical parameter changes, except the pronounce increase of Vi in the early 60^{th} due to atmospheric nuclear bomb testing.

Because of difficulty to parameterize Vi on the basis of experimental data, our approach is based on the use of theoretical calculations. Namely it is convenient to use the integral representation for electric current contribution into the ionospheric potential. This approach was suggested by *Kalinin et al*. [2011] who developed the spherical numerical model of the GEC and applied it for the calculation of the IP for different-type cloud contribution into the circuit. As applied to the single electric current layer as a model of the electrified cloud supporting the circuit, this approach leads to the following expression for the current contribution into the IP:

$$V_k = \frac{j_0 S_k H_0}{\sigma_0 S_E} \exp\left(-\frac{z_b}{H_0}\right)\left\{1-\exp\left(-\frac{\Delta z}{H_0}\right)\right\}, \qquad (1)$$

where j_0 is the magnitude of the electrical current; S_k is the area of the layer; S_E is the area of the Earth's surface; H_0 is the characteristic vertical scale of the conductivity profile $\sigma = \sigma_0 \exp(z/H_0)$; Δz is the vertical scale of the region occupied by electrical current, z_b is the height of its bottom (the cloud bottom). Treating j_0 as the mean magnitude of the external current supporting the electrical structure of a cloud (i.e., the convection region in a GCM model), which is assumed to be dipolar, S_k as the area occupied by convection, Δz as the mean cloud thickness, we can apply the expression (1) for the calculation of the convection region contribution into the total potential. Taking by so, we simplify the real situation, in particular because the multi-layer clouds and MCS [e.g., *Stolzenburg and Marshall*, 1998*; Davydenko et al.,* 2004] are not considered. But as the first step, this model seems reasonable as dipole-like clouds are recognized as the main contributors into the circuit [e.g., *Williams,* 2005]. It is especially important to note that the suggested IP parameterization takes into account the contributions of both thunderstorm clouds and electrified shower clouds (ESCs) because both of them are associated with the convection areas and respective electrical charging currents determining V_k value in the expression (1).

We use a high-resolution General Circulation Model (GCM) of the atmosphere and ocean INMCM4.0 for the modeling the global electric circuit (GEC) evolution. The main characteristics of a model are: atmosphere - 2x1.5 degrees in longitude and latitude, 21 levels; ocean - 1x0.5 degrees in longitude and latitude, 40 levels; the coupling without flux adjustment [*Volodin et al.*, 2010].

IP was determined as the sum over all the sources existing simultaneously over the globe. The area occupied by a separate source S_k was calculated as $S_k = \alpha S_{cell} P / W$, where S_{cell} is the square of the model cell where the convection arises, P is the precipitation per time step (mm), W is the precipitable water volume (mm). An only coefficient α, characterizing an area occupied by the convection (electrified clouds), has been changed for parameterization adjusting. It turned out that the IP value is close to the observable values when this coefficient equals 0.4. Other parameters were taken in the modeling as constant values: $j_0 = 3 \cdot 10^{-3}$ CGS (which is equal 10 nA/m^2), H_0 = 6 km, $\sigma_0 = 3 \cdot 10^{-14}$ S/m. The horizontal inhomogeneities of the conductivity were not taken into account.
A pronounced characteristic of the Earth's electric field is its diurnal variation as found originally in analysis of electric field measurements on board the ship [*Hoppel et al.*, 1986], therefore the test of the parameterization with the diurnal variation description is of a special interest. In a model experiment the calculation of Vi in 1891-2010 has been carried out. It was found that the calculated IP diurnal variation averaged over all the days corresponds rather well to the measured values. Diurnal V_i variation averaged over all the days of 1986-2005, is presented in Figure 1. IP maximum takes place in a model at 16-20 UT when convection in Africa and South America are the most intensive. Note that the measurements reveal a broad IP maximum around 19 UT [*Markson*, 2007]. This shift of the model maximum to the early time can be explained by the fact that in the climate models convection occurs at once the static stability violates, while real convection develops during 1-3 hours.

Further test should be the study of the seasonal (annual) variation. We found that the annual IP variation has a maximum in the summer of the North hemisphere when the convection over the land dominates (Fig.2), and the wet South Asian monsoon and general increase of precipitation in tropics occur. This behavior agrees with experimental data, in particular with the data on air-Earth current suggesting that the electrical parameters peak in the northern hemisphere summertime [*Adlerman and Williams*, 1996; *Williams*, 2009] Note that the reanalysis of all available measurements of ionospheric potential [*Markson*, 2007] shows a consistent result on the annual variation, with maximum in NH summer. The annual variation of the global circuit with northern hemisphere summer maximum is attributable to the asymmetry in land mass between the northern and southern hemispheres and the global variation in air temperature that accompanies that asymmetry [*Williams*, 1994; *Reddell et al.*, 2004].

To demonstrate the role of different factors of the formulae (1) in the modeling and their distribution over the globe, the mean annual values of the vertical scale Δz and the cloud bottom z_b are presented in Figure 3a,b. It is seen that in the areas of frequent convection z_b is of order of 500 m; Δz is of order of 8 - 10 km in the areas of frequent convection. Figure 3c shows the distribution of convection events (measured as an event fraction N_c among all the model steps) over the globe as found in the modeling. Over the ocean in the areas of intensive convection the amount of these events is as big as 0.9, which means that convection arises at almost each time step. Over the land in Africa and South America the model gives $N_c \approx 0.5$ mainly due to the infrequent night convection. It is seen that the amount of Vi is determined manly by the convection area in the course of the modeling with IP parameterization (1).

LONG-TERM GEC VARIATION

The results of the numerical experiment for the study of IP evolution in XXth century are presented in Fig.4. It was found that the global change in the model is accompanied by Vi decrease.

Inter-annual variability of the IP is low and does not exceed 1% from the mean value. It should be emphasized however that it is correlated tightly with the mean SST in the Pacific ocean (180W-100W, 5S-5N – El-Nigno area). The IP maximum corresponds to the SST minimum. This result can be explained taking into account that during El-Nigno (positive temperature anomaly) precipitations in the equatorial part of the Pacific increase while in other tropic zones including the land areas they decrease. The comparison of simulation results with the observational data on lightning activity on the ENSO time scale [Chronis et al., 2008; Satori et al., 2009] serves a separate detail paper.

Figure 4 in the paper by [Markson, 2007] summarizes the measurements of the three groups conducting reliable Vi measuring programs during the last 50 years (several hundred soundings in total). It is seen from this figure that the sounding series give more or less close results around the mean value 240 kV, and it is difficult to reveal any reliable trends connected with the definite physical parameter changes, except the pronounce increase of Vi in the early 60th due to atmospheric nuclear bomb testing.

A numerical experiment for the study of atmospheric electricity in XXI century has been performed for scenario RCP 8.5 (Representative Concentration Pathway 8.5 Wm^{-2}) when global warming is about 2.5 degrees for the century (Fig.5). Numerical experiments for XXI century perspective show that the tendency of the ionospheric potential decrease will remain for scenario RCP 8.5. It is caused by the decrease of the convection area (Fig.5). The latter is understandable because the temperature increase leads to the increase of the difference between the dry adiabatic gradient and the moist adiabatic gradient.

It is known that due to the global warming the air moisture content increases about 13% per degree – the same rate as for the saturation humidity, while the global precipitation increases at a much smaller rate of about 1 to 3% per degree [*IPCC-4*, 2007; *Wentz et al*., 2007]. As a result, the convection area calculated as the relation of the precipitation per time step to the total moisture (precipitable water volume), decreases with global warming. It is interesting that for the lightning flash rate, using Price&Rind parameterizations, it was found that a mean flash rate is increasing by about 20% for the century (from 60 to 72 fl/s) for scenario RCP 8.5 [*Mareev and Volodin*, 2011].

DISCUSSION AND CONCLUSIONS

A General Circulation Model (GCM) of the atmosphere and ocean has been used for modeling the GEC short-time variability and long-term evolution in this paper. It was possible due to the ionospheric potential parameterization proposed, taken into account quasi-stationary currents (dipolar current generators) of electrified clouds (including thunderstorms) as principal contributors into the DC global circuit. The results have shown that many of the calculated parameters are consistent with measurements and estimates made on the global circuit. On the other hand, using of GCM allows us to study the influence of different factors on the GEC state, first of all an implication of convection intensity and its trends in a warmer climate.

One of the most important aspects of this approach is an account for all the electrified clouds- both thunderstorms and ESCs because both of them are represented by the electric current in the PI parameterization. Note that the existence of ESCs, with an electrical polarity appropriate for contributing to the potential difference between Earth and atmosphere, has recently been verified in aircraft overflights of cumulonimbus clouds by NASA Marshall Space Flight Center [*Mach et al*., 2009; *Mach et al*., 2010; *Mach et al*., 2011].

The mean current for oceanic storms with lightning was 1.6 A whereas the mean current for land storms with lightning was 1.0 A. The mean current for oceanic storms without lightning was 0.39 A, and the mean current for land storms without lightning was 0.13 A [*Mach et al*., 2010]. Mean contributions to the global electric circuit from land and ocean thunderstorms are 1.1 kA (land) and 0.7 kA (ocean). Contributions to the global electric circuit from electrified shower clouds are 0.22 kA for ocean storms and 0.04 kA for land storms [*Mach et al*., 2011]. The mean total conduction current for the global electric circuit is 2.0 kA. The means that for the number of storms contributing to the global electric circuit, 1100 are land storms with lightning, 530 are ocean storms without lightning, 390 are ocean storms with lightning, and 330 are land storms without lightning. A closer fit to the Carnegie curve is possible if the contributions from electrified shower clouds are increased by a factor of 3 or 4.

Another assessment of the role of non-thunderstorm clouds in the diurnal variation of the GEC [*Liu et al*., 2010] made use of TRMM satellite observations (the Lightning Imaging Sensor (LIS) and the Precipitation Radar) to estimate the global population of ESCs. Assuming that the Wilson current for an individual electrified shower cloud is 25% of that for a thunderstorm, the total charging current to the GEC from ESCs was found to be of the same order as that from thunderstorms, in agreement with Wilson's (1920) initial speculation.

It is well recognized by now that the GEC and global lightning activity form a natural framework for investigating climate issues [*Williams*, 2005, 2009]. Moreover, the ionospheric potential Vi and the mean global flash rate can serve as global indices relating the state of the GEC to the planetary climate [e.g., *Price*, 1993; *Williams*, 1994; *Markson et al.*, 1999; *Markson*, 2003]. It is important, however, that the GEC forms due to continuous operation of ionization sources, along with meteorological factors. It makes the problem of recognizing the long-trends of the GEC and their physical mechanisms especially difficult. A brief discussion of experimental efforts to reveal possible long-term trends in Vi can be found in *Williams* [2009]. So far there is no clear manifestation of such a trend [*Markson*, 2007].

For the common scenario of greenhouse gas emission and global warming, in the mean the tropical atmosphere is becoming more stable because the vertical gradient of temperature is decreasing due to the more rapid increase in the temperature of the upper troposphere than in the lower troposphere (e.g., [*Houghton et al*., 2007; *Galin et al*., 2007]). This behavior is in line with the conclusions by *Del Genio et al*. [2007] who studied the change in convection in a warmer climate with the GISS model, and found that the number of storms in the regions of analysis was diminished, while the very strongest storms with a strong updraft increased (see also [*Price*, 2009]). The discussion about the relation of convection to the mean surface temperature, particularly in tropics, can be found also in [*Mokhov and Akperov*, 2006; *Zelinka and Hartmann*, 2010; 2011].

Our model, however, needs to be further studied in terms of the trend in CAPE (Convective Available Potential Energy) in a considered scenario, and, respectively, the concrete mechanism connecting the temperature change with the GEC response [*Williams*, 1994]. We did not take into account potentially important contributors into the Vi – Austausch (convective) generator operating in the fair weather regions, and lightning. Both of them need to be studied better to be taken into account in the Vi parameterization. The latter also seems not to be a big contributor into the mean quasi-stationary state of the GEC, which is the focus or our study, while temporally and regionally their contribution may be substantial [*Mareev et al.*, 2008, 2013; *Davydenko et al*., 2009].

A drawback of this model so far is also the simplified treatment of the conductivity profile in the atmosphere and the current density in electrified clouds. These limitations impede a direct comparison of the modeling results with the record of Vi over the last 70 years [*Markson*, 2007]. As to observational evidence for the long-term evolution of GEC, this question is still unresolved. An expanded critical discussion of the observational claims for a decline in the GEC can be found in *Williams* [2009]. As was mentioned earlier, the available evidence is that the global circuit is rather stable on long time scales [*Markson*, 2007].

In a model experiment the calculation of lightning activity in 1891-2010 has been carried out using the well-known parameterizations [*Price and Rind*, 1992; 1993]. The obtained results correspond rather well to the modern picture of lightning distribution globally observed on-board the spacecraft. In general, the flash rate obtained in a model is close to the presently observed one, while in Africa it is slightly underestimated whereas in Indonesia - slightly overestimated. The mean flash rate over the globe in the model equals about 60, which corresponds rather well to modern estimates based on spacecraft data.

As a conclusion, a General Circulation Model (GCM) of the atmosphere and ocean is used for modeling the global electric circuit (GEC) short-time variability and long-term evolution. The main characteristics of the used model NMCM4.0 are: atmosphere - 2x1.5 degrees in longitude and latitude, 21 levels; ocean - 1x0.5 degrees in longitude and latitude, 40 levels; the coupling without flux adjustment.

The diurnal, seasonal and annual variability of the GEC were modeled and compared with available data. Numerical simulations suggest the decrease of the ionospheric potential by about 10% for the XXI century if the global warming follows an assumed greenhouse gas emission scenario RCP 8.5.

Inter-annual variability of the IP is low and does not exceed 1% from the mean value. It should be emphasized however that it is correlated tightly with the mean SST in the Pacific ocean (180W-100W, 5S-5N – El-Nigno area). The IP maximum corresponds to the SST minimum. This result can be explained taking into account that during El-Nigno (positive temperature anomaly) precipitations in the equatorial part of the Pacific increase while in other tropic zones including the land areas they decrease.

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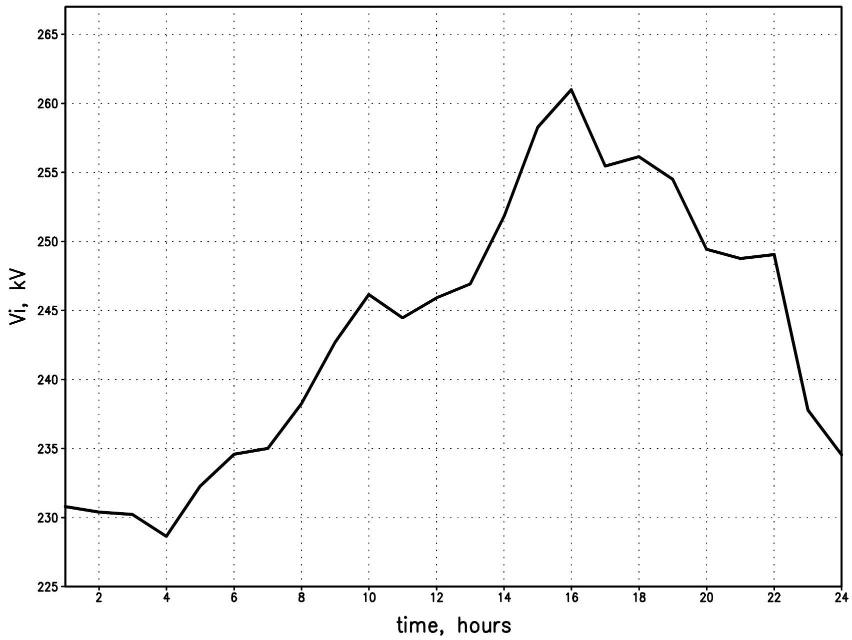

Fig.1. Diurnal V_i variation averaged over all the days of 1986-2005.

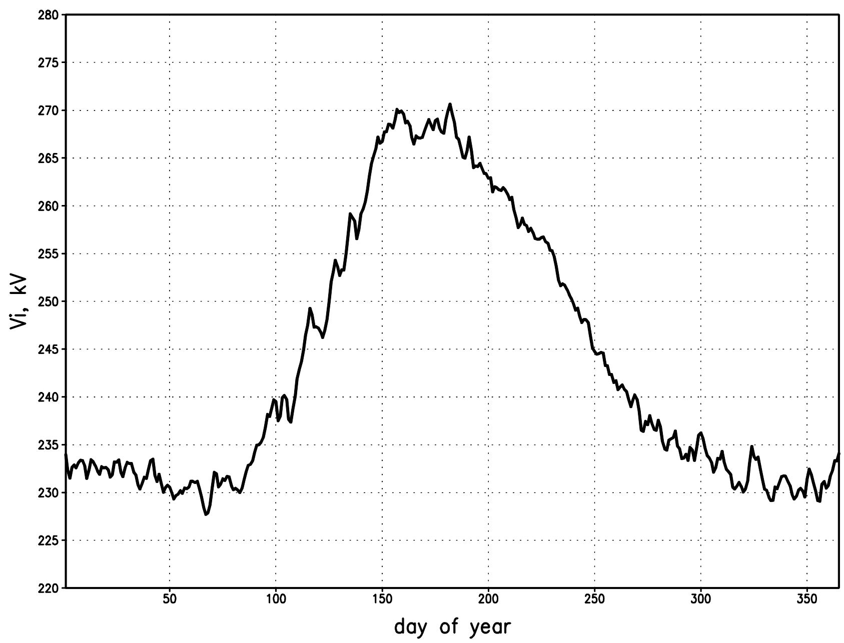

Fig.2. Annual V_i variation averaged over all the hours of 1986-2005.

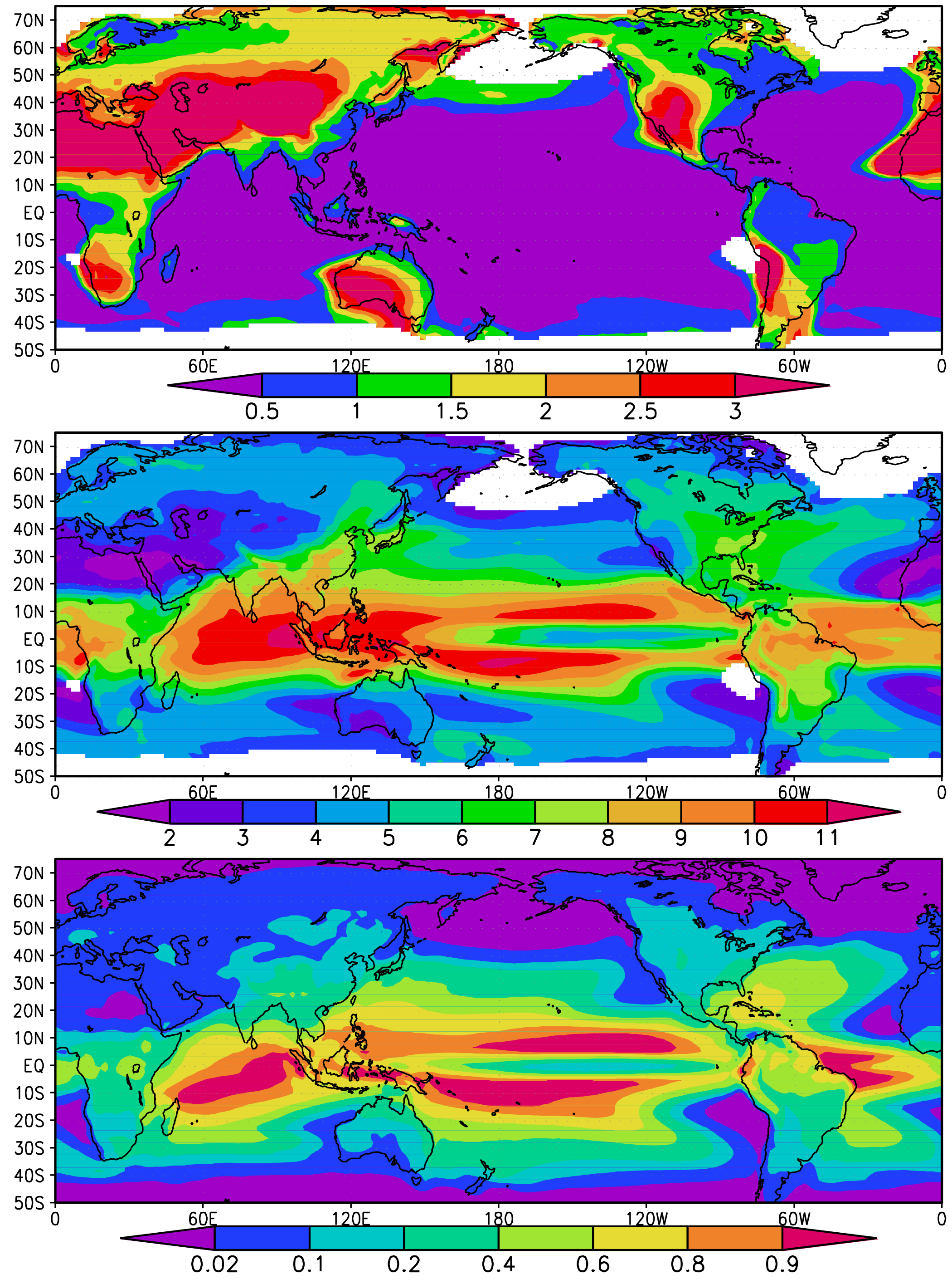

Fig.3. The mean annual values of the vertical scale Δz (top panel) and the cloud bottom z_b (middle panel). The distribution of convection events (measured as an event fraction among all the model steps N_c) over the globe (bottom panel).

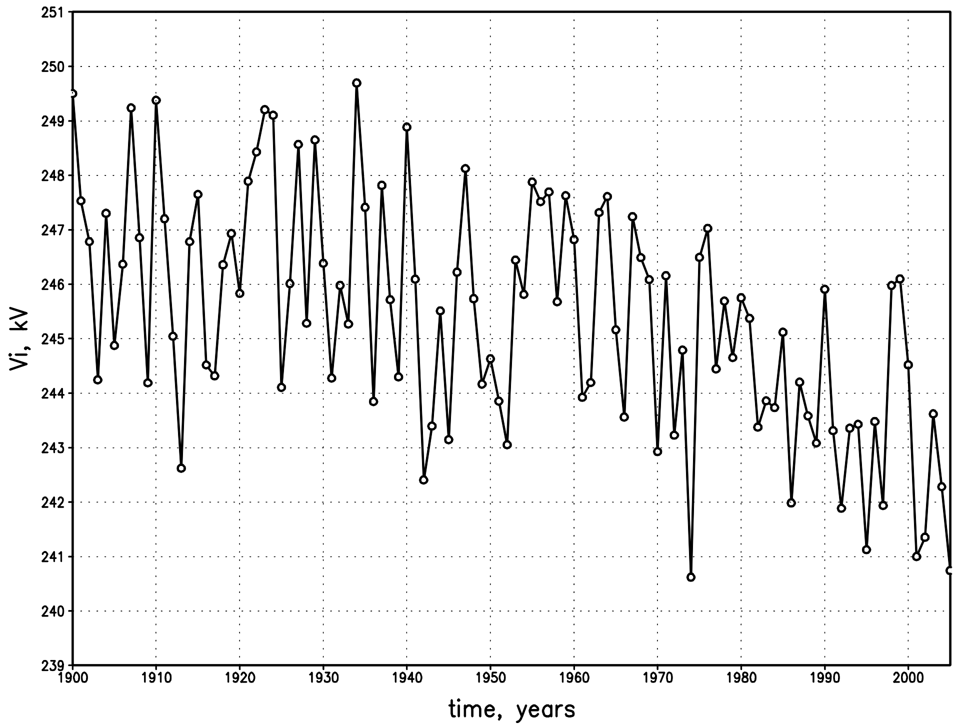

Fig.4. V_i mean-annual evolution in the model in the XX century.

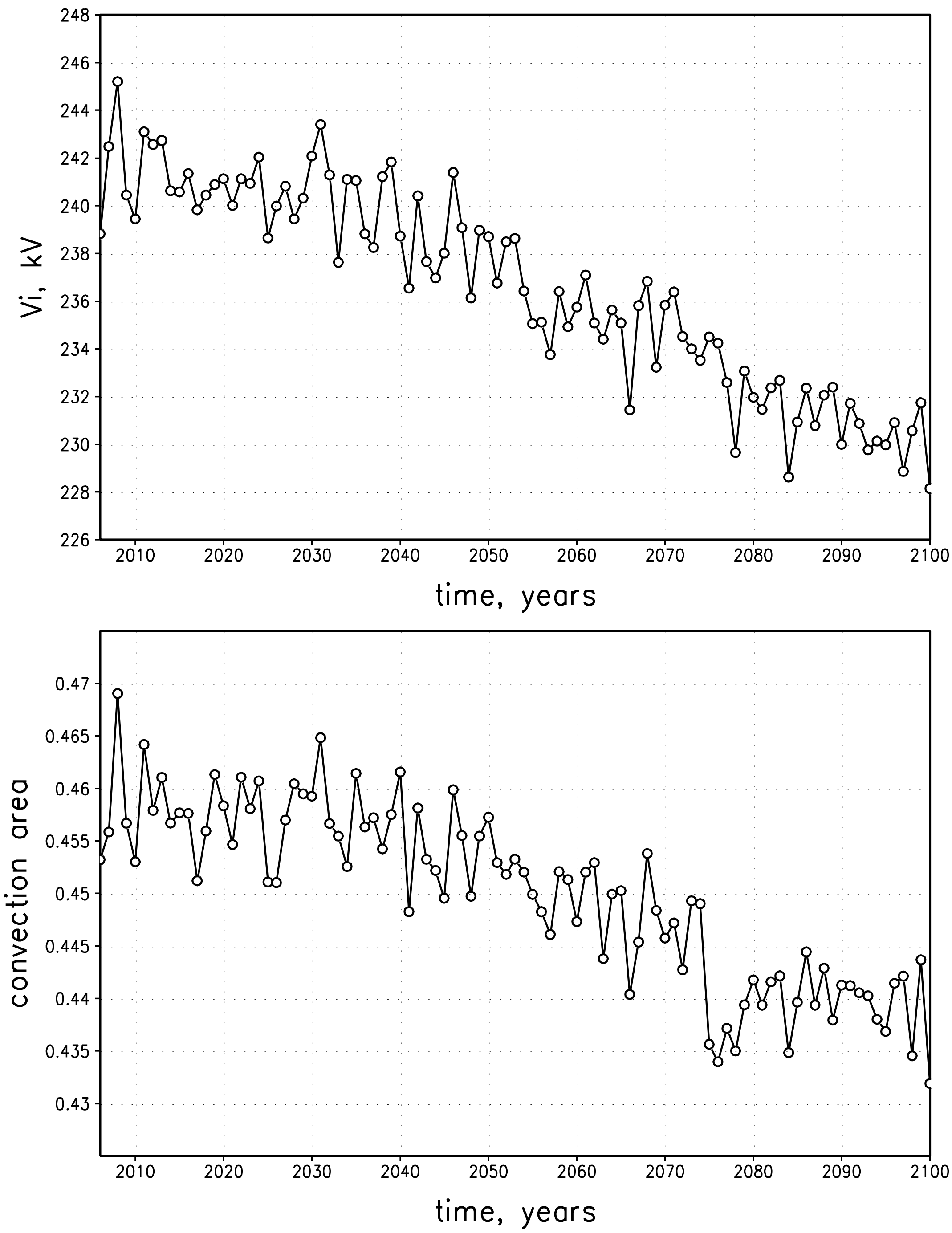

Fig.5. V_i mean-annual evolution in the model (top) and mean-annual square of convection (non-dimensional) calculated as the relation of convective precipitation over temporal step to the air-column moisture content (bottom).

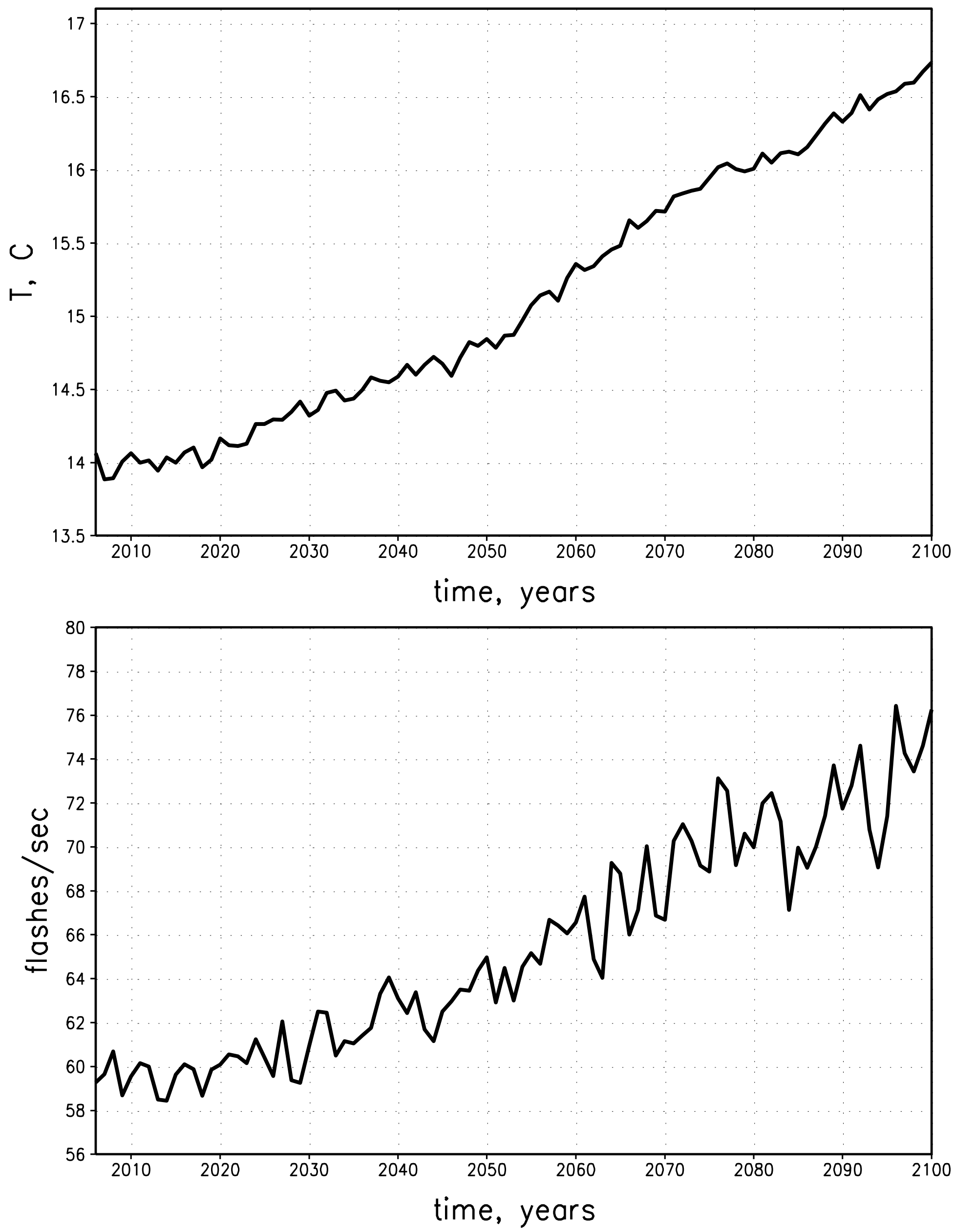

Fig.6. The growth of the temperature (top) and mean annual flash rate (bottom) in the XXI century.