Thunderstorm activity influence mechanism on lower ionosphere

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Abstract The influence of a charged cloud the electric field on chemical processes in the air at heights of 95-100 km has been studied. Numerical simulation of the plasma at these altitudes is performed, the concentrations of main charged particles are determined under the conditions of the electric field created by the unipolar charge of the cloud. It is shown that the electric fields of the clouds after the discharges of linear lightning affect the electron concentration at these altitudes.

1. Introduction

The study of electric fields influence on the ionosphere, in particular of thunderstorm clouds, is of considerable interest for global satellite positioning systems GPS/GLONASS. Since in normal geomagnetic conditions, the average electron concentration in the altitude layer 95 - 100 km of the order of $10^3 \text{cm}^{-3}$, then in this case the characteristic delay time of the signal is of the order of 100 ns, and the usual horizontal positioning error is several meters [1,2]. The situation drastically changes when the periods of increased activity of the Sun are formed and strong magnetic storms appear in the Earth's ionosphere. In these cases, the operation of satellite navigation systems is violated and leads to significant errors of the order of hundreds of meters, and sometimes the satellite signal disappears at all [3]. This is a fundamental scientific and technical problem, which has not been yet solved.

In recent years, mainly with a help of ballistic missiles it has been established that the strongest distortions of satellite signals occur in the ionospheric layer 80 - 110 km [4]. If the concentration of slow electrons at the upper 110-km boundary is of the order of $10^6 \text{cm}^{-3}$ [5], in the 90-100-km layer that we are examining, it corresponds to a value of the order of $10^5 \text{cm}^{-3}$, then the GPS/GLONASS satellite systems experience noticeable perturbations [6]. In this paper, an analysis is made of the increase in the electron concentration as the result of thunderstorm activity. This phenomenon has not been studied earlier.

Strong interest to influence of electric fields on the ionosphere is connected with creation of artificial perturbations of $D$-layer of the ionosphere by powerful short wave radiation such as transmitting complexes Sura and Poisk [7,8] and by investigations in the field of non-linear propagation of radio waves in the ionosphere [9].

Interest to ionization processes at high altitudes is caused by a possibility of ionization processes in the air under thunderstorm conditions when the appearance of atmospheric discharges such as sprites, and jets takes place. As follows from [7], it is the thunderstorm phenomena that lead to their realization.
The implementation mechanism is as follows. When a cloud strikes the lightning on the ground, the charges of the same sign are leaking, while the charges of the other sign remain on the cloud. The magnitude of charges on the cloud reaches 5 C, which create an electric field above the cloud. This electric field falls off slowly with altitude, and the density of neutrals exponentially fast, so at heights of 70-100 km the conditions necessary for the implementation of sprites are realized. It was shown in [8] that simultaneously with the realization of the conditions for the appearance of streamer discharges, avalanche ionization occurs, leading to a significant increase in the electron concentration of the electron and gas temperatures, which depends on the magnitude of the external electric field that can be realized by the experimental devices, clouds, and mesospheric processes.

When lightning fronts move at altitudes of 2-10 km in the mesosphere at altitudes of 90-100 km, conditions can be created for the formation of a front of ionized air with a width of ~ 1%, larger than the width of the cloud front at the Earth. In this case, the lifetime of such an ionized region will be equal to the time of neutralization of the cloud by tropospheric ions, which can reach hundreds of seconds.

The purpose of this work is: to determine the possible electron concentration of the plasma on the basis of plasma chemical kinetics studying at altitudes of 90-100 km in a thunderstorm field.

2. Formation of the charged region in the lower ionosphere

For analysis, we use a well-known expression for the dependence of the quasi-stationary electric field over the height [10] \( h \)

\[
E = \frac{zQ}{\pi \varepsilon_0 h^3} \left[ 1 + \left( \frac{h_1}{2h_i-h} \right)^3 \right],
\]

(1)

here \( E \) is the value of the electric field at the required altitude, \( h_i \) is the height of the ionosphere, which is assumed to be an ideal conductor (in the calculations \( h_i = 120 \) km), \( z \) is the height of the charge \( Q \) over an ideally conducting surface (5 km, \( z \ll h \)). This formula describes the electric field strength over a charged cloud, taking into account the polarization effect in the ionosphere.

Estimates obtained on the basis of (1) give the following electric field value of 1.1 V/m at the altitude of 95 km and 0.9 V/m at the altitude of 100 km for a charge of the cloud equal to 5 C located at the altitude of 5 km. With this respect, the problem is similar to those considered in [7]. Consequently, the presence of charges on the clouds which can occupy several tens km areas [11] and the maximal charge areas, according to figure 3.4 from [11] can be of several km, lead to a sharp increase in the electron concentration. In the case of the cloud system, when the electric field strengths of individual clouds add up in the mesosphere the effective charge effect can be much greater at the mesoscale level.

To study the chemical kinetics of plasma in air at altitudes of 90-100 km, as in our works [8-10], as the starting point in the analysis of the dry chemical plasma-chemistry, we chose a system of chemical reactions corresponding to the works [12-16]. This model includes 26 components (neutral, positive and negative ions, electrons and excited particles) and more than 180 plasma-chemical reactions with their participation. In this case, the electron energy distribution function was considered to correspond to a glow discharge in air, the rate constants of electron-molecular reactions were calculated on the basis of the Boltzmann equation with cross sections from [17]. The rates of excitation, dissociation, and ionization of molecules by fast particles are taken from [18].

Along with the balance equations for atomic particles, an equation for the temperature of electrons and gas was solved. In the equation for the electron temperature we took into account: rotational and elastic excitation of molecules, the effects of electron heating in the recombination of electrons and ions [15], the cooling of electrons during the triple attachment of an electron to an oxygen molecule; ionization and excitation of molecules in collisions of electrons with air-molecules. Heating of electrons in the external electric field of the cloud was taken into account. We also considered heating of electrons during the injection of fast electrons of the background into the region below the vibrational excitation threshold [14,19] as it is usually applied in problems connected with degradation of energy of fast particles. In the equation for electron temperature we accounted cooling of electrons in elastic and inelastic collisions with \( O_2 \) and \( N_2 \) molecules.
In the equation for the gas temperature $T$ we included terms corresponding to heating as a result of the relaxation of the vibrational and electronic degrees of freedom of molecules, heating and cooling of the gas in chemical and plasma-chemical reactions (heating by electrons in collisions is Joule heating). Reactions involving positive ions $O^+, O_2^+, O_3^+$, $O_6^+$, $O_8^+$, $N^+, NO^+, N2^+$, negative ions $O^-, O_2^-, O_3^-$, atoms $N, O$, and molecules $O_2, O_3, N_2, N_2O, NO$ were taken into account in the simulation.

Excited vibrational states of nitrogen $N_2$ ($\nu$), excited electronic states of nitrogen $N_2^+$ ($b$), $N_2^-$ ($z$), excited vibrational states of oxygen $O_2$ ($\nu$), excited electronic states of oxygen $O_2^+ (^1\Delta_g)$ were also accounted. The recombination reactions of each positive ion with each negative ion are taken into account. The data on these processes were determined on the basis of the Flannery approach [15], taking into account the gas temperature and pressure. In the calculations, it was assumed that de-excitation of vibrational and rotational states occurs mainly in collisions with molecules. The model also takes into account the processes of charge exchange of ions [20]. The data on excitation and ionization of the background in the ionosphere was taken from [21], where we used the total excitation and ionization rates at the considered altitude. The power $W$ inputted into the gas by the fast particles of the background is usually determined by us in units of eV/(cm$^3$sec), and the excitation rate of the molecules $Q$ is connected with it by the relation [14,18] $Q = W/U_i$, where $U_i$ is the ionization cost, in particular in the air, $U_i = 31.6$ eV.

In the analysis, the background values of the components were calculated first for a complete set of components at given values of the excitation and ionization costs as functions of the altitude and the temperature, taken from [21, 22].

They served as initial values for calculating the kinetics of charged, neutral, and excited particles in the plasma. This corresponded to the model establishment of plasma-chemical equilibrium at a given altitude at a given pressure and temperature.

The plasma in the calculations is represented as an ideal gas with an adiabatic exponent of 1.4, which restricts the applicability of the model only to the case of a weakly ionized gas, when the concentrations of charged particles are much smaller than the concentration of diatomic components of the air.

In this study and other ones on a similar subject, we use a model described by the ODE system of plasma chemical kinetics, taking into account the energy equations of gas and electrons. The model makes it possible to find the time dependences for the concentrations of the components of a weakly ionized plasma and temperatures. In the context of the purposes of the simulation, it is not necessary to consider more complex models that take into account the motion of the plasma and the dependence of the concentrations on the spatial coordinates, since we are interested in the most common fundamental aspects - the composition of the plasma, its concentration, the influence of external factors such as electric field, effect of fast particle fluxes and others. Spatial distributions are significant in more specific applied problems of plasma interaction with bodies, as well as in the application of developed fundamental concepts and methods for analyzing thermal inhomogeneities arising in the ionosphere. In addition, the spatial-temporal modeling, taking into account the fairly complete plasma chemical description used by us, including dozens of components and hundreds of reactions, requires a dramatic increase in computational resources and a fundamental development of the computational methods used.

From the point of view of taking into account the motion, the model includes two approximations: the approximation of constant density and the approach of constant pressure. In the first case, the gas does not have time to move in the volume under consideration during the times under consideration, in the second case times are so large (or linear dimensions are so small) that the gas pressure is equalized by the gas dynamic motion. When considering processes in a gas, motion can occur as a result of change in pressure during heating or cooling. Thus, in the absence of heating or cooling, these models are equivalent. As can be seen from the results of numerical simulation presented below, the processes of plasma modification that we are interested in under the influence of an electric field occur at a very slightly varying gas temperature, and therefore they are adequately described in any of the two indicated approximations. The thermal instability observed at the final stage, accompanied by strong heating and
an increase in the degree of ionization, is described qualitatively within the framework of the model, and it should be noted here that calculations in the constant-pressure approximation yield qualitatively the same results. A more accurate simulation of the stage of thermal instability and subsequent processes goes beyond the scope of this paper and requires both the development of a description of plasma chemical reactions at relatively high temperatures and the development of the model in the direction of non-fulfillment of weak ionization approximations and a slight change in the partial composition of the gas as a whole.

3. Calculation results
The calculations were performed over a wide range of excitation rates by the external electric fields. The data from [17, 18] and presented in the Table were chosen as the basis. The values of $E = 1.0, 1.5$ and $2.0 \text{ V/m}$ obtained by formula (1) at heights of 95 and 100 km were taken as the background electric field. The following notation is used in the figures below: $e$ - electron concentration, $O^+ - O_2^+$, $O_2^- - O_2^+$, $N - O_2^+$, $NO - NO^+$, $N_2O - N_2O^+$, $O^+ - O_2^+$, $N_2 - N_2^+$, $O - O_2^+$, $N_2O - N_2O^+$, $O^+ - O_2^+$, $O_2^+ - O_2^+$, $O_3^+ - O_3^+$, $O_4^+ - O_4^+$, $O_6^+ - O_6^+$, $O_8^+ - O_8^+$, $N_2 - N_2^+$, $N_2O - N_2O^+$, $N_2O - N_2O^+$, $N_2 - N_2^+$, $N_2O - N_2O^+$, $O^+ - O_2^+$, $O_2^+ - O_2^+$, $O_3^+ - O_3^+$, $O_4^+ - O_4^+$, $O_6^+ - O_6^+$, $O_8^+ - O_8^+$, $N_2 - N_2^+$, $N_2O - N_2O^+$, $N_2O - N_2O^+$, $O^+ - O_2^+$, $O_2^+ - O_2^+$, $O_3^+ - O_3^+$, $O_4^+ - O_4^+$, $O_6^+ - O_6^+$, $O_8^+ - O_8^+$, $N_2 - N_2^+$, $N_2O - N_2O^+$, $N_2O - N_2O^+$, $O^+ - O_2^+$, $O_2^+ - O_2^+$, $O_3^+ - O_3^+$, $O_4^+ - O_4^+$, $O_6^+ - O_6^+$, $O_8^+ - O_8^+$, $N_2 - N_2^+$, $N_2O - N_2O^+$, $N_2O - N_2O^+$, $O^+ - O_2^+$, $O_2^+ - O_2^+$, $O_3^+ - O_3^+$, $O_4^+ - O_4^+$, $O_6^+ - O_6^+$, $O_8^+ - O_8^+$, $N_2 - N_2^+$, $N_2O - N_2O^+$, $N_2O - N_2O^+$, $O^+ - O_2^+$, $O_2^+ - O_2^+$, $O_3^+ - O_3^+$, $O_4^+ - O_4^+$, $O_6^+ - O_6^+$, $O_8^+ - O_8^+$, $N_2 - N_2^+$, $N_2O - N_2O^+$, $N_2O - N_2O^+$, $O^+ - O_2^+$, $O_2^+ - O_2^+$, $O_3^+ - O_3^+$, $O_4^+ - O_4^+$, $O_6^+ - O_6^+$, $O_8^+ - O_8^+$, $N_2 - N_2^+$, $N_2O - N_2O^+$, $N_2O - N_2O^+$, $O^+ - O_2^+$, $O_2^+ - O_2^+$, $O_3^+ - O_3^+$, $O_4^+ - O_4^+$, $O_6^+ - O_6^+$, $O_8^+ - O_8^+$, $N_2 - N_2^+$, $N_2O - N_2O^+$, $N_2O - N_2O^+$, $O^+ - O_2^+$, $O_2^+ - O_2^+$, $O_3^+ - O_3^+$, $O_4^+ - O_4^+$, $O_6^+ - O_6^+$, $O_8^+ - O_8^+$, $N_2 - N_2^+$, $N_2O - N_2O^+$, $N_2O - N_2O^+$.

| h, km | $N_e$, cm$^{-3}$ | $T_{gas}$, K | $N_e$, cm$^{-3}$, December | $Q$, (cm$^3$s)$^{-1}$ |
|-------|-----------------|-------------|---------------------------|-----------------|
| 95    | 2.93 $10^{13}$  | 188         | 2 $10^4$                 | 100             |
| 100   | 1.93 $10^{13}$  | 195         | 5 $10^4$                 | 5.0 $10^2$       |

Figures 1a-c show the plasma component concentrations at the altitude of 95 km. Figure 2 shows the plasma component concentrations at the altitude of 100 km. Symbols $T$ correspond to gas temperature, which rises at the stage of thermal instability taking place under long influence of electric field.

Figure 1a Main charged particles in air at the altitude of 95 km at the external electric field of 1.0 V/cm, initial $E/N = 3.14 \cdot 10^{-14}$ V·cm$^2$ (symbols $T$ correspond to $\log(T,K)$).

An investigation in such a wide range of gas excitation by the external electric field was caused by the need to elucidate the behavior of the main components excited by the external source. In this case, we present data over a wide range of excitation times. Therefore, the results obtained are also useful in analyzing the effect of not only charged clouds, but also artificial sources of the electric field.

It can be seen from the calculations that even under the conditions of excitation with one cloud charge at the altitude of 95 km, the electron concentration increases by a factor of 1.5-2 in the time $10^2-10^3$ seconds. At long times, the input of energy by a discharge leads to the heating of the gas and the
development of thermal instability accompanied by a sharp increase in the electron concentration. With an increase in the electric field by a factor of 1.5, the electron concentration increases in 10^2 seconds by an order of magnitude with respect to the background concentration of 10^4 cm^{-3} and reaches the value of 2.5⋅10^5 cm^{-3} during the next 10^2 seconds. With an increase in the electric field up to 2.0 V/m, the electron concentration rises to 10^5 cm^{-3} during 6 seconds, it is followed by a rapid increase in the electron concentration accompanied by the gas heating.

As the field increases, along with the positive NO^+ ion, the role of the O_2^+ ion becomes significant. Also, at a maximum field of 2 V/cm considered, the role of the negative O^- ion becomes significant at times greater than 0.1 s.

**Figure 1b.** Main charged particles in air at the altitude of 95 km at the external electric field of 1.5 V/cm, initial \( E/N = 4.7 \cdot 10^{-14} \text{ V cm}^2 \), (symbols \( T \) corresponds to \( \lg(T, K) \)).

**Figure 1c.** Main charged particles in air at the altitude of 95 km at the external electric field of 2.0 V/cm, initial \( E/N = 6.3 \cdot 10^{-14} \text{ V cm}^2 \) (symbols \( T \) correspond to \( \lg(T, K) \)).
**Figure 2a** Main charged particles in air at the altitude of 100 km at the external electric field of 1.0 V/cm, initial $E/N = 4.8 \cdot 10^{-14}$ V·cm$^2$ (symbols $T$ corresponds to lg (T,K)).

**Figure 2b** Main charged particles in air at the altitude of 100 km at the external electric field of 1.5 V/cm, initial $E/N = 7.1 \cdot 10^{-14}$ V·cm$^2$ (symbols $T$ corresponds to lg (T,K)).

**Figure 2c** Main charged particles in air at the altitude of 100 km at the external electric field of 2.0 V/cm, initial $E/N = 9.6 \cdot 10^{-14}$ V·cm$^2$ (symbols $T$ corresponds to lg (T,K)).
Calculations for 100 km show that even at \( E = 1.0 \) V/m, the electron concentration reaches \( 10^5 \text{cm}^3 \) during the time of \( 10^2 \) seconds, and during \( 1.5 \cdot 10^3 \) seconds the plasma transits into a thermal instability regime with avalanche growth of the electron concentration. At \( E = 1.5 \) V/m, the electron concentration increases to \( 10^6 \text{cm}^3 \) in 6 seconds. At long times from 10 to 100 seconds, the input of energy by a discharge leads to the heating of the gas and the development of thermal instability accompanied by a sharp increase in the electron density to. With an increase in the electric field to \( E = 2 \) V/m, the electron concentration increases to \( 10^6 \text{cm}^3 \) in 1.5 seconds and reaches the value of \( 3.0 \cdot 10^7 \text{cm}^3 \) during the next 6 seconds.

The ion composition changes with an increase of the electric field (within 100 seconds) from the main \( NO^+ \) ions to the mixture of \( O_2^+ \) and \( NO^+ \) ions, at that the negative ion \( O^- \) begins to play an important role in the balance of particles at this altitude. Under the influence of fields of 1.5 V/cm and 2 V/cm, the plasma becomes electronegative in the intermediate stage of plasma formation, at times from 0.1 s. up to 10 s.

Considering the general features of the ionization process under the influence of an electric field at altitudes of 95-100 km, we should note a significant increase in the concentration of charged particles for a relatively long time, taking place without heating the gas. Heating occurs later, with the development of thermal instability. The description of this stage within the framework of the model is of a qualitative nature and is of interest to us only in terms of fixing the transition of the cold plasma to a heated state with an increased degree of ionization occurring at sufficiently large fields.

It should be noted that after rapid heating of the plasma under the influence of thermal instability, one observes a substantial dissociation of oxygen and nitrogen molecules. However, at the growth times of the electron concentration, the concentrations of the atoms remain smaller than the concentrations of the \( O_2 \) and \( N_2 \) molecules, so we can assume that the parameters of the model (the adiabatic exponent) do not change in the calculations.

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**Conclusion**

Based on the plasma-chemical model, the composition of air plasma at heights of 95-100 km in a wide range of air excitation by the electric field of clouds or some other external sources of the electric field was analyzed. It showed that in the stationary conditions at fields \( E = 1.5 \sim 2 \) V/m comparable and somewhat larger than the electric fields created by individual clouds, sharp ionization can occur. With the formation of electrons with a concentration of up to \( 10^5 \text{cm}^3 \) and above, which can affect the functioning of electronic instruments at mesospheric heights. This effect will be manifested much greater at passing of thunderstorm fronts above the ground, when a separate effect of clouds merge into the total effect of the front. The same impact can also have artificial sources of a strong field, the actions of which have also to be taken into account.

The increase in the electron concentration by two orders of magnitude as a result of thunderstorm activity calculated in this paper should lead to rather strong distortions in the operation of satellite positioning systems. Since previously, this phenomenon has not been systematically studied it requires further research.

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