A self-consistent model of sprite influence on the chemical balance of mesosphere

A. Evtushenko, F. Kuterin, E. Mareev

IAP RAS, Ul'yanova 46, 603950, Nizhny Novgorod, Russia

We develop a plasma-chemical model which describes the dynamics of perturbations of chemical composition of the mesosphere and self-consistent electric field between the altitudes 60 and 90 km due to sprite generation. Model simulations take into account sharp increase in the electron temperature and electric field, which lasts from tens of microseconds to milliseconds, and self-consistent electric field modification in the mesosphere. The perturbed concentrations of electrons, neutrals, ions, cluster ions, excited atoms and molecules have been estimated for typical flash parameters as dependent on the altitude. We have paid special attention to the dynamics of the normalized electric field, depending on the altitude and time.

The conditions for the discharge in the mesosphere (at the altitudes of 70-75 km) are usually realized after the positive cloud-to-ground discharge, leading to the formation of an uncompensated negative charge in the cloud, often during the continuing current stage. We have assumed that the Earth's surface is an ideal conductor, so that the electric field of this negative charge could be represented in the dipole approximation at the mesosphere altitudes. The electric field which is necessary for breakdown of the atmosphere depends on the gas pressure, i.e. decreases exponentially with height. At a certain height the electric field begins to dominate over the breakdown field, leading to the initiation of a sprite. Then the uncompensated charge in the cloud is growing, and the electric field is increasing too. However, the development of the sprite changes sharply the ion composition of mesosphere and conductivity. At the altitudes of sprite development the electric field begins to relax.

We use a system of 267 chemical reactions and 58 components for numerical modeling of the chemical composition of mesosphere [1]. The eectric field is determined as a solution of the differential equation $\frac{\partial E}{\partial t}+\frac{\sigma E}{\varepsilon_0}=\frac{\partial E_{ext}}{\partial t}$, where the external electric field E_{ext} decreases due to the conductivity of mesosphere σ [2]. E_{ext} is the electric field in dipole approximation which is generated by current flowing in the lightning channel $I(t)=I_0\cdot\frac{(t/\tau_1)^2\cdot e^{-t/\tau_2}}{1+(t/\tau_1)^2}$, where $I_0=250kA$, the transferred electric charge is 100Q. The parameters τ1=70 μs and τ2=500 μs are the characteristic relaxation times. The conductivity is determined by the expression $\sigma=\frac{e^2N_e}{m_e\nu_e(T_e)}$, where the frequency of electron attachment depends on the electron temperature and the density of neutrals as $\nu_e(T_e)=1.84\cdot10^9\cdot(N_m/10^{17})\cdot(T_e/1000)^{5/6}$. We that in excess of the critical field, the electron temperature is proportional to the electric field: $T_e/T=(E/E_p)^{3/4}$.

Results

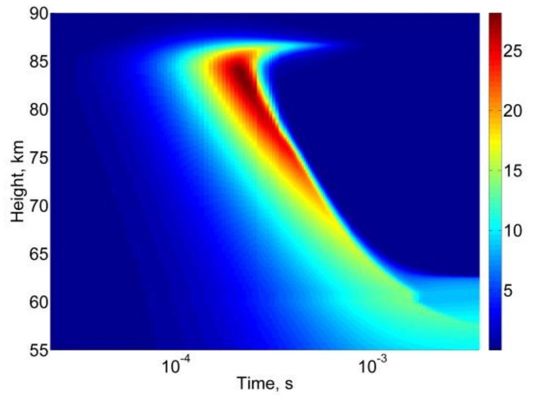

Fig.1. Perturbation of electric field normalized to the concentration of neutrals with a factor of 10^{16}

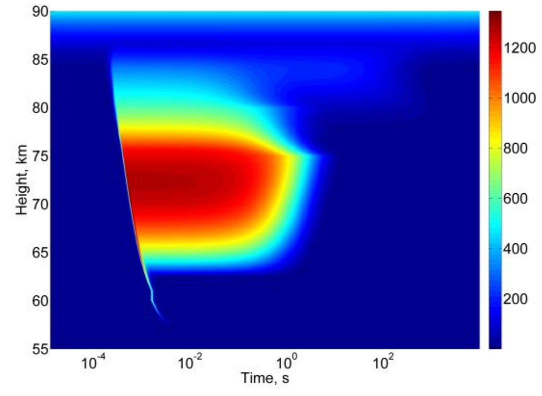

Fig.2. Perturbation of electrons concentration, cm^{-3}

Fig.1 shows the development of θ depending on the altitude. It is seen that the discharge does not begin immediately after the start of the electric current in the troposphere. Indeed, only after 200 μs the parameter θ at an altitude of 84 km reaches the breakdown value when the rate of electrons ionization exceeds their attachment rate. In the altitude range from 78 to 85 km θ reaches its maximum value 26 V·cm^2. Above 86 km the sprite does not ignite because of the sharp growth of conductivity with height. It is seen that after the parameter θ reaches great enough values (more than 20), there is a sharp decrease due to increase of conductivity in this region. The threshold field is moving down to a height of about 65 km with some time delay. This picture corresponds in general to the features of the optical images of sprites obtained in the experiments with high-speed cameras.

For the heights from 67 to 78 the maximum value of θ changes from 18 to 25 (i.e. less than the maximum value, corresponding to the upper altitudes), but the maximum observed perturbation of the electron density is just at these altitudes (Fig.2). This is due to the fact that the concentration of neutrals is significantly higher in this region and more molecules are able to be ionized during the perturbation of an external field.

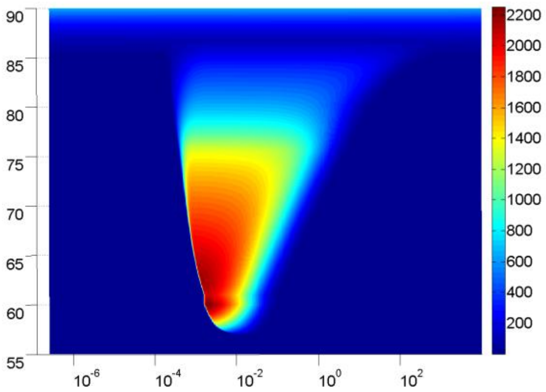

Fig.3. Perturbation of O_2^+ concentration, cm^{-3}

The dynamics of ions O_2^+, $H_5O_2^+$ are shown in Fig.3 and Fig.4. Ion O_2^+ reaches maximum values during the sprite discharge. The main source of density perturbations of O_2^+ is the reaction of ionization of oxygen molecules in the electric field. Reducing the concentration of O_2^+ is associated with recombination and conversion through a series of chemical reactions to the cluster-ions. The relaxation at the bottom of the sprite is much faster than at the top, while the disturbance is less at the top.

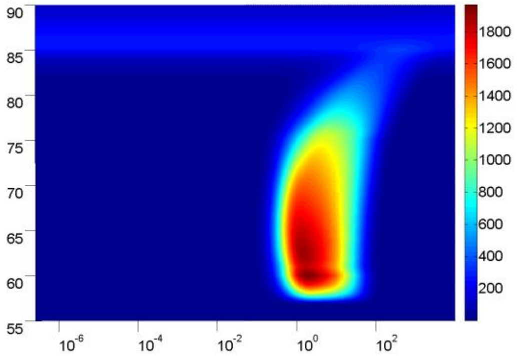

Fig.4. Perturbation of $H_5O_2^+$ concentration, cm^{-3}

$H_5O_2^+$ is one of the most important cluster ions at the heights of the sprite. It reaches maximum values practically at the same time at altitudes from 58 to 73 kilometers Fig.4. Its relaxation time is large so that during the series of sprites the perturbation of $H_5O_2^+$ can be accumulated.

We have investigated a self-consistent set of equations for electric field, conductivity, concentration of chemical components and parameters of cloud-to-ground lightning discharge in a 1D approach. Further development of our model will include diffusion and full three-dimensional consideration. We are also planning to use our model to describe other types of high-altitude discharges (elves, jets) in the atmosphere.

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References

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