Thunderstorms as Interactive Component of Global Ecodynamics

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***Abstract* — An analysis of thunderstorms is realized to understand the interrelation between different atmospheric processes and to assess the tendencies in generation of the atmospherics. In the paper an analytical description of natural atmosphere-electric discharges is given which can be used in modeling of these atmospheric phenomena.**

***Index Terms* — Global ecodynamics, natural disasters, monitoring systems, ecology, atmospheric chemistry**

I. INTRODUCTION

Thunderstorms are one of dangerous natural phenomenon that yields numerous disasters both natural and human character. It is known that the ratio of lightning strikes over land and oceans constitutes 100:1, which leads on the land to forests frequently catching fire. On the average, the density of lightning strikes, for instance, in tropical forests and moderate-zone forests constitutes, respectively, 50 and 5 strikes per km^2 per year. There are four main types of thunderstorms: single cell, multi-cell, squall line (also called multi-cell line) and super-cell. Each year, many people are killed or seriously injured by thunderstorms despite the advance warning. Therefore, study and understanding of the thunderstorm role in the environment is important problem.

II. THUNDERSTORMS AND ATMOSPHERIC CHEMISTRY

The level of understanding the photochemical processes in the troposphere that affect its composition depends substantially on adequacy of ideas about the budget and distribution of nitrogen oxides NO_x ($NO+NO_2$). Due to reactions of the catalytic cycle with the participation of peroxides radicals, NO_x play the decisive role in the processes of tropospheric ozone formation and affect the cycle of HO_x ($OH+HO_2$). One of the most important unclear aspects of the problem under discussion is insufficient reliability of data on the contribution of lightning strikes to the global budget of NO_x. According to the earlier estimates, this contribution varied within 2 to 20 Tg N $year^{-1}$, with most probable values of about 2-6 Tg N $year^{-1}$ (Kondratyev, 2005).

Crawford et al. (2000) carried out an analysis of results of aircraft measurements within the programme of the field experiment SONEX on studies of ozone and nitrogen oxides in the troposphere. Results of the analysis revealed the presence in the upper troposphere of episodes of NO_x concentration increase determined, apparently, by the impact of lightning strokes. The correlation with specific periods of lightning activity could be found out from analysis of "reverse" trajectories of the motion of air masses as well as from the data of observations at the national network of lightning record. The Lagrangian numerical modeling of "reverse" trajectories has been carried out to trace the evolution of NO_x plumes during a 1-2-day interval between their occurrence and obtaining of aircraft measurement data. Calculations were made for pre-calculation of expected changes of concentrations of HNO_3, H_2O_2, CH3COOH, HO_2, and OH. Depending on conditions, the initial concentration of NO_x varied within 1 to 7 ppb. Since the calculated estimates of HNO_3 concentration turned out to be overestimated compared to those observed, the reasons of such differences were analyzed, and it was shown that the observed values of H_2O_2 concentration agree with the supposed removal of H_2O_2 from the atmosphere due to convection. Although it is possible that in the upper troposphere the concentration of CH_3COOH grows due to convection, the numerical modeling has led to the conclusion that this increase can be only of short duration (less than 2 hours), which excludes the possibility to detect this component during aircraft measurement. The possibility of CH_3COOH concentration increase is excluded, too in view of a high level of NO concentration.

Reaction between NO and HO_2 in all the cases considered favors a decrease of HO_2 concentration. In some cases the calculated values of OH concentration doubled, but at a maximum level of NO_x concentration the loss of hydroxyl due to the reaction $OH+NO_2$ compensates the formation of hydroxyl due to reactions NO_2+NO. An additional increase of OH by 30-60% can, however, result from convective transfer of CH_3COOH.

To estimate the contribution of lightning and anthropogenic sources to the formation of NOx concentration on global scales, Kurz *et al.* (2002) undertook a numerical modeling of the frequency and global distribution of lightning strokes and the resulting formation of NO_x using the complex model of climate and chemical processes taking place in the atmosphere ECHAM4.L39(DRL)/CHEM(E39/C) whose important feature is a realistic simulation of processes responsible for the formation of penetrating convection.

Calculated estimates of the height of convective clouds, on the whole, agree well with those observed. But in mid-latitudes of Western Europe the calculated values were underestimated. The calculated spatial distribution of lightning strokes agrees well with the observed distribution, though the calculated ratio of the density of strokes over land and over the oceans turned out to be underestimated. In mid-latitudes of Western Europe the density of strokes is underestimated compared to that observed, which can be explained by inadequate scheme of convection parameterization.

According to numerical modeling results, the NO_x formation is most intensive in the tropics and in mid-latitudes, and is clearly separated (in space) from NO_x emissions due to aviation. The lightning-induced maximum level of NO_x emissions is located at altitudes approximately 5 km below the level of the tropopause, with the level of emissions exceeding 3 times the respective anthropogenic level. Besides, it is important that maximum aircraft emissions of NO_x tend to be at much higher altitudes and farther north (being concentrated mainly within the North-Atlantic corridor 30-60°N at a level of about 200 hPa, that is, 12 km) compared to NO_x formed due to lightning strokes.

Zhang *et al.* (2003a) analyzed possibilities of the numerical modeling of nitrogen oxides formed due to lightning strokes using the 2D version of the model that simulates an electrization of the storm. It is supposed that the formation of NO is determined by dissipation of energy whose value is calculated from the value of the electric field before and after a lightning stroke. The rate of formation of energy responsible for NO formation is $9.2{\cdot}10^{16}$ molecules J^{-1}. Considering a limited set of chemical reactions in which NO, NO_2, and O_3 participate, a numerical modeling has been carried out of processes taking place in a small storm with 10 intra-cloud strokes during 2 minutes. The level of dissipation of energy varied between 0.024 and 0.28 GJ. After cessation of lightning strokes the integration continued during 18 minutes more. Analysis of the modeling results has shown that the mixing ratio of NO formed within a cloud (by order of magnitude) is 10 ppb after most powerful strokes and 1-2 ppb on the windward side of the thundercloud anvil at the end of the integration interval. These estimates agree with the data of observations. A comparison with results of the earlier numerical modeling with the use of different 2D model revealed, on the whole, an agreement of estimates, but the results discussed are characterized by greater volumes of energy at high altitudes, which can partially result from a longer integration time and lacking of consideration of the strokes onto the Earth in the model in question, as well as from some assumptions made earlier. On the whole, the numerical modeling of lightning formation carried out recently and their impact on NO formation should be considered more adequate than in previous studies. The necessity of further improvement of the model has determined the development of a new 3D model of the processes of formation of electric charges in thunderclouds with a more complete than earlier consideration of chemical processes of nitrogen oxides formation under the influence of lightning strokes (Zhang *et al*., 2003b).

A totality of considered GHGs includes in this case NO, NO_2, O_3, CO, CH_4, OH, and HNO_3. The numerical modeling has been carried out for concrete conditions of thunderclouds (storm) observed on 19 July 1981 with 18 intra-cloud strokes during 3 minutes. The numerical modeling has been carried out for a period of 38 minutes, before the thundercloud dissipated. The level of energy dissipated at lightning strokes varied within 0.91 to 2.28 GJ. The maximum level of the NO_x mixing ratio due to lightning strokes reached 35.8 ppb. At the cloud's dissipation, after cessation of lightning strokes, maximum concentrations of NO and NO_2 (in both cases) constituted about 6.3 ppb and were observed at an altitude of about 4 km. The NO mixing ratio in an anvil reached a maximum of about 2 ppb at an altitude of about 10.5 km. These results agree well with observational data.

Quite surprising was the formation of the NO_2 plume at a concentration of about 0.5 ppb, which reached the surface. In the case of NO there was no plume. On the other hand, NO was transported from the cloud's centre to the anvil absent in the case of NO_2, which was determined, probably, by the impact of photolysis. The ratio of concentrations NO_2 / NO decreased with altitude in accordance with observational data. The formation of NO calculated per unit length averaged $2.03{\cdot}10^{22}$ molecules m^{-1}. The results obtained show that the short-lived storms determine the formation of the vertical profile of NO_x concentration that differs from the earlier observed C-shape profile.

Mansell *et al.* (2002) carried out a numerical modeling of lightning strokes with the use of a stochastic model of dielectric break and parameterization of electrification mechanisms. This model enables one to simulate a 2D development of a stroke as a stochastic "step-by-step" process. The stroke channels propagate over a homogeneous spatial grid, and the direction of propagation (including diagonals) for each step is considered random with probability of the choice of a certain direction depending on the total electric field. After each step the electric fields are calculated anew with the use of the Poisson equation in order to take into account the impact of the channel's conductivity. The applied parameterization of the process of lightning strokes formation provides a realistic 3D simulation of ramified strokes. The model is able to simulate the formation of different kinds of lightning strokes, including intra-cloud strokes, negative and positive strokes "cloud-ground" (CG).

According to numerical modeling results, the hypothesis that negative strokes appear only when the region of the positive stroke is located beneath the centre of the negative stroke can be considered substantiated. The calculated positive CG strokes were observed only in the parts of the thundercloud where two charged layers located near the Earth had an approximately similar "normal dipole" structure (i.e., positive charges were above negative ones).

Brown *et al.* (2002) studied relationships between CG lightning strokes and stages of the vertical motions development in the region of thunder centre taking as an example the data of observations of a multi-cell thunder centre formed on 11 July 1989 in the region of the city of Elgin (North Dakota). Radar observations of reflectance and vertical velocity enabled one to identify some cells within the thunder centre and trace the evolution of each cell. The evolution process took place in accordance with the model of thunder centre developed in the late 1940s and in the following succession:

- maturing of upward motions and increase of the cells vertical extent at the stage of cumulus clouds development;
- maximum development of vertical motions in the upper part of a cell and downward fluxes with rains from the

middle part of the cell;

- light rains at the stage of the cell's dissipation.

On 11 July there was observed a trend of formation of the cells' clusters, each cluster consisting of both growing (at the stage of maturing) and disintegrating cells. There were no CG strokes when the zone of storm's convection contained only one cluster of cells. The strokes took place only in the presence of two or more clusters. Except two cases, lightning strokes were observed in the zone of the storm's convection, as a rule, closer to the growing (mature) than to dissipating cells. The discussed observational data favor the hypothesis according to which rains falling at the sites of downward fluxes determine the conditions favoring the formation of lightning strokes that reach the Earth. However, it follows from observations that the complicated structure of the electrical field caused by superimposed fields of several cells especially favors an appearance of CG strokes. This situation can promote an earlier formation of CG strokes in the process of new storm cells formation.

III. THE ELECTROMAGNETIC FIELDS OF LIGHTNING

Although studies of lightning were started in the late 1700s, only in the early 20th century observations of the electric field were carried out to retrieve the spatial distribution of charges in thunderclouds responsible for the formation of lightning. Then intensive studies began of the distribution of low-frequency electromagnetic waves generated by lightning strokes (atmospherics). Random natural fields received on the Earth's surface in the frequency range from several Hz to MHz are created mainly by thunderstorm sources. Their study for a formalized description in the interests of radar observations has been carried out by Remizov (1985). Radio-noise caused by thunderstorms is disastrous for communication systems just as thunderstorms themselves are disastrous for population as a factor that can lead to fires and destructions.

Chronis and Anagnostou (2003) discussed preliminary results of the functioning of the experimental network recording the lightning strokes (ZEUS) which consists of six receivers located in Western Europe and functions from July 2001. The receivers make it possible to record the lightning-generated low-frequency electromagnetic waves (5-15 kHz) which propagate via the waveguide "Earth – ionosphere" over distances of several thousands km. Estimates have been obtained of the errors of observations at the network ZEUS (from the viewpoint of reliability of detection, localization, and characteristic of lightning strokes) by comparing with the data of independent observations. Such comparisons have been made for three regions: the eastern coast of the USA / north-western sector of the Atlantic Ocean, Africa, and Spain. Data for comparison were results of observations made with the use of the lightning sensor mounted on the TRMM satellite to study precipitation in the tropics, as well as data of the Spanish network for lightning observations. Results of comparisons have shown that the errors of localization (determination of coordinates) of lightning vary within 40 to 400 km at distances up to 5000 km and farther. Within the territory on which the network is located the errors do not exceed 40 km.

Formation of positive charges in the lower parts of clouds revealed by calculations with the use of the so-called tripole model of the thunderclouds, was verified by results of direct balloon soundings and remote sensing from the data of ground measurements of the electric field. However, since the sources of these charges have not been understood clearly, Mo *et al.* (2002) undertook direct aircraft measurements of positive charges in the lower parts of clouds with the use of two aircraft flying close by.

Data of observations obtained near New Mexico (USA) on 10 August 1997 demonstrated (at least, in some cases) that near the bottoms of clouds (at an altitude of about 3.4 km) there were located positive charges formed, apparently, under the influence of lightning strokes. The charge recorded in one of the cases at an altitude of about 4 km was ~1.25C, which agrees with the data of balloon and ground measurements of electric fields. Numerical modeling with electric fields prescribed from the data of aircraft observations near the idealized charge dipole with the instant introduction of the positive charge gave results which agree well with observations. The observational data indicate that at a ripe stage of formation of the horizontal distribution of the charge near the cloud bottom this distribution can be very complicated and is characterized by a combination of the contacting regions with opposite charges.

Rakov and Tuni (2003) studied an adequacy of numerical modeling of the lightning electric field at a great distance using the model of the transmission line (TL) and modified model MTLE taking into account an exponential decrease of current with altitude depending on polar angle (elevation) and the rate of propagation of the opposite charge. The shape of the wave of the latter was approximated by a step function. The same presentation was used for the TL model, whereas in the case of the MTLE model it was supposed that the electric field increases instantly to the level corresponding to TL and then decreases exponentially. The exponential decrease with altitude (in the case of MTLE) results in a considerable decrease of the electric field intensity during about 1 microsecond after reaching a maximum, especially at low values of the polar angle and high rate of propagation.

Calculations made by Marshall and Stolzenburg (2002) showed that in the case of positive CG strokes at which Q-flashes occur, the level of energy constitutes about $1 \cdot 10^{10}$ J, and the area of stroke is ~ 40×40 km^2. An estimation of total electrostatic energy stored in two stratus clouds of mesoscale convective cloud system gave values $5 \cdot 10^{11}$ and $2 \cdot 10^{12}$ J. These levels of energy are sufficient to provide hundreds or thousands of typical lightning strokes but only 10-100 positive CG strokes with the accompanying Q-flashes.

Using the Pockels sensors (Miki *et al.*, 2002) in the International Center for Lightning Research and Testing (ICLRT) in the State of Florida, Miki *et al.* (2002) carried out measurements of the shape of the electric field wave at horizontal distances from 0.1 to 1.5 m from the lightning channel. The dynamic range of the measuring system varied between 20 kW m^{-2} and 5 MW m^{-2}, and the band width in the interval from 50 GHz to 1 MHz. Also, electric fields were measured near the bottom of the channel and at distances 5, 15, and 30 m from the lightning channel. Using the Pockels Sensor, measurements of electric fields were made for 36 strokes in 9 "trigger" flashes. For 8 of 36 strokes measurements were also made of horizontal electric fields. According to the results obtained, the shape of the electric field wave looks like an impulse with its front edge determined by the stroke leader, and the rear edge determined by the inverse stroke. Six of 36 studied shapes of the electric field wave were close the V-shape, whereas the other 30 were characterized by much slower variations in the phase of reverse stroke than at the leader stage. The vertical electric field reached a maximum in the interval from 176 kW m^{-1} to 1.5 MW m^{-1} (an average of 577 kW m^{-1}), and the horizontal electric field – in the range between 495 kW m^{-1} and 1.2 MW m^{-1} (an average of 821 kW m^{-1}). These values are characterized by a 40% underestimation.

IV. THUNDERSTORMS AS RADIO-INTERFERENCE

Remizov (1985) studied amplitude and statistical characteristics of atmospherics using non-traditional methodologies of radio-interferences initiated by the thunderstorms. Knowledge of distribution of the time intervals between impulses both interior of group structure of irradiation in the thunderstorm families and between the groups is important for the plane of radio station regimes. Distribution of intervals between the groups τ_r has mainly exponential character:

$$W(\tau_r) = (1/\tau_{r0})\exp\{-\tau_r/\tau_{r0}\}$$

where τ_{r0} is the average interval between groups that is varied from units to tens of seconds.

The flow of atmospheric impulses is described by the Poisson model. It allows to install the reliable regime for radio stations basing on the frequency ranges (1-30 kHz) and (30-1000 Hz).

V. CONCLUSION

The natural catastrophes are environmental phenomena which must be analysed to design the monitoring systems to collect and process the data to solve the complex problems of environment modeling to predict natural disasters. In the paper an analysis of thunderstorms is proposed to understand the interrelation between different atmospheric processes and to assess the tendencies in generation of the atmospherics.

Analytical description of natural atmosphere-electric discharges is given. The presented models can be used in the predicting the scale of future natural disasters.

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