*PRESENT STATE OF RESEARCH ON ATMOSPHERIC ELECTRICITY**

I. M. IMYANITOV and K. S. SHIFRIN

Usp. Fiz. Nauk **76**, 593-642 (April, 1962)

CONTENTS

INTRODUCTION

THIS review is devoted to the present state of our knowledge of atmospheric electricity.

An outstanding contributor to this field was Jacob Il'ich Frenkel. It must be noted that his contribution to geophysics was not limited to atmospheric electricity. In 1944 he wrote an important paper "Contribution to the Theory of Seismic and Seismoelectric Phenomena in Moist Earth." In this paper he developed a theory of electric phenomena accompanying the propagation of elastic oscillations in moist earth, the theory of the so-called E-effect, a seismoelectric phenomenon discovered shortly before by A. G. Ivanov.

In 1945 Frenkel announced a new theory to explain the origin of the earth's principal magnetic field. It is known that the metallic matter in the earth's core has very low viscosity. Assume that this matter contains sources of heat, say radioactive substances. Convective motion will occur under certain conditions in the earth's core. A weak random magnetic field induces currents in the moving metallic masses. If the convective motion is of the right type, these currents reinforce the initial random field, until equilibrium sets in, in which the field buildup is balanced by an increase in the Joule losses. This spontaneous field buildup is due to the energy of the convective motion. It is completely analogous to the buildup of a self-excited generator. The order of magnitude of the necessary field can be readily estimated. This work by Frenkel was later continued by Elsasser, Bullard, and others, and is widely recognized at present. In addition to these three principal trends, Frenkel undertook several other important geophysical investigations. These include the evaporation of liquid drops in an air stream, new ideas on the connection between condensation nuclei in the atmosphere and the sun's ultraviolet radiation, the vertical distribution of gases in the earth's atmosphere, and others.

Frenkel's activity in geophysics is far from limited to his geophysical papers. His purely theoretical research on the theory of phase transformation, viscous flow, and plasticity are also of great importance. This pertains in particular to his classical "Kinetic Theory of Liquids," which can serve as a handbook for all geophysicists who investigate the formation of clouds and precipitation in the atmosphere, or the internal structure of the earth's sphere.

Of great value to Soviet geophysicists were not only Frenkel's scientific articles, but personal contacts with him. Frenkel showed lively interest in literally all branches of geophysics. This included problems in meteorological optics, methods of artificial precipitation, problems in dynamic meteorology, and atmospheric acoustics. He was able to advance original ideas and point out new paths in all these fields.

However, Frenkel paid most and persistent attention to atmospheric electricity.

We group under the term atmospheric electricity all processes occurring in the troposphere and partly in the stratosphere. Electric phenomena in the upper layers of the atmosphere and in the ionosphere, which differ appreciably in their nature and in the required research procedures from the phenomena in the lower layer, will not be considered. In examining the processes occurring in the lower layers we shall touch upon only the main problems: the structure of the atmospheric electric field, its nature, the space-time variations, and the space charges and currents flow-

*The introduction, and sections 1 and 2 were written jointly; sections 3 – 10 were written by I. M. Imyanitov.

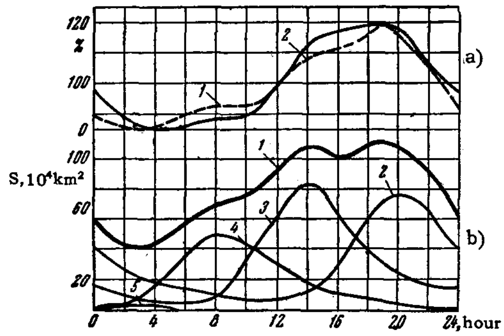

FIG. 1. a) Daily course of unitary variation of electric field intensity (Greenwich time).[10] 1 – Above the oceans; 2 – in polar regions. b) Daily course of the area covered by thunderstorms. 1 – For the entire earth's surface; 2 – in America; 3 – in Africa and Europe; 4 – in Asia and Australia; 5 – in New Zealand.

ing in the atmosphere. We shall consider these phenomena for both the case of "good weather" and for days with "disturbed" conditions, for different types of clouds, showers, and thunderstorms. Questions such as the occurrence and dynamics of development of line lightning, the theory of the lightning rod, ball lightning, and the like will be left out. An analysis of these questions would call for a much longer review.

The study of atmospheric electric phenomena, started by Franklin, Dalibar, Lomonosov, and Richman in the middle of the 18th century, was first centered on lightning and storms, brilliant natural manifestations which naturally attracted the attention of scientists.

The electric phenomena occurring in the atmosphere in the absence of clouds were discovered almost simultaneously by Lomonosov[1] and by Lemonnier.[2] Gradually, particularly in the beginning of the 19th century, interest in the study of lightning and thunderstorms greatly subsided. The main attention of the researchers was concentrated on electric fields in good weather. Thunderstorms and lightning were regarded as disturbances that distort the pure field pattern in the cloudless atmosphere. Electric phenomena in clouds and thunderstorms were regarded as separate from those occurring in the cloudless atmosphere and essentially different from them.

In the 1920's Simpson,[3] Mauchly,[4] and Swerdlup[5] observed the so-called unitary field variation, i.e., the synchronous variations in the field intensity E at different points on earth. The major principal significance of this discovery to the study of electric phenomena in good weather is by now quite clear. This phenomenon is illustrated by the curves of Fig. 1a. Wilson has advanced the hypothesis that the unitary field variation is due to thunderstorms, which cause the earth and the high layers of the atmosphere to be oppositely charged. This assumption was confirmed by Whipple and Scrase.[6] They established that the daily variation of the field is similar to the daily variation of the total area on the earth's sphere over which thunderstorms occur at the given instant. The dependence of S on the time is shown in Fig. 1b (S is in 10^4 km^2). This gave rise to the notion that in clear days the electricity is closely connected with the thunderstorm activity of the clouds—the factor excluded as anomalous in research on the field of good weather.

It must be added that until recently the connection between the "cloudy" electricity and the electricity of good weather was obscured by a large number of extraneous interfering factors and was exceedingly unclear. Thus, for example no unitary field variation was observed at all, over the continents, where the overwhelming majority of atmospheric electric measurements are made. This is due to the influence of the earth's surface and of neighboring well-conducting walls (the well known electrode effect), to fluctuations in the space charges and in their vertical distribution, to horizontal inhomogeneities in the earth's surface, and to a few other factors which come into play in measurements made above the continents. The unitary variation was noted only after measurements were made over the oceans and in the polar regions, where the conditions are much more homogeneous.

Because of the unclear general picture, most researchers have found it necessary, to improve the methods used for field measurements on land, to accumulate long series of observations, etc. One of the main investigators in the field of atmospheric electricity, H. Israel,[7] remarked in 1939 that in order to find a way out of the resultant quandary it is necessary to revise the methods and continue measurements on land for another 50 years.

Lack of firmly established general concepts, and a paucity of experimental data characterized the situation in the middle 1940's, when Frenkel started to develop a theory for atmospheric electricity phenomena.

Frenkel's principal contribution was a general theory of atmospheric electricity in consistent and clear form. This theory was based on two principal ideas: a) close connection between the processes in the clouds and in the free atmosphere, and significant influence of all clouds, not merely storm clouds, on the formation of the electric field; b) independence of the atmospheric-electricity phenomena in the lower layers of the processes occurring in the ionosphere, and the rejection of the theory of the so-called "spherical capacitor."

The unified picture of the atmospheric-electricity phenomena, by which the phenomena in the clouds and in the free atmosphere are really different aspects of the same natural process, has found its expression in Frenkel's book "Theory of Atmospheric Electric Phenomena,"[8] published in 1949. At that time there were no systematic data on the electric characteristics of the free atmosphere, and particularly of the clouds. The publication of the book played a major

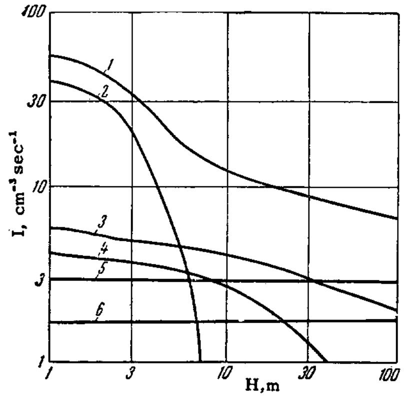

FIG. 2. Change in intensity of ionization at the earth's surface with altitude.[21] 1 – Total ionization; 2 – ionization by α radiation from the earth; 3 – ionization by α radiation from radioactive gases; 4 – ionization by β radiation from the earth; 5 – ionization by γ radiation from the earth; 6 – ionization by cosmic rays.

role in the progress of research on the electricity in the free atmosphere. One cannot regard it as accidental that systematic research in this field began precisely following its publication. Although the research results did not always agree with the predictions, the general ideas formulated in this book are still the most fruitful in the study of atmospheric electricity.

We consider below the main facts on atmospheric electricity, established by the end of the 1940's essentially as a result of measurements made on the earth's surface, as well as the new data of good weather electricity and on different types of clouds, which became known recently, primarily through measurements in the free atmosphere.

We shall not discuss at all the measurement methods, their accuracy, and other aspects of research

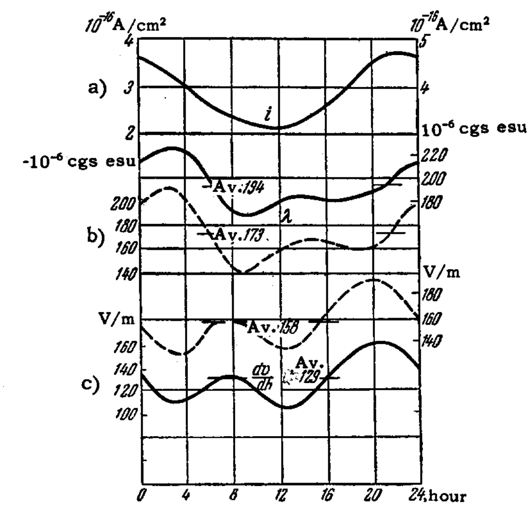

FIG. 3. Daily course of the elements of atmospheric electricity at a continental station (local time).[10] a) Vertical current. b) Conductivity. c) Field intensity. Solid curves – days of "good" weather; dashed – all days.

methodology. In the discussion we shall merely attempt to use the most reliable experimental material available. Methodology problems are partly touched upon in [9].

1. BASIC INFORMATION

By the end of the 1940's much information accumulated on atmospheric electricity, principally as a result of measurements on the earth's surface.

It was established that the electric field has the same direction as would obtain were the earth to be negatively charged and the atmosphere positive. The mean field intensity at the earth's surface is about 130 V/m. During precipitation and particularly during thunderstorms, snow storms, dust storms, etc, the field intensity may change sharply, sometimes reaching about 10,000 V/m, and the field direction is frequently reversed. The electric field of good weather is shown to exhibit several regularities of behavior.*

1. The daily course of the field intensity over the continents has the form of a double wave (Fig. 3). The maxima and minima of the field and its mean value vary at different stations. Thus, for example, the average field intensity is 171 V/m in Slutsk (Leningrad), 70 V/m in Uppsala (Sweden), 304 V/m in Kew (England), 86 V/m in Java, and 88 V/m in the antarctic.[10]

2. The daily course of the field intensity over the oceans and polar regions has the form of a single wave (Fig. 1, curve 1), the field variation at various points occurring in synchronism at a single universal time, with relatively constant amplitudes and mean values. Above the oceans, for example, the mean value of the field intensity is about 113 V/m, and the amplitude of the variations is about 17% from the mean. This is the so-called unitary variation of the field intensity.

3. At all points of observations, the annual course of the electric field has the form of a simple wave with a minimum in the summer of the northern hemisphere. This was demonstrated most clearly by N. A. Paramonov.[11]

4. The field intensity has a clearly pronounced latitudinal variation. The greatest field intensity is noted in medium latitudes, decreasing towards the poles and towards the equator.

5. The field intensity decreases with altitude in nearly exponential fashion. This conclusion, incidentally, is based on several tests [12,13] whose results are doubtful, owing to methodological errors.[9]

Investigations of the electric field in bad weather have led to the following conclusions.

1. The electric field intensity above thunderstorm

*By "good" weather we mean weather when the electric field depends little on local conditions, i.e., when there are no clouds, precipitation, fog, dust, strong wind, etc.

clouds usually has a direction opposite that of good weather.

2. The character of the variation of the field on earth during the passage of a thunder cloud and the variations of the field occurring when lightning strikes indicate that the storm clouds can be likened as a rule to electric dipoles charged positively above and negatively below.[14] The existence of such a charge distribution was later corroborated by Simpson and his co-workers,[15-17] although the low values of field intensity (~ 100 V/cm) measured by him raised serious doubts (later confirmed) concerning the accuracy of the measurements performed.

3. Precipitation-producing clouds cause irregular and abrupt changes in the field on the earth's surface. Clouds that produce no precipitation cause a certain reduction in the good-weather field.[18]

4. Clouds produce a certain increase in (absolute) field intensity in the summer and a decrease in the winter.[19]

5. Air pollution usually increases the field intensity.

6. Dust and snow storms cause a sharp increase in the absolute values of the field intensity and may reverse its direction.

Along with the field, a major characteristic of atmospheric electricity is the current flowing in the atmosphere. The electric conductivity of the atmosphere, discovered by Coulomb[20] in 1785, became a subject of detailed study only at the end of the last century. It was established that in good weather the atmosphere becomes conducting because the air is ionized by radioactive radiation from the earth's surface, by radioactive impurities in the air, and by cosmic rays. Figure 2 shows the altitude variation of the total ionization of the atmosphere and the contributions from the individual components mentioned. At altitudes greater than 2 or 3 km, the main factor ionizing the atmosphere are cosmic rays. Coulomb forces cause the atomic ions resulting from the ionization to combine within about 10^{-6} sec with several dozens neutral molecules, and this gives rise to relatively stable particles, so-called light ions, with approximately equal mobility $u_{\pm} \sim 1$ cm^2/V-sec.

The light-ion concentration $n_{\pm}$, determined by the ionization and recombination conditions, amounts to about 400 cm^{-3} in clean air near the earth's surface. In this case the conductivity of the air is about 2×10^{-4} esu. It is connected with $u_{\pm}$ and $n_{\pm}$ by the formula

$$\lambda = e(n_- u_- + n_+ u_+). \qquad (1)$$

The conductivity is greatly influenced by nonradioactive impurities in the atmosphere. Light ions settle on these impurities (minute dust particles, droplets, and other particles with dimensions from 10^{-7} to 10^{-5} cm) and form heavy and ultra-heavy ions with mobilities that do not exceed 10^{-3}—10^{-4} cm^2/V-sec.

For light particles, the ionization-recombination equation has the form

$$\frac{dn_+}{dt} = I - \alpha n_+ n_- - \beta n_+ N_- - \gamma n_+ N_0. \qquad (2)$$

Here N_- is the concentration of negatively charged heavy ions, N_0 —concentration of neutral particles, α, β, and γ —corresponding recombination coefficients, and I —ionization intensity. We have left out from the right side several terms which are usually of small order of magnitude. Analogous equations can obviously be written also for n_-, N_-, N_+, and N_0. Thus, in the stationary state and in quiet air we have $dn_+/dt = 0$, and

$$n_+ = \frac{I}{\alpha n_- + \beta N_- + \gamma N_0}. \qquad (3)$$

If the number of heavy particles is large, then the concentration n_+, as follows from (3), should noticeably decrease.

Since the mobility of the heavy ions is very low, the contribution these ions make to the conductivity is usually negligible. If $\gamma N_0 + \beta N \gg \alpha n_+$, and if we assume that $\beta \approx \gamma$ and put $N_0 + N_{-1} = N$, we get $n_+ \sim N^{-1}$. Since (approximately) $n_+ = n_-$ and $u_+ = u_-$, this means that

$$\lambda \sim N^{-1}, \qquad (4)$$

i.e., the conductivity of the atmosphere decreases greatly with increased pollution. The number N may reach 10^5 cm^{-3}; in industrial cities it amounts to about 10^3—10^4 cm^{-3}. This decreases the number of light ions in dusty air to 20—30 cm^{-3} and reduces the conductivity to 10^{-6} esu.

The daily and annual variations of the conductivity at the earth's surface are influenced by the daily and annual variation of the two factors determining the conductivity, namely the ionization intensity and the atmospheric pollution. The conductivity usually increases at local nighttime and decreases in the daytime (Fig. 3), when the developing convection increases the number of heavy particles in the atmosphere. In the winter the conductivity in northern latitudes is lower than in the summer, since the snow cover stops radioactive emission from the earth from ionizing the atmosphere. The conductivity increases with altitude approximately exponentially. The columnar resistance (resistance of a vertical air column 1 cm^2 in cross section between the earth and the ionosphere) was measured once to be 10^{21} ohms, half of this amount being made up by the layer between 0 and 2 km altitude.[22]

Compared to air, the earth's surface can be regarded as an ideal conductor, since the conductivity of sea water is 14 orders of magnitude greater than that of air, while the conductivity of the ground is 10 or 11 orders of magnitude greater. The conductivity of the ionosphere also exceeds the conductivity of the lower layers of the atmosphere by ten orders. The atmosphere is therefore usually regarded as a dielectric with variable conductivity, contained between conducting shells—the earth and the ionosphere.

In bad-weather zones, additional sources of ionization may be the following:

1. Brush discharge from various sharp points on the earth's surface (tree branches, grass, antennas, etc.), starting with electric fields of intensity exceeding about 10 V/cm.

2. Electrification occurring when contact is broken between particles; this happens usually in shower and thunderstorm clouds, dust storms and snow storms, volcanic eruptions and similar phenomena; in thunder clouds, for example, this electrification may increase the conductivity by almost two orders of magnitude.[23]

3. Lightning discharges. The presence of a field in a conducting medium causes current to flow. In good weather zones, where the horizontal dimensions of the zone are much greater than the vertical ones, the electric field is vertical. The density of the conduction current flowing through the atmosphere is

$$i_n = \lambda E, \tag{5}$$

where E is the field intensity and λ the conductivity. In good weather zones we have on the average $i_n = 3 \times 10^{-16}$ A/cm². This current is not the same at all stations. Its average annual value is 3.2×10^{-16} A/cm² over the oceans, 3.5×10^{-16} under Leningrad (Pavlovsk), 4.3×10^{-16} in Spitzbergen, and 1.7×10^{-16} A/cm² in Samoa and in Davos (Switzerland). Since the relative daily variations of the conductivity above the continents are greater than the field variations, the daily course of the conductivity current above the continents recalls in many respects the daily variation of the conductivity (Fig. 3). Over the oceans, where the daily variation of the conductivity is quite weak, the daily variation of the vertical current is very similar to the daily unitary variation of the field intensity.

Over the entire earth as a whole, the total conductivity current in the good weather regions (the good weather current) is approximately 1500 A; this current charges the earth positively. Direct measurements show that in the good weather zones the current density is practically constant with altitude. From (5) and Poisson's equation for the one-dimensional problem

$$\varepsilon \frac{\partial E}{\partial z} = 4\pi\varrho \tag{6}$$

it follows in this case that the space charge density ρ in the atmosphere, determined by the altitude distribution of the conductivity, is

$$\varrho = -\frac{i_n \varepsilon}{4n\lambda^2} \frac{\partial \lambda}{\partial z}. \tag{7}$$

The time necessary to establish stationary distribution is determined by the ratio $\epsilon/4n\lambda$, where ϵ is the dielectric constant of the atmosphere. Since ϵ remains practically constant in the atmosphere (changes occur only in the fifth significant figure), the equilibrium time depends on λ. In clean atmosphere at the earth's surface, with $\lambda = 2 \times 10^{-4}$ esu, the relaxation time is about 500 sec; it decreases with increasing altitude.

Since the space charge is unevenly distributed in the atmosphere, and the turbulent diffusion coefficient k in the atmosphere is quite large, a diffusion current

$$i_g = -k \frac{\partial p}{\partial z}, \tag{8}$$

flows in some cases in the atmosphere, in addition to the conduction current, and also a convection current i_k, due to the convective transport of space charge with velocity v:

$$i_k = \varrho v. \tag{9}$$

Thus, the total current in the atmosphere in the good weather zone is

$$i = i_n + i_g + i_k = \lambda E - k \frac{\partial \varrho}{\partial z} + \varrho v. \tag{10}$$

The vertical component of i_k is usually very small in good weather zones.

The diffusion current is usually also quite small. Only near the earth's surface does it begin to play an appreciable role, since the earth's negative charge causes a noticeable positive space charge to accumulate in the atmosphere near the earth's surface (the electrode effect).

The electrode effect greatly complicates the measurements near the earth's surface, since all the instruments are then under disturbed conditions. Calculations show[25,26] that the thickness of the disturbed layer can reach hundreds of meters in the case of strong turbulence and decrease to 10 or 20 meters in weak turbulence. Since the turbulence in the atmosphere has both daily and annual variations, the electrode effect influences the variations of the corresponding atmospheric-electricity elements. Thus, for example, changes in the turbulence alone may cause the potential of the atmospheric field at a height of 2 meters to fluctuate approximately 20% about its mean value.

The earth's average electric charge, usually estimated at -5.7×10^5 Coulombs (calculated from data on the average field intensity in good weather regions), does not vary with time. This means that simultaneously with the positive "good weather current" the earth receives a negative current also equal to 1500 A. The possible sources of this current are the bad weather zones, where the current has additional contributions from charge exchange between the earth and the atmosphere due to lightning, from brush discharge by sharp objects near the earth's surface, and from electric precipitation current.

The charge carried by one lightning is about 20—30 Coulombs, while the brush-discharge current reaches several microamperes per sharp point; according to a rough estimate by Wormell[27] this amounts to about 100 Coulombs per km² (in England). The precipitation current carries in the main a positive charge to the earth. The current density in a continuous rain ranges from 10^{-16} to 10^{-14} A/cm^2. Thunderstorm downpours and showers may have a current density as high as 10^{-12} A/cm^2 and even more.

Thus, Schonland[28] measured a maximum current of 2×10^{-11} A/cm^2, Chalmers and Little[29] observed a precipitation current -7.3×10^{-12} A/cm^2. The determination of the current balance in bad weather zones is very difficult because the main components are difficult to measure or even to estimate. The currents from individual clouds differ greatly in magnitude and in sign, and the balance in individual years may likewise diverge greatly. In various regions of the earth the balance of these currents is also different. As a result, only individual data on the current balance are available. Thus, for example, Wormell[30] gives the following annual current balance per km^2 in Cambridge (England):

Conduction current	+ 60 C
Current from sharp points	– 100 C
Current from precipitation	+ 20 C
Lightning current	– 20 C
Total	– 40 Coulomb/km^2 year.

These figures are highly approximate, particularly when it comes to estimating the current from sharp points, the main item in the balance. No such balance was measured for other places; yet it may differ greatly from that given above. Thus, for example, according to V. V. Zykova[31] the current from sharp points in south Sakhalin charges the earth positively.

Gish and Wait[32] attempted to calculate the upward current from thunder clouds by measuring the field intensity and the conductivity above these clouds and to determine the current flowing to the earth, assuming it to be equal to the current flowing upward from the cloud. According to their data, the current per storm is about 0.5 A. According to Brooks, some 1800 storms occur simultaneously over the earth's sphere. Thus, if the thunderstorms in the central part of the USA, where the measurements were made, are sufficiently typical of the entire earth's sphere, then the lightning current to the earth is on the order of −1000 A. Later Stergis, Rein, and Kangas estimated the current from one thunderstorm in Florida to be 0.8 A and found that the current brought by lightning to the earth is about 1400 A. These estimates however, are quite arbitrary in character, particularly if it is recognized that they are based on measurements of currents of only a few thunderstorms.

2. TWO THEORIES

The main facts listed above were used in several dozen theories concerning atmospheric electricity (see [35]). For various reasons, the majority of these theories have been discarded by now. This pertains in particular to all mechanisms wherein the earth is charged by extraterrestrial sources. In view of the

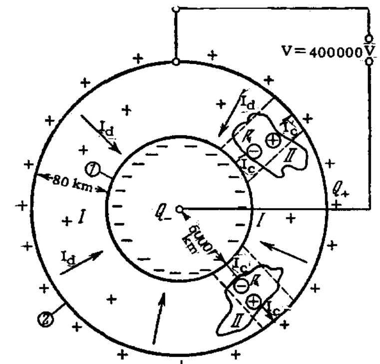

FIG. 4. Diagram illustrating the spherical-capacitor theory.[42] I – Good weather regions; II – thunderstorm regions; 1 – earth; 2 – ionosphere.

high conductivity of the atmosphere, as noted above, the electric charges reaching the earth will be transferred to the atmosphere and can be observed only by instruments placed outside the atmosphere.[36] Within the confines of the earth's atmosphere, the appearance of such charges can manifest itself only in brief field variations.

Let us consider two of the best developed theories. The first is based on the views of Wilson[37] and was developed in [10,38–40,21].

According to this theory, the electric field of the atmosphere exists because the earth (1, Fig. 4) and the upper layers of the atmosphere (the ionosphere, 2) act as capacitor electrodes carrying negative and positive charges Q_- and Q_+, respectively, and producing a certain potential difference V so that a field is created in the atmosphere. Because of the conductivity of the atmosphere, a "good weather current" I_d flows continuously between the ionosphere and the earth's surface, tending to discharge the capacitor. The density i_d of this current is constant with altitude and amounts to $E_h\lambda_h$, where E_h is the field intensity and λ_h is the conductivity of the air at altitude h. The field intensity of the atmosphere should decrease with altitude, following an exponential law because the conductivity of the atmosphere, as indicated above, increases exponentially with altitude.

To maintain the charges on the electrodes of this capacitor it is obviously necessary to have charging currents offsetting the discharge current.

It was proposed that the charging currents I_c are produced in all the thunderstorm regions on the earth, II (Fig. 4), where the field direction is opposite to that observed in the good weather regions I. Since the charges Q of the earth and of the atmosphere are determined by the ratio of the charging and discharging currents, an increase in the thunderstorm activity should be accompanied by an increase in the charges, and consequently by an increase in the potential difference V between the earth and the ionosphere. Because of the good conductivities of the earth and of the ionosphere, the settling charge is distributed over the entire surface of the corresponding sphere within a very short time (on the order of several seconds). Thus, changes in the potential difference V should be practically simultaneous over the entire earth. A decrease in thunderstorm activity should be accompanied by a corresponding decrease in the potential V and in the intensity of the atmospheric field.

If it is assumed that the entire current I_c to the earth and to the ionosphere, produced by the thunderstorm clouds, is proportional to the area covered by the thunderstorms, then the close correlation between the course of thunderstorm activity and the unitary potenial gradient variation (see Fig. 1a and b) becomes understandable. If R is the columnar resistance, then the discharge current density i_d will be

$$i_d = \frac{V}{R}. \tag{11}$$

On the other hand, $i_d = \lambda E$. Comparing these relations, we obtain

$$\frac{V}{R} = \lambda E. \tag{12}$$

The last equation is useful because it relates the potential V, which is the same over the entire earth's sphere, with the characteristic R of an air column above the point of measurement and with the local characteristics λ and E, measured at any altitude, and in particular near the earth's surface. The variations of the field intensity E at the earth's surface can be attributed, in accord with (12), to one of the three factors (or to some combination of the three).

When R and λ are constant, the variation of E should follow that of V, i.e., it should be simultaneous over the entire earth. When V and λ are constant, the field E should vary with R. This can be related with the passage of fronts, cloud systems, and the appearance of large dust zones. When V and R are constant, the variations of E are related to those of λ. Local variations in conductivity, occurring in the surface layer adjacent to the earth, hardly influence the resistance R of the entire air column. If we measure E and λ independently and assume (12) to be correct, we readily can interpret the nature of the different variations.

A characteristic example of the role of local variation in conductivity was cited by Stewart.[41] He showed that the decrease in the average annual values of the field intensity observed between 1952 and 1958 by several English and Portuguese stations, and which led to nearly half the field intensity by 1958, was due to the increase in the ionization of the atmosphere in the layer of air near the surface. This increase in ionization turned out to be due to increased β emission from radioactive substances settling on the earth as a result of nuclear explosions. Since the ionization in the lower layer (up to 2 meters) has approximately doubled, the conductivity has increased, and the field intensity decreased, by the same amount.

The spherical-capacitor theory explains many phenomena observed in nature. For a direct verification of this theory one would have to measure the potential difference between the earth and the ionosphere and demonstrate that it is the same for the entire earth and that it experiences synchronous fluctuations due to the unitary variation. It would be further necessary to confirm experimentally the data on the balance of the currents charging and discharging the earth in the ionosphere. The measurements of currents above thunderstorms, reported in [32] and [33], are patently not convincing, in view of the arbitrary nature of several of the estimates.

The second theory which we now consider was developed in 1949 by J. I. Frenkel.[8] He assumed that most clouds are electrically polarized (form electric dipoles). The field intensity inside the clouds was assumed to be approximately 10,000 V/m. The polarized clouds should induce charges on the earth's surface. The sum of the charges induced by all the clouds produces the observed earth's field. Differences in the conductivity of the atmosphere under clouds and in good weather zones are due to the appearance of a certain excess charge on the earth's surface, the field of which is superimposed on the field of the induced charges and guarantees the existence of the good-weather field in large cloudless regions (for example in the Sahara desert).

It is assumed in accordance with this theory that the ionosphere (or the upper conducting layers of the atmosphere) plays no essential role in the course of the atmospheric-electricity processes, and the electric field of the atmosphere was attributed wholly to electric phenomena occurring in the troposphere and their interactions with the earth.

The unitary variation of the field intensity can be attributed in this theory to variations in the conditions under which the earth as a whole is charged. Fluctuations in the potential of the upper layers can occur in this case in non-synchronous fashion, and in general are not connected directly with the field measured at the earth. The field in regions of bad weather, for example above thunderstorm and shower clouds, has direction opposite to that in good weather regions. According to Frenkel's theory, the changes in the conditions under which the earth is charged as a whole are determined by a relation that follows from the equality of the currents in the good and bad weather regions:

$$\lambda_1 E_1 S_1 = \lambda_2 E_2 S_2, \tag{13}$$

where λ_1, E_1, and S_1 are the electric conductivity, field intensity, and area of the earth's surface in the good weather zones, respectively, while λ_2, E_2, and S_2 are the same for the bad weather zones. Since the total positive charge induced by the polarized clouds is equal, in accordance with the theory, to the total negative charge, we have $E_1S_1 = E_2S_2$.

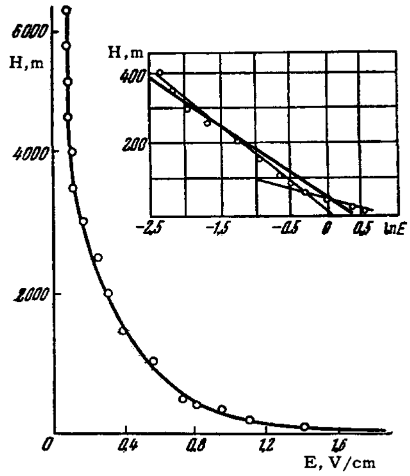

FIG. 5. Variation of field intensity E with altitude H.[63] Group I. Leningrad, 1958 (H in the upper plot is in dekameters).

If $\lambda_1 = \lambda_2$, the total charge of the earth's surface is zero. However, under clouds whose field can cause brush discharge from objects on earth, particularly under thunderstorm and shower clouds, we have $\lambda_2 > \lambda_1$, meaning that $E_1S_1 > E_2S_2$, i.e., the surface of the earth as a whole should in this case be negatively charged, with uniform charge distribution in good and bad weather zones. The charge remaining in the atmosphere in the bad weather zones is carried away, in accordance with Frenkel's ideas, by the air currents into the good weather zone.

Frenkel also studied in great detail several elementary processes whereby the cloud particles are charged and the charges macroscopically distributed in the clouds. However, the almost total lack of information on the space charge in the clouds and the rate of its redistribution, and the lack of data on the value of the charges of individual particles in the clouds, have

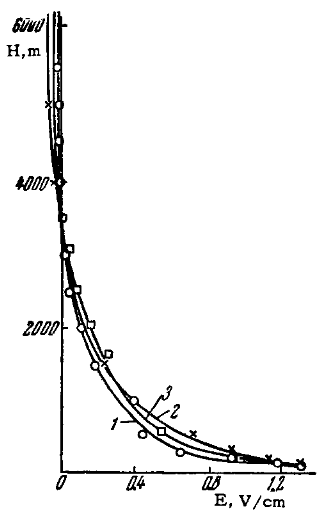

FIG. 6. Variation of field intensity E with altitude H.[63] Group II. 1 – Leningrad; 2 – Kiev; 3 – Tashkent.

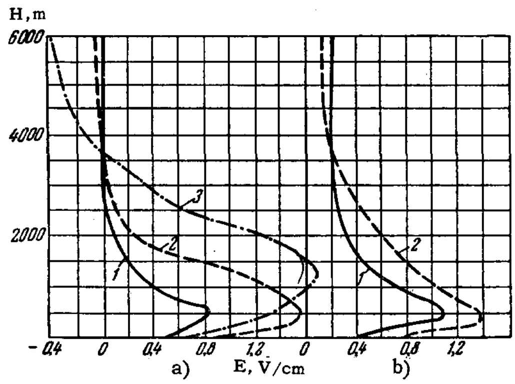

FIG. 7. Variation of field intensity E with altitude H.[63] Group III. a) 1 – Leningrad; 2 – Kiev; 3 – Tashkent. b) 1 – Leningrad; 2 – Kiev.

made it impossible to verify the theory as a whole and to compare it with observed facts.

Let us consider the present status of information on atmospheric electricity. Principal attention will be paid to information obtained in a new field of research, the electricity of the free atmosphere.

3. VERTICAL STRUCTURE OF FIELD, CONDUCTIVITY, AND CURRENT IN GOOD WEATHER

The altitude variation of the electric field intensity above the continents was investigated most fully during the time of the International Geophysical Year at three Soviet stations, in Leningrad, Kiev, and Tashkent.[42] An analysis of more than 2,000 soundings of the atmosphere yielded systematic information on the altitude variation of the electric field above these points.[43] It was found that even in days of good weather the field profiles can be quite varied. It is advantageous to break these down into three basic groups.

The first group includes profiles[44] with exponential decrease of the field intensity E with altitude z (these comprise 40% of the cases):

$$E = E_n e^{-az}; \qquad (14)$$

Here E_n is the field intensity at the 50-meter level and $a = 1\ km^{-1}$. Figure 5 shows a profile of this type (measurements near Leningrad).

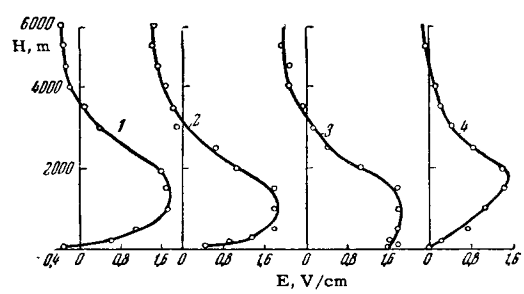

FIG. 8. Transformation of the electric field intensity profile during the day, for group III. Tashkent, June 1958[63]. 1 – 0[00], 2 – 6[00], 3 – 12[00], 4 – 18[00] (Greenwich time).

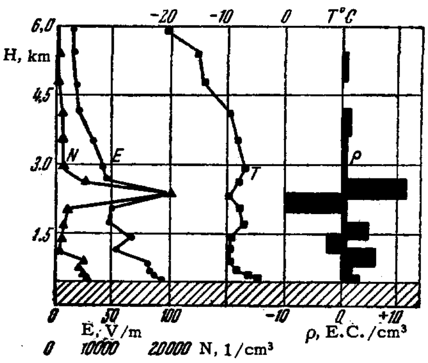

FIG. 9. Altitude variation of the number of nuclei (N), field intensity (E), temperature (T) and space-charge density (ρ).[51]

In the upper right corner of Fig. 5 is a semi-logarithmic plot of the altitude variation of the field. We see from this part of the figure the extent to which formula (14) represents the true altitude variation of the field, and also that the replacement of (14) with a two-term exponential equation, as is customarily done, permits a more accurate description of the field variation in the lowest layer alone.

Profiles of this type yield $a = 1.2\ \text{km}^{-1}$ for Kiev and $a = 1.5\ \text{km}^{-1}$ for Tashkent. We add that over the oceans, where such profiles are also encountered, $a = 0.25\ \text{km}^{-1}$.[51]

In many cases the field intensity first decreases with height in accord with (14), and then reverses sign, usually at 3500–4000 meters (Fig. 6). Profiles of this type were assigned to the second group.

Finally, in more than 40% of the cases the field first increases with altitude and then starts decreasing (Fig. 7). Profiles of this type comprise the third group. Usually the field reverses direction at 3500–4000 meters (Fig. 7a), but in some cases it remains positive up to the maximum sounding height (Fig. 7b). A similar variation of the field with altitude is observed on cloudy days.

Profiles of these types were noticed by several investigators,[44-51] but except for [44] and [51] only a few profiles were investigated in each of these studies. The profiles of the field above the continents can change noticeably during the course of the day, as can be seen from Fig. 8, obtained for strongly turbid atmosphere. These changes are closely connected with the changes in the humidity and dust content of the atmosphere and with air movements. The profile of the field is connected with the vertical course of the impurities. From the constancy of the conduction current density it follows that $E \sim \lambda^{-1}$, and since $\lambda \sim N_0^{-1}$ for large N_0, we get

$$E = BN, \tag{15}$$

where B is a certain constant [see (4)].

Thus, in regions where the atmosphere contains many impurities, a linear relationship should exist between the impurity concentration and the field intensity. This variation was thoroughly traced in several examples. Simultaneously with field measurements, A. L. Dergach[52] measured also the altitude variation of the number of condensation nuclei. Their number was found to decrease with altitude as $N = N_0 e^{-bz}$. The average value of the coefficient b for altitudes 0–3 km above Leningrad was found to be 1.05 [compare with the value of the coefficient a for Leningrad in (14)]. The close agreement between the variation of the field intensity with altitude and that of the number of condensation nuclei was observed also in individual flights. This dependence was noted in [51,53] (Fig. 9). We notice a curious connection between the horizontal visibility in the atmosphere, S_0, and the intensity of electric field E. Since $S_0 \sim N_0^{-1}$, we have when (15) is applicable (see, for example, [149])

$$ES_0 = \text{const.} \tag{16}$$

The vertical conductivity profile consists of two parts: a surface part with reduced conductivity, pertaining to the mixing layer, where N is large and $\lambda \sim N_0^{-1}$, and the region above, which extends to about 30 km. In this region the conductivity varies exponentially, as follows from the theory of ionic equilibrium of the atmosphere in the cosmic-ray field. It is connected with the pressure p and temperature T by the relation

$$\lambda(h) = \lambda(0)\left(\frac{p(0)}{p(h)}\right)^r \left(\frac{T(h)}{T(0)}\right)^S; \tag{17}$$

where $r = 1-0.64$ and $S = 1.7$ (see [55,57]) (according to [56], $r = 0.5$ and $S = 1.25$). The existence of such an altitude variation of conductivity above the continents was investigated in great detail by R. Sagalyn and G. Faucher,[54] by Stergis et al,[55] and by others.[48,50] Since the solid and liquid impurities in the atmosphere usually accumulate between the earth's surface and the temperature inversion layers, which delay the exchange, a minimum of λ and maximum of E are usually observed under such inversion layers.[44]

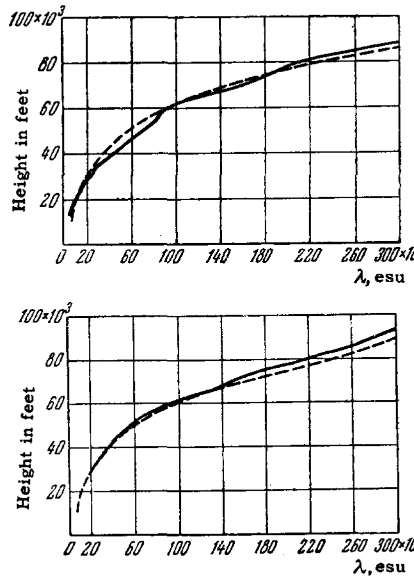

FIG. 10. Variation of conductivity with altitude.[55]

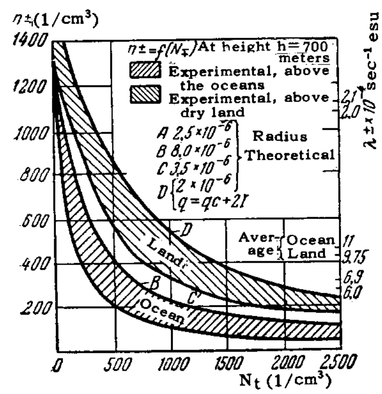

FIG. 11. Comparison of results of simultaneous measurements of the concentration of light ions (n) and the number of charged nuclei (N).[56] A, B, C, and D – curves calculated from the ionization-recombination equation for the indicated particle radii, assuming that only cosmic ionization is present.

Sagalyn's investigations [56] have shown that a lower conductivity is observed in the mixing layer also over the oceans. The influence of the continental conditions is noted at distances up to 300 km from the shore.

The difference between the dependence of light-ion concentration on the number of charged heavy particles (condensation nuclei) in the atmosphere over the continents and oceans is clearly seen from the data of Fig. 11.[56] The figure shows that for the same content of heavy charged particles, the number of light ions is larger over the continents than over the oceans. The reason for it is that the ionization intensity due to radioactive impurities is larger over the continents than over the oceans.

It is essential to note that the value 1.28, which is usually assumed on the basis of the data of Gish and Sherman [22] for the ratio of the negative to positive conductivity λ_-/λ_+ is found to be too high. According to [56] $\lambda_-/\lambda_+ = 1.05 \pm 0.1$ at altitudes 200–5,000 meters, while [58] gives 1.07 ± 0.1. In the mixing layer, Kraakevik [56] obtained a value $\lambda_-/\lambda_+ = 1.04 \pm 0.13$, and above this layer he obtained $\lambda_-/\lambda_+ = 1.08 \pm 0.1$. Thus, the assumptions made in the derivation of formula (4) can be assumed to hold true in the atmosphere.

The daily variations of the profile of field intensity (see Fig. 8) can be ascribed to a considerable degree to variations in the conductivity, which are connected with the daily course of the number of particles in the atmosphere at different altitudes, which depends in turn on the variation in the mixing conditions in the atmosphere during the day and on the conditions governing the coagulation of the particles. [59]

Simultaneous measurements of the variations of the field intensity and of the conductivity with altitude enable us to check the validity of the assumption that the vertical current in the atmosphere is essentially the conduction current, and to estimate the value of the diffusion current in those cases when this assumption is not valid. I. Kraakevik [60] observed that the conduction current above the mixing layer remains constant within ± 10%, while in the mixing layer it may be on the average 30%, and sometimes even 200% larger than the conduction current at considerable altitude.

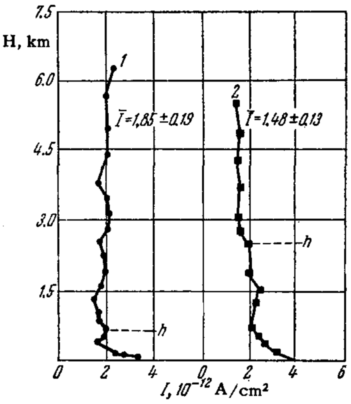

FIG. 12. Variation of conduction current density with altitude above the east coast (2) and the west coast (1) of the USA.[60]

If it is assumed that the total current remains constant, then the observed effect can be ascribed only to turbulent diffusion i_{dif} [see formula (8)], produced by the upward-moving positive space charge in the mixing layer. An example of such a profile of conduction current is shown in Fig. 12. As can be seen from the figure, in the first current profile the current density above the mixing layer is equal to $(1.85 \pm 19) \times 10^{-16}$ A/cm^2, and below the mixing layer it increases with increasing height reaching 3.5×10^{-16} A/cm^2 at 15 meters. We can thus assume that at this level the diffusion current has reached a value 1.85×10^{-16} A/cm^2.

The second field profile in Fig. 12 shows the presence of a diffusion current reaching 2.9×10^{-16} A/cm^2.

Variation of current with altitude was observed also in [13], but the usually observed variations were attributed to considerable measurement errors. In many joint measurements of the variations of conductivity and field intensity with altitude, carried out by Rossman, [61] one can also notice an altitude variation of the current, but here the current increased with altitude. An increase of conduction current with altitude, amounting to as much as 30%, was noted also above Japan. [50]

The existence of noticeable diffusion currents could be established also near the earth's surface. [62] It was noted that this current amounts on the average to 7–30% of the conduction current and can vary from 1.55×10^{-16} to -4×10^{-16} A/cm^2.

Even greater discrepancies between the total current on earth and the conduction current were noticed in [66], in which results in central America, which is the world's focus of thunderstorm activity, are discussed. During the rainy (thunderstorm) season, the conduction current amounted to 14.1×10^{-16} A/cm^2, and the total current on the earth was -9.7×10^{-16} A/cm^2, while during dry seasons the values were 16.1 and 15.6×10^{-16} A/cm^2 respectively in one period, and

1.4 and 2.7 × 10^{-16} A/cm² in the other, the field being positive all the time. Thus, during the time of rain one observes on the earth a negative diffusion current, reaching −4.3 × 10^{-16} A/cm², while during the second dry period the diffusion current is positive at +1.3 × 10^{-16} A/cm².

The conduction current density above the oceans, according to Kraakevik, [60] amounts to −2.7 × 10^{-16} A/cm² and is constant with altitude within ±2%. Assuming this estimate to be correct for the earth as a whole, an estimate of 1400 A is given in [60] for good weather on earth.

It must be stated that diffusion current can be produced not only by positive but also by negative space charges.

The data of the present section call for a certain modification in the concept of "good" and "bad" weather.

In "good" days the atmosphere contains no additional* space charges that modify appreciably the earth's space charge, while in "bad" days the field of the space charges produced in the atmosphere greatly influences the general course of the field.

Thus, the term "good" weather should probably apply only to periods when profiles of group I appear. Vertical sounding is one way of distinguishing these periods.

4. DISTRIBUTION OF SPACE CHARGE IN THE ATMOSPHERE

The altitude variation of the space charge $\rho(z)$ can be calculated from data on the variation of the electric field intensity with altitude using formula (6).

For profiles of group I we obtain from (14)

$$\varrho = -\frac{a\varepsilon}{4\pi} E_n e^{-az}. \tag{18}$$

We note that the space charges are much closer to the earth over the continents than over the oceans.

From data on the altitude variation of the field we can also calculate the charge of a column of air of unit cross section. The daily variation of this charge has the appearance of a simple wave. From the time variation of this charge we find that the current charging this air column amounts to 10^{-13}—10^{-14} A/m², i.e., 1—10% of the conduction current. This ratio shows that the assumption that the current in the atmosphere is stationary is in general valid. The average value of the space charge of an air column in the 0—600 m layer amounts to 0.5 × 10^{-3} esu/m³ in Leningrad, 0.4 × 10^{-3} esu/m³ in Kiev, and 0.22 × 10^{-3} esu/m³ in Tashkent. The charge of the column is less than the surface density of the earth's own charge.

In the case of profiles of group II, the variation of

*The field due to the earth's charge cannot fail, of course, to evoke corresponding space charges in a conducting atmosphere, but the field due to these charges should be exactly offset by the earth's own charge.

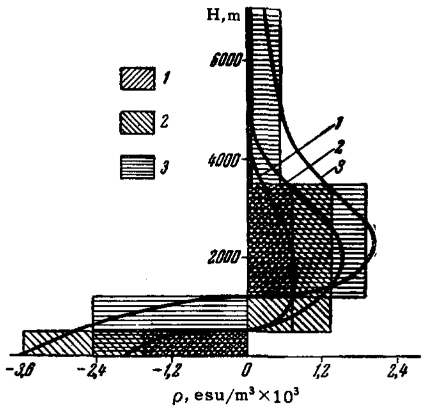

FIG. 13. Variation of space charge density with altitude for field profiles of group III.[63] 1 – Leningrad; 2 – Kiev; 3 – Tashkent.

the space charge is similar to that given by formula (18) up to the altitude at which the field reverses direction. In the layer from 0 to 6,000 meters, the value of this charge is higher than the surface charge density of the earth.

In the case of profiles of group III, the distribution of space charge is shown schematically in Fig. 13. We see that the atmosphere becomes polarized for profiles of this group, with negative space charges below and positive above. The entire positive charge in the vertical column of air is frequently greater in absolute magnitude than the sum of the negative charge of the column and the surface charge of the earth. The average negative space charge is 1.6 × 10^{-3} esu/m³ in Leningrad, 3.6 × 10^{-3} esu/m³ in Kiev, and 2.4 × 10^{-3} esu/m³ in Tashkent; the corresponding average positive charge is about 0.4, 0.6, and 0.95 × 10^{-3} esu/m³.

The profile of the space charge may experience considerable changes during the day. This is shown schematically in Fig. 14, plotted from the data of Fig. 8. Both the magnitude and the locations of the negative and positive charges change abruptly over the day. Since the appearance of space charges is connected with the settling of light ions on heavy particles, the electric field influences little the displacement of the charges.

In fact, considerable space charges are produced in the mixing layer, as indicated above, also by ions

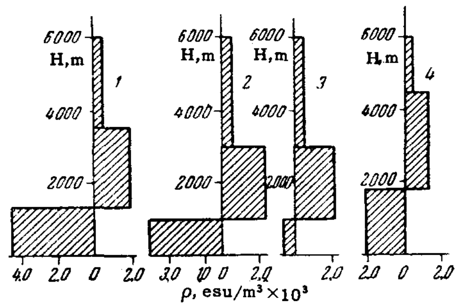

FIG. 14. Transformation of the space-charge profile during the day (Tashkent, June 1958[63]).

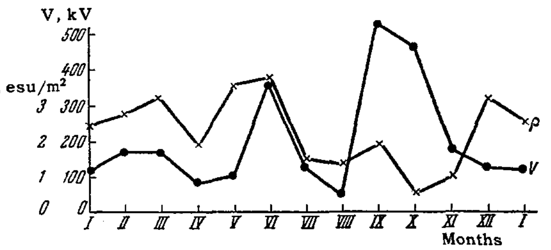

FIG. 15. Annual variation of the space charge (ρ) in a vertical column 6,000 meters high, and of the potential (V) at 6,000 meter altitude.[63]

with mobility less than 10^{-3}—10^{-4} cm^2/V-sec. In a field of intensity 1—2 V/cm, the linear speed of these ions does not exceed 10^{-3}—10^{-4} cm/sec, i.e., merely several centimeters per hour, whereas the observed displacements of the space-charge layer amount to several meters or sometimes several times ten meters hourly. The observed displacements are those connected with the turbulent diffusion, convective movements of the air, and the displacement of the particles in the gravitational field.

The annual variation of the air column of unit cross section within the layer 0—6000 meters and of the potential at an altitude of 6,000 meters above Leningrad in 1958 is shown in Fig. 15. This variation is similar in many respects to the annual variation of the space charge near the earth's surface. A minimum is noticed, in particular, in the fall. The changes in the charge amount to 0.5—3.8 esu/cm^2, whereas the amplitude of the annual variation of the earth's charge density does not exceed 0.5 esu/m^2.

The appearance of separate charges in the atmosphere during days of "good" weather can be explained in part by variations of conductivity with altitude. One of the possible reasons for this separation may be the accumulation of charges in a poorly conducting layer.

The influence of space charge in the atmosphere on the overall course of the field intensity above the earth is illustrated by the data of Fig. 16, which shows the latitudinal variation of the field intensity over the oceans, obtained during the time of three marine expeditions to the Antarctic shore.[64] The maximum, which is regularly noticed in the region 10—20° southern latitude, is apparently connected with the intensified thunderstorm activity at these latitudes, which leaves a positive charge in the atmosphere.

5. TIME VARIATION OF FIELD AND POTENTIAL AT HIGH ALTITUDES

In comparing the sounding data obtained in different times, we can disclose the daily variation of the field intensity at high altitudes.

Fig. 17[63] shows the daily variations of the field intensity (Greenwich mean time) at altitudes from 0 to 500 meters and the potential at an altitude of 6,000 meters near Leningrad and Kiev.

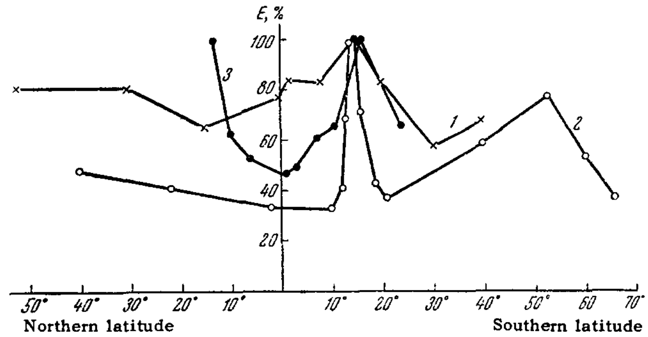

FIG. 16. Latitudinal variation of the field intensity over the oceans.[64] 1 – Fall; 2 – winter; 3 – fall.

Two facts are striking. The variation of the potential at 6,000 meters does not agree at all with the unitary variation, while the variation of the field intensity, which does not agree with the unitary variation at the earth's level and above 400 meters, agrees well with the unitary variation at 200—300 meters. The fact that the unitary variation manifests itself only at certain altitudes is a characteristic of all three groups of profiles, although the altitudes are different for the different groups.

In the case of profiles of group III,[43] for example, the unitary variation appeared in the summer of 1958 at an altitude of 700 meters in Leningrad, at 1,000 meters in Kiev, and at 700—1000 meters in Tashkent. The correlation coefficients between daily variation of the field intensity, measured at the same points, and the unitary variation measured over the oceans are 0.92, 0.7, and 0.96, respectively. These data explain the appearance of unitary variation on the top of the Eiffel Tower, already noticed by Chauveau,[67] although no correct explanation was proposed at that time for this phenomenon, and it was assumed that the collector was located outside the layer in which the electrode effect occurs.

The unitary variation occurs at a definite altitude only, because the field due to the space charges located above and below this altitude, and also due to charges induced by them in the earth and in the atmosphere, cancel each other and thus permit the earth's field to manifest itself.

If we have data on the levels h at which the unitary variation is observed, we can estimate the height H of the effective layer of the space charge in the atmosphere.[43,68]

Assuming that $\rho = \rho_0 e^{-az}$ inside this layer, we obtain for continents ($a = 1$ km^{-1}) and oceans ($a = 0.25$ km^{-1}), for h = 0.2 and 1 km respectively,

$$H = 0.5 \text{ and } 2.5 \text{ km and } H = 0.4 \text{ and } 2 \text{ km}.$$

These low values of H show that the effective height of the induced charges is that of the lower troposphere. The same region contains obviously charges induced in the atmosphere by the earth's charge. The conductivity

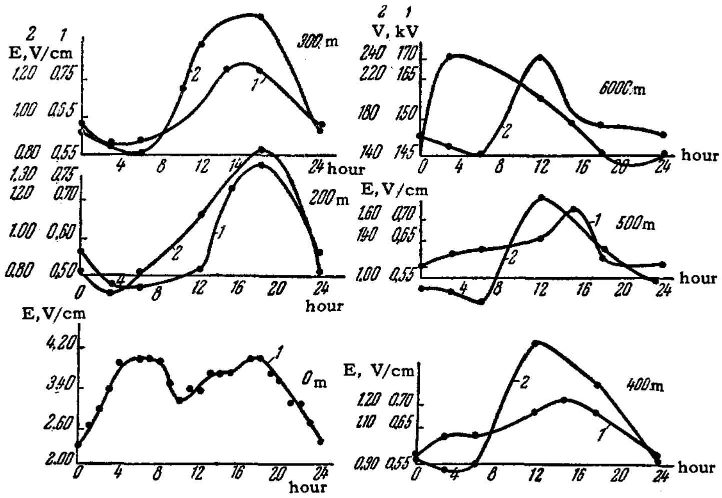

FIG. 17. Daily variation of field intensity at altitudes from 0 to 500 meters and of the potential at 6,000 meters (summer, 1958[63]). 1 – Leningrad; 2 – Kiev (Greenwich time).

is low and cannot ensure equalization of the potential within the required time.

Let us examine the data obtained by measuring the potential. These should help ascertain whether the assumptions underlying the theory of the "spherical capacitor" and the theory of J. I. Frenkel are correct.

Integrating the curve E = f(z) we can calculate the potential V at the altitude h:

$$V(h) = -\int_0^h E\,dz. \tag{19}$$

As follows from the altitude variation of the field intensity (see Figs. 6 and 7, and also [68]), the potential does not always increase with altitude monotonically, and sometimes starts decreasing beyond a certain altitude.

The daily variations of the potential at 6,000 meters, measured simultaneously in three continental stations, are shown in Figs. 18a, b, and c.[63] It is essential to note that neither the mean values of the potential at high altitude nor its time variations are the same at

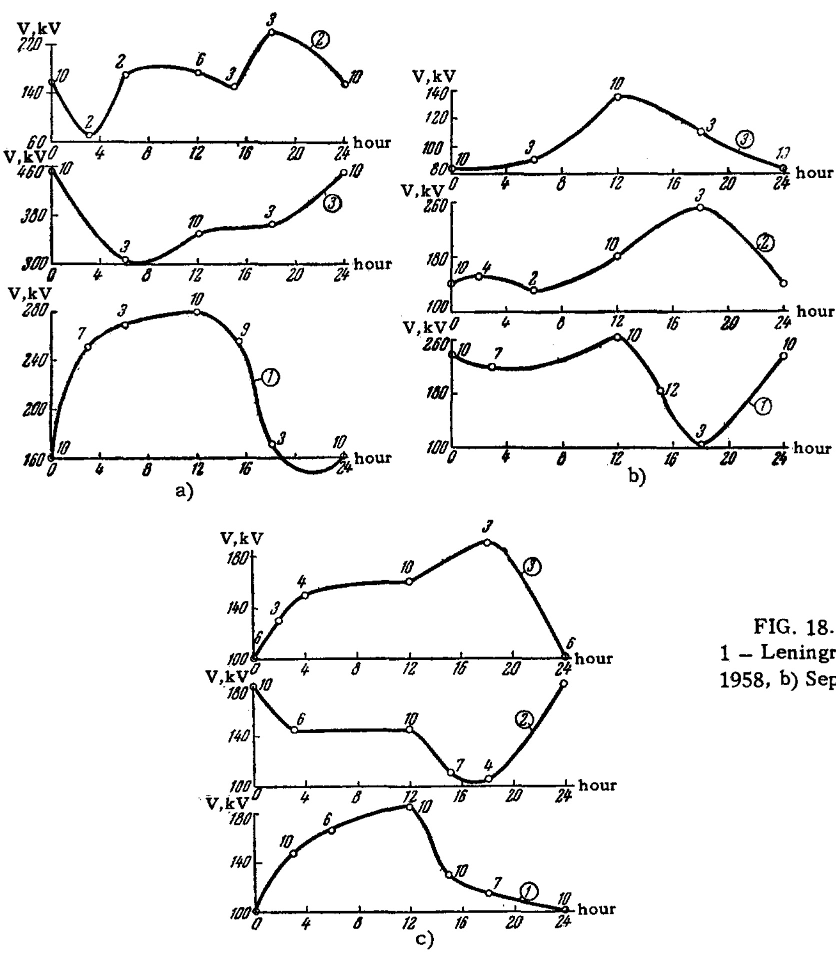

FIG. 18. Daily variation of the potential at 6,000 meters.[63] 1 – Leningrad; 2 – Kiev; 3 – Tashkent (Greenwich time). a) June 1958, b) September 1958, c) December 1958.

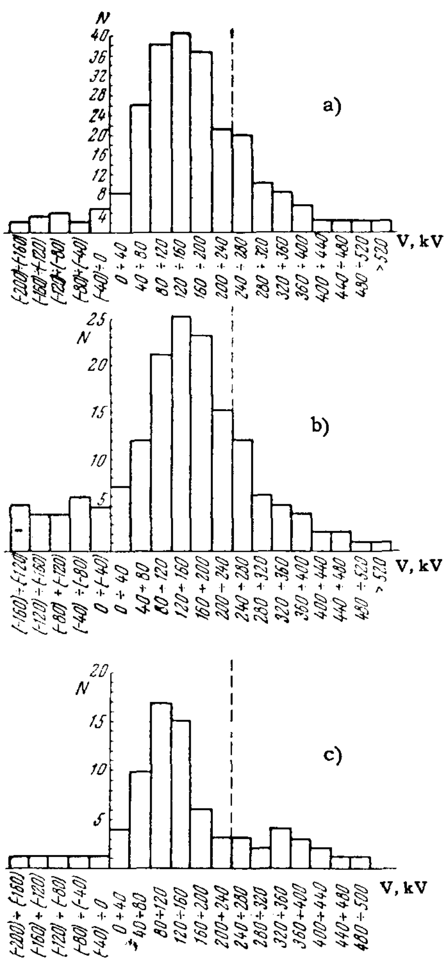

FIG. 19. Histograms showing the potential at 6,000 m.[63] a) Leningrad, 1958; b) Kiev, 1958; c) Tashkent, 1958.

the different points of observation. During the time of the International Meteorological Interval in June 1958 (Fig. 18a) the mean potential at 6,000 meters was 230 kV in Leningrad, 160 kV in Kiev, and 370 kV in Tashkent. The corresponding values were 220, 170, and 110 kV in September 1958 and 140, 140, and 150 kV in December 1958.

Neither are the relative variations of the potential at high altitudes similar. Thus, in June 1958 the relative changes in potential at the points of observation were 28%, 22%, and 50%, respectively.

The daily and annual variations of the potential over different continental stations are not in phase with each other, nor are they in phase with the unitary variation of the field intensity.

The unitary variation of the potential does apparently occur over the oceans [51] at 6,000 meters, the mean registered value of the potential being 231 kV.

The relative amplitude of the annual variation of the potential over Leningrad exceeds greatly the annual amplitude of the unitary variation. [63]

Figure 19 shows histograms of the electric potential at 6,000 meters over three continental stations. [63,68] The dashed lines in the figure denote the values of the potential expected from Gish's formula. [70]

We see that the most probable values of the potential are less than expected. For Leningrad and Kiev, the most probable value of the potential lies between 120 and 160 kV, while for Tashkent it lies between 80 and 120 kV. In many cases, negative potentials reaching −200 kV are observed.

In individual good weather days, the potential over the point of observation can reach 5×10^5 V; cases of $+3 \times 10^7$ V and -3×10^6 V were observed in cloudy days.

The measured value of the potential at 6,000 meters differs slightly from the potential of the ionosphere. According to Gish [70] the potential at 6,000 meters should amount to about 70% of the potential of the ionosphere; if we start from Eq. (2), the percentage is more than 95, and over the oceans (after Clark [51]) it is about 80. Thus, the measured values of the potential enable us to estimate the potential of the ionosphere, which should amount [68,69] on the average to about 200—250 kV.

6. DESCRIPTION OF ELECTRIC PROCESSES IN REGIONS OF GOOD WEATHER

Certain facts, such as the non-synchronous variation of the potential at high altitudes over different points of the earth's surface, the lack of similarity between the unitary variation of the field intensity and the daily course of the potential, the non-monotonic variation of the field intensity with altitude, or the low effective height of the induced charges, cannot be reconciled with the "spherical capacitor" theory.

On the other hand, the weak influence of the high layers of the atmosphere on the electric processes in the "good" weather zone in the troposphere justify one of the main premises of Frenkel's theory. At the same time, many observed facts, hitherto unknown, cannot be fitted in the frame of either basic theory. Among these facts are the considerable diurnal and annual variations of the space charges in the atmosphere, with a relative amplitude that exceeds the relative amplitude of the variation of the earth's surface charge, the polarization of the atmosphere in clear weather, and the existence of considerable diffusion currents flowing towards the earth's surface.

Many previously known and recently discovered facts can be explained with the aid of a somewhat different scheme. [44,68]

Let us imagine a well-conducting sphere, the earth, surrounded by a poorly conducting medium, the atmosphere. We assume that clouds or dust layers have appeared above some part of the earth's surface and the charges in the atmosphere became separated. The field due to these charges is confined to the region of the clouds and will be regarded as local. If precipitation, the settling of dust on the earth, or some other factor causes the charges to settle on the earth, they become distributed within a certain time over the entire earth as a whole. In this case there will be superimposed on the local field an additional field over the entire earth's surface. The direction of the field will be such as to tend to discharge the earth into the atmosphere.

Let us assume (Fig. 20) that a charge $-Q$ has settled on an area S_1 in some zone from a previously neutral atmosphere. If the area of the entire earth is S, then the additional charge on the earth's surface in that zone will assume a value $-Q_1 = QS_1/S$, after a certain time determined by the conductivity of the atmosphere and the conditions under which the charge is transported by the air currents. This charge, in conjunction with the charge of the atmosphere, produces in the atmosphere the field variation shown in Fig. 20c (compare with the measured variation in Fig. 7). The charges of the first zone, which have settled on the earth, will produce on the remaining surface of the earth an additional charge $Q_2 = -Q_1S_2/S$, where $S_1 + S_2 = S$. The altitude variation of the field obtained after the establishment of the stationary current will then be given by the curve of Fig. 20a (compare with the measured altitude variation of the field in Figs. 5—7). It is significant that the field due to the charges in the atmosphere can no longer offset the field due to the earth's charge, and a positive field will appear in the second zone, which can be called the good weather zone, extending up to very high altitudes and decreasing with increasing conductivity. As positive charges are transported by the air currents from the first zone to the second zone of the atmosphere, the latter becomes richer in positive charges to an extent that may even be sufficient to offset the earth's field at a certain altitude (see Fig. 20b and compare with Fig. 6).

If we further extend this pattern to the earth as a whole, then a series of zones of the first type, poor weather zones, will exist simultaneously and generate charges; this series will undoubtedly include the thunderstorm zones.

Active sources of charge separation in the atmosphere may be clouds which are usually positively polarized (see below). These zones also include deserts and semi-deserts, and apparently other zones in which charges can become separated. Such a zone, as already pointed out, is identified by a field variation similar to that of Fig. 20c. The clearly pronounced latitudinal course of space-charge distribution in the atmosphere, which apparently gives rise to a latitudinal variation of the field intensity along with the variation of the ionization of the atmosphere due to the latitudinal variation of the cosmic rays,[150] is due to the geographic distribution of these zones.

Analogously, there should exist in the atmosphere a series of good weather zones, similar to the second

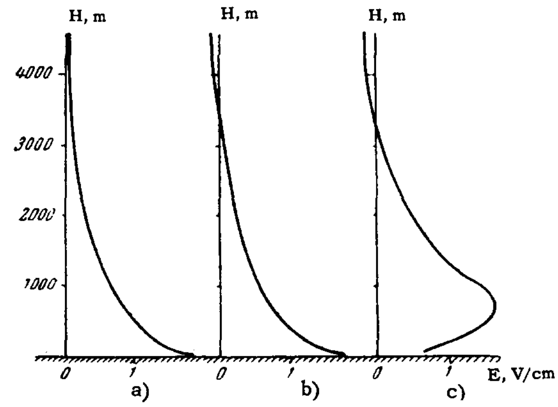

FIG. 20. Field intensity profiles in regions where the atmosphere gave up negative charges to the earth, (b) and (c), and in regions where there is no excess charge in the atmosphere (a).[63]

zone and characterized by the altitude variation shown in Fig. 20a. The continuous formation and disappearance of such zones gives rise to the good weather field, determined essentially by the earth's own charge and by the altitude variation of the atmospheric conductivity. This field may become clearly pronounced near the earth's surface where the space charge is produced only under the influence of the earth's field and the displacement of the ions is due essentially to the electric field, while the diffusion and convection currents play a secondary role. Such regions may be oceans, polar regions, and high mountain regions. The field is negative in the upper part of the troposphere and above, and in poor weather zones, and positive in good weather zones. The appearance of fields in the upper layers of the atmosphere may give rise to compensating currents in the same layers. Thus, a compensating current should flow in the upper layer of the atmosphere between the two types of regions. The level at which this horizontal current begins lies obviously at the altitudes where the field reverses sign, i.e., 3—4 km. At these altitudes, obviously, the electric atmospheric field lines begin to deviate from vertical.

The air streams should continuously transport the space charges from the poor weather region to the good weather zones and vice versa. The electric field and the diffusion and convection currents transport these space charges in a vertical direction.

Thus, the field in the atmosphere is determined by the field of the earth's charge and the field of the local charges of the atmosphere. Since the latter is quite large, there is no similarity in either the magnitude or in the variation of the potential of the atmosphere over different points of observation. The changes in the earth's own charge manifest themselves in the field variations noted simultaneously at different points on the earth's surface.

The space charges can be produced in good weather zones by five processes.

1. Separation of light ions of different polarities by the electric field.

Table I. Characteristic of stratified clouds [76]

Type of cloud	Number of investigated clouds	Potential $V_{6,000}$, kV	Charge of air column $Q_{0-6,000}$, esu/m²	Average height of lower boundary of clouds (meters)	Average thickness of clouds (meters)	Electric field intensity in the clouds (V/cm)						Space charge density in the clouds, ×10² (esu/m³)			Total charge of vertical cloud column (esu/m²)	Potential difference between the upper and lower boundaries of the cloud, ΔV(kV)
						Average		Maximum		Minimum						
						E_{av}	$\|E_{av}\|$	E_{max}	$\|E_{max}\|$	E_{min}	$\|E_{min}\|$	ρ_{av}	ρ_{max}	ρ_{min}		
St	116	62	2,6	350	500	0,9	1,6	2,1	2.6	−0,3	0,7	0,7	3,8	−2,2	2,8	17
Sc	357	242	1,8	1000	500	0,3	1,8	1,6	3,1	−0.5	0,8	0,8	5,5	−1,8	3,4	2,4
As	218	660	0,5	3400	950	−0,2	3.2	4,7	8,4	−3,3	1,2	−0,1	5,2	−12,4	1.0	87
Cs	48	0	2.9	5500	1100	0,0	2.8	1.9	6,8	−2,4	0,7	1,2	4,8	−0,4	−3,8	−323
Ns	155	380	−8,7	900	2100	0,3	5,6	12,9	18.6	−9,8	0.4	0,2	34,5	−18,1	−0.3	−78

Table II. Relative distribution of electric field intensity in clouds of stratified form, percent [76]

Type of cloud	Interval of mean field intensities in a 100 meter layer (V/cm)													
	< −14	−14 — −10	−10 — −6	−6 — −4	−4 — −2	−2 — −1	−1 — 0	0 — 1	1 — 2	2 — 4	4 — 6	6 — 10	19 — 14	> 14
St			3	2	4	3	16	24	32	15	1			
Sc			4,5	3,5	6	6	13	24	25	14	2,5	1,0		
As	1	3	4	2,5	2,5	3,5	10	12,5	18.5	23,5	9	8,5	3,5	1
Cs		1	2	1	5	15	22	15	15	13	4	6		
Ns	3	3	7	10	12	10	10	10	9	9	3,5	5,5	4	3

2. Transport of space charges from poor weather zones.

3. Adsorption of light ions from the atmosphere by the aerosol particles with subsequent spatial separation due to differences in the weights of differently charged ions bound to different sorts of particles.

4. Entry of particles that have become charged on breaking away from the earth into the atmosphere.

5. Charging of particles in the atmosphere by interaction with one another or by transfer of the charge from the particles to the atmosphere, with subsequent spatial separation of oppositely charged particles of different sizes.

The first process is predominant only in a clean atmosphere, and results in profiles of the first type. The second process undoubtedly appears, for example, in the case of profiles of the second type, but cannot explain the daily variations of the space-charge profile, the connection between the daily variation of the measured space charges, and local characteristics of the atmosphere such as aerosol concentration, radioactivity of the atmosphere, etc. The mechanism of the third process was already considered; without raising the question of the elementary processes that bring about the settling of ions on the heavy particles, the accumulated space charge can be determined from the altitude distribution of the aerosols. The space charge distribution characteristic of field profiles of the third type can also be produced by the fourth and fifth processes. Charging of particles that break away from the earth cannot occur when the wind is weak and over surfaces with dense vegetation.

The daily altitude variation of the space charge distribution also indicates that this charging process cannot be predominant. The role of the fifth charging process is still an open question at present. The elementary processes that can bring about the charging of aerosol particles of different sizes by charges of opposite polarities have not yet been investigated; some ideas in this direction are now being tested. [71–74] For the time being they have led to mutually contradictory results (see, for example [71–73]).

Both main theories of atmospheric electricity deal with the possible generators that maintain the good-weather field. According to Wilson, Israel, et al, these sources are the thunderstorm clouds; according to Frenkel these are all clouds, or at least clouds with vertical development. Let us examine the main characteristics of the electricity of clouds.

7. ELECTRICITY OF STRATIFIED CLOUDS

Stratified clouds, which extend over territories that are hundreds of times larger than those occupied by thunderstorm clouds, may stay for weeks above the same point. Almost half of the earth's surface is covered with stratified clouds. The electric charges and currents in these clouds, although much smaller than in thunderstorm clouds, can consequently play an appreciable role in the overall exchange of charges

Table III. Sizes of charges in clouds of different structures [75,76]

Type of cloud	Arrangement of charges	Type of electric structure							
		Polarized clouds				Unipolarly charged clouds			
		Positive polarization		Negative polarization		Positively charged		Negatively charged	
		Charge of column with 1 m² area (esu/m²)	Average space charge density (esu/m³)	Charge of column with 1 m² area (esu/m²)	Average space charge density (esu/m³)	Charge of column with 1 m² area (esu/m²)	Average space charge density (esu/m³)	Charge of column with 1 m² area (esu/m²)	Average space charge density (esu/m³)
Stratus (St)	Upper charge	+2.5	$0.5\cdot10^{-2}$	−8.8	$-3.0\cdot10^{-2}$				
	Lower charge	−2.5	$-0.5\cdot10^{-2}$	+8.8	$+1.2\cdot10^{-2}$				
	Excess charge	+2.7	$+0.5\cdot10^{-2}$	+2.5	$+0.4\cdot10^{-2}$	7.5	$+1.9\cdot10^{-2}$	−6.4	$-1.6\cdot10^{-2}$
Stratocumulus (Sc)	Upper charge	+3.0	$+0.5\cdot10^{-2}$	−3.7	$-1.8\cdot10^{-2}$				
	Lower charge	−3.0	$-1.0\cdot10^{-2}$	+3.7	$+0.5\cdot10^{-2}$				
	Excess charge	+4.3	$0.6\cdot10^{-2}$	+3.2	$0.45\cdot10^{-2}$	6.9	$1.7\cdot10^{-2}$	−10.6	$-2.5\cdot10^{-2}$
Altostratus (As)	Upper charge	+2.9	$0.5\cdot10^{-2}$	−3.5	$-0.6\cdot10^{-2}$				
	Lower charge	−2.9	$-0.5\cdot10^{-2}$	+3.5	$+0.6\cdot10^{-2}$				
	Excess charge	−1.9	$-0.2\cdot10^{-2}$	0	0	+23.2	$3\cdot10^{-2}$	−4.5	$-0.5\cdot10^{-2}$

between the earth and the atmosphere. The electric properties of these clouds remained practically unknown until recently. Let us examine the electric characteristics of individual types of stratified clouds (Tables I, II, III) as given by [75,76].

a) Low stratus clouds. [75] The thicknesses of the investigated clouds ranged from 100 to 1,000 meters. The field intensity ranged essentially from −1 to +3 V/cm (80% of the cases).

Based on their electric structure, these clouds can be classified in four types. In 50% of the cases the clouds were positively polarized. In addition, an excess positive charge was observed in the clouds. In 10% of the cases negative cloud polarization was observed. Many of the investigated clouds had unipolar charges. In 30% of all cases the clouds were positively charged. The remaining 10% were negatively charged. The profile of the field intensity for all types is shown in Figs. 21a–d. The sizes of the charges are listed in Table III. The altitude variation of the electric field during days when only stratus clouds are observed is shown in Fig. 23a. We see that these clouds are associated with the appearance of a considerable negative charge on the earth's surface and a rapid decrease of the field with increasing altitude. Above 3,000 meters, the field intensity is close to zero.

b) Low stratocumulus clouds. [75] The thicknesses of the investigated clouds range from 100 to 1800 meters. The field intensity in these clouds varies essentially between −2 and +3 V/cm (80% of the cases). Like the stratus clouds, these clouds have four types of electrical structure: positively polarized (45%) (Fig. 22a), negatively polarized (13%, Fig. 22b), positively charged (23%) (Fig. 22c), and negatively charged (7%) (Fig. 22d).

In 12% of the cases the clouds either had charges smaller than the measurement accuracy, or had a complicated electric structure (the clouds had three charges with vertical arrangement + − + or − + −).

The altitude variation of the electric field in days when only stratocumulus clouds are observed is shown in Fig. 23b. As in the preceding case, a negative space

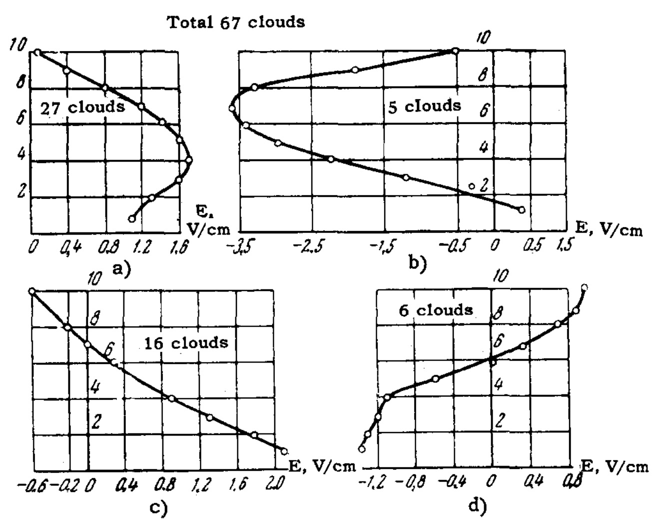

FIG. 21. Four types of field intensity profiles in stratus clouds.[75] a) and b) – clouds with positive and negative polarization; c) and d) – clouds with positive and negative charge.

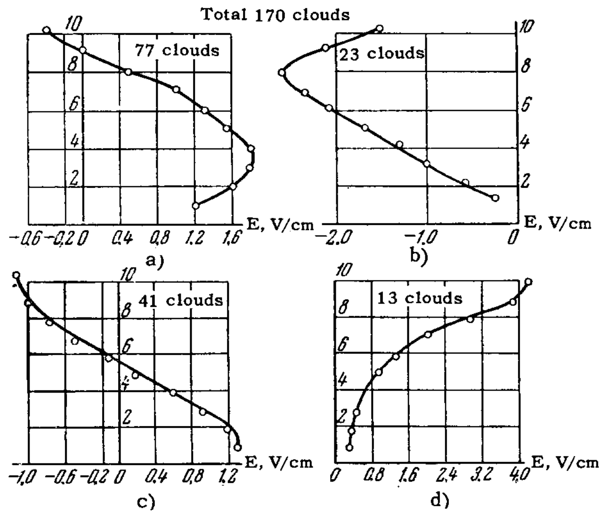

FIG. 22. Four types of profiles of field intensity in stratocumulus clouds.[75]

charge is produced under the clouds, but above the clouds the field intensity remains appreciable up to 6,000 meters.

The conductivity in stratus and stratocumulus clouds or in fogs that have similar properties is several times lower than the conductivity in clear atmosphere, the conductivities of both polarities being approximately the same. According to [77] the conductivity in supercooled clouds decreases by a factor of 3–5 (as much as 20 in individual cases), according to [79] (on Mt. Elbrus) it decreases to approximately 1/3, according to [78] it decreases to about 1/4. In fogs [19] the conductivity is decreased to about 1/3.

The charges of the droplets in stratus clouds and fogs were measured in [80–83]. The probability of charging a drop to either polarity is approximately the same. The measured charges q were found to be proportional to the drop radius: $q = kr$ (Table IV).

Measurements in fogs[80] yielded $k \simeq 16$, measurements on Mt. Elbrus[81] yielded $k \simeq 13$, measurements on an airplane[82] yielded $k \simeq 18$, while measurements[83] on an aerostat balloon yielded $k \simeq 20$ (the radius is in microns and q in elementary charges). Many drops remained practically uncharged or very weakly charged.

Quite different data are cited by Twomey[84] (stratus clouds, observations on mountains, in Tasmania), where the charge turned out to be several times greater and proportional to the square of the radius (see Table IV).

Table IV. Charges of droplets in clouds and fogs, expressed in elementary charges[83]

Measurement conditions	Drop radius (microns)			
	2	5	8	10
Fog, measurements on a plain[80]	20	75	42	46
Stratus and stratocumulus clouds on a mountain[81]	28	68	81	104
Stratus and stratocumulus clouds—airplane measurements[82]	25	94	127	188
Clouds—aerostat measurements[83]	36	96	—	—
Clouds, measurements on mountains[84]	—	200	800	1000
Thunderstorm clouds[104]	—	270	320	—

We note that the charges of the drops turned out to be much less than would follow from the assumption that the electric kinetic potential of the water is the cause of the charge, but several times greater than would follow from the diffusion mechanism of charging the drops.[8]

c) Altostratus clouds.[76] These clouds are produced at considerable altitudes (above 2,000 meters), where the good weather field is appreciably attenuated.

These, too, exhibit the four types of distribution mentioned. Positive polarization is noticed in 30% of the cases, negative in 25%, positive charge in 12% and negative charge in 13% of all cases. In addition, in 10% of the cases weakly charged clouds are observed, while another 10% comprise clouds with a complicated charge structure such as + – + or – + –.

The field variation in days when these clouds were present is shown in Fig. 23c; again we see a negative space charge between the surface of the earth and the base of the cloud. Negative polarization is more frequently observed in these clouds, and the clouds themselves have an excess negative charge.

d) Cirrostratus clouds.[76] These clouds lie high above the earth's surface at a level of 5,000 meters and above. Nonetheless, they decrease noticeably the field intensity at the earth's surface (see Fig. 23d). The field in these clouds is usually negative.

In addition to the previously noted types of polarized clouds, two other types are frequently encountered, in which the upper and lower parts of the clouds have positive charges, and the middle of the cloud is negative (distribution of the + – + type), as well as clouds with a distribution – + –.

As can be seen from the foregoing, stratus clouds that produce no rain exert an appreciable influence

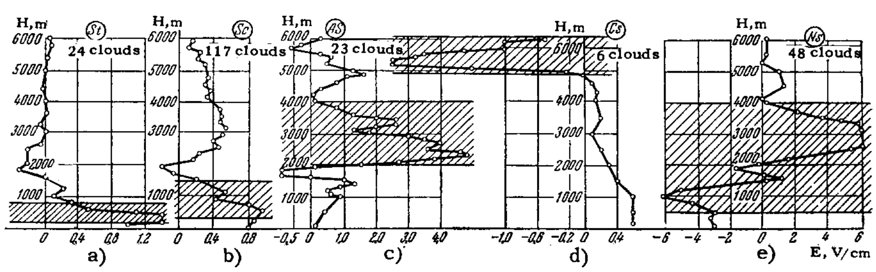

FIG. 23. Altitude variation of electric field in days with stratified clouds.[76] a) Stratus, b) Stratocumulus, c) Altostratus, d) Cirrostratus, e) Nimbostratus clouds. The shaded region shows the heights at which the clouds of the given type were located.

Table V

Form of cloud	Interval of most probable values of average electric field intensity in the clouds, V/cm	Interval of cloud thickness, m	Remark
Cumulus.	0–10 [44]	100–1500 [95,99]	Field data pertain to cloud thickness smaller than 4,000 meters
Cumulus congestus.	0–10 [92]	1500–5000 [95,99]	
Thunderstorm	300–2000 [94-96]	2000–12000 [98,97,94]	

on the electric characteristics of the atmosphere. Attention should be called first to the appreciable electric space charge produced by these clouds, ranging from 3 esu/m^2 to several times 10 esu/m^2. We recall that the surface charge of the earth amounts to about 3 esu/m^2, and its unitary variation amounts to only about 20% of this quantity.

Thus, the variation in the charges of the clouds exceeds greatly the observed unitary variations of the charge of the earth. It must also be recalled that stratus-type clouds cover almost 50% of the earth's territory. Consequently the total contribution which they make to the charge exchange between the earth and the atmosphere can be quite large. The appearance of a negative space charge near these clouds should be accompanied by diffusion currents which carry negative charges to the earth. The first attempt to measure these currents directly[62,66] yielded favorable results.

The character of decrease in the field intensity with increasing distance from the cloud to the earth shows that this field is produced not directly by the charges of the cloud, but by the charges which these clouds produce and redistribute. The clouds act not as field generators, but as generators of space charge in the atmosphere.[44] Only high clouds of the cirrostratus type fail to produce a considerable negative space charge at the earth's surface. Stratus clouds, as shown by the data of Table I, greatly influence the potential of the atmosphere at an altitude of 6,000 meters. They produce in this potential relative changes which are much greater than the changes due to the

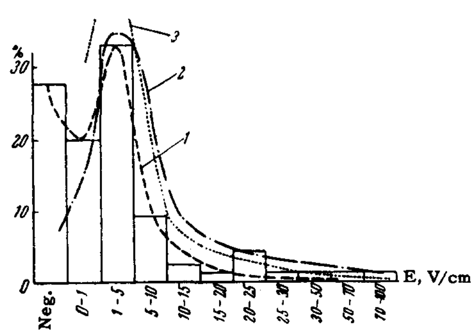

FIG. 24. Frequency of occurrence of average values of field intensity in all the investigated cumulus congestus clouds (1), in cumulus congestus clouds with positive average field intensity (3), and in cumulus clouds (2).[92]

unitary variation. Thus, the stratus clouds apparently play an appreciable role not only in the formation of the bad weather field, but also in good weather.

The mechanism whereby the space charges are produced in this case is not clear at all. We have seen that the charges on droplets of these clouds are small and the spectrum of the positively charged drops is approximately similar to the spectrum of the negatively charged ones. We cannot assume in this case that gravitational coagulation of the minute drops guarantees accumulation of the charges on the large drops, since the coalescence of the drops leads in such a case to a relative decrease in the charges on the drops. It can be assumed that in these clouds there occurs, under definite conditions, an exchange in charges between drops of different dimensions or between the drops and the air. One of the possible mechanisms of this type was considered by V. Ya. Nikandrov,[86] who assumed that evaporation may charge a liquid because of the difference in the mobilities of the anions and cations in the liquid (see[74]). In addition, an important role may be played in the electrification of altostratus and cirrostratus clouds by the precipitation particles falling from these clouds.[89]

e) Nimbostratus clouds.[76] Precipitation from the cloud contributes to an accumulation of electricity in the cloud. The electric structures of nimbostratus clouds are highly varied and complicated. Along with the aforementioned four types, clouds are encountered with three and even four layers of charges. The general characteristics of nimbostratus clouds are given in Table I.

The altitude variation of the electric field intensity in the presence of nimbostratus clouds is shown in Fig. 23e.

It is interesting that the measured altitude variation of the field intensity in these clouds agrees, in general outline, with the field profile proposed by Chalmers[106] for nimbostratus clouds.

The measured cloud profiles agree with those obtained under the assumption that the space charge carried by the rain is positive and that the melting of the snow flakes from which the drops are formed occurs in the upper part of the cloud.

In nimbostratus clouds one observes a higher field intensity than in other types of stratus clouds. These clouds reverse the sign of the field intensity at the earth's surface and produce near the earth a positive space charge. The charge of these clouds is for the most part negative. The average charge of a precipitation drop near the earth's surface ranges from 10^{-4} to 10^{-3} esu [86–88,105], the negative charge being somewhat higher than the positive one. On the whole, however, the charge carried by the precipitation from these clouds is positive. For example according to [90] and [91], one gram of positively charged drops carries 0.21 esu, while 1 gram of negatively charged drops carries 0.08 esu. These numbers may vary in individual drops by as much as a factor of 10.

Positively and negatively charged drops are encountered simultaneously in precipitation on earth. However, under the clouds all the drops have essentially like charges. Thus, some of the drops exchange charges as they fall. The current carried by the precipitation from the clouds is about 5×10^{-16}—5×10^{-15} A/cm^2. [90,91]

As pointed out by E. K. Fedorov, [105] the average and maximum charges of both positively and negatively charged drops increase and decrease simultaneously, i.e., the precipitation does not remove appreciable charges even from isolated regions of the clouds.

8. ELECTRICITY OF CUMULUS AND CUMULUS CONGESTUS CLOUDS [44,65,92]

Cumulus and cumulus congestus clouds are of particular interest, because they develop into shower and thunderstorm clouds, which produce the greatest electrification of the atmosphere. Many characteristics of cumulus congestus clouds (turbulence, water content) are similar to those observed in thunderstorm clouds. A hypothesis has been advanced that cumulus congestus clouds are by way of a model of thunderstorm clouds, in which it is safer to carry out the investigations. This assumption, as will be demonstrated below, is not confirmed, but certain regularities in the charging of thunder clouds can be deduced from research on cumulus congestus clouds.

Investigations of cumulus clouds [44,65,92] have shown that their field is highly irregular; in a single flight through a cloud one can encounter several field extrema, both positive and negative. The average field intensity in cumulus clouds is as a rule positive. Negative values are observed in approximately 25% of the cases; they are usually connected with the appearance of large drops in the clouds and with the start of precipitation.

The measured average values of the field intensity are shown in Fig. 24. Curve 2 characterizes the average value of the field intensity in cumulus clouds. [44] Curve 1 gives the values of the field intensity in thick convective clouds. If one excludes from the statistics the clouds that are in the state of transition towards the shower and thunderstorm cloud, [93] then the distribution of the frequency of occurrence of the average values of the field intensity will be characterized by curve 3 of Fig. 24.

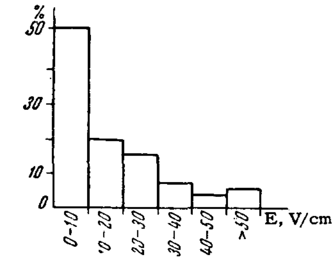

FIG. 25. Frequency of occurrence of extremal values of field intensity in cumulus congestus clouds.[92]

The connection between the vertical dimensions of the cloud and the average field intensity in the cloud is shown in Table V.

The data of Fig. 24 and Table V show that the vertical dimensions of the convective clouds do not influence greatly the average values of the field intensity in them, so long as the qualitative jump connected with the appearance of the ice phase does not occur in the cloud; the latter brings a new electrification mechanism into being. [93,95]

The extremal values of the field intensity in cumulus congestus clouds may exceed the mean values considerably. Figure 25 shows the frequency of occurrence of the extremal values of the field in these clouds. These extrema are noticed for both vertical and horizontal components of the field intensity. [101]

In cumulus congestus clouds, extremal fields are usually encountered in zones of relatively small dimensions (50—150 meters). It is frequently suggested that very large field intensities can occur in cumulus congestus clouds within limited volumes and give rise to discharges. The measurement data do not confirm this assumption. The probability of occurrence of large fields does not increase with decreasing dimensions of the zone.

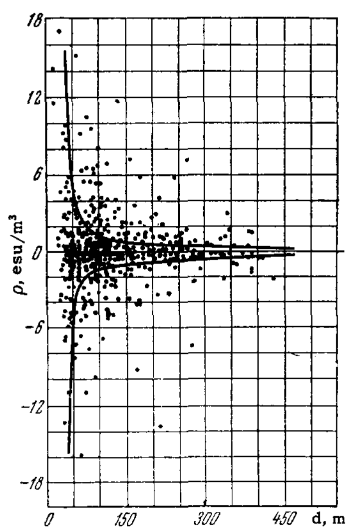

FIG. 26. Connection between dimensions of zones where the charges are inhomogeneous, and the absolute values of the extrema of the space charges in these zones.[92]

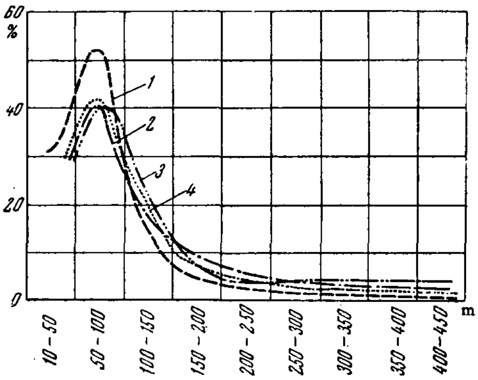

FIG. 27. Frequency of occurrence of linear dimensions of zones where the field intensity has extremal values (3), of the airplane charge (2), and also of the jet dimensions as obtained with an accelerograph (1) and from data on the temperature pulsation (4).[65]

The average space charge density did not exceed 1 esu/m^3 in 80% of the cases. The most probable values of the average density range from 10^{-2} to 2×10^{-1} esu/m^3 (50% of the cases).

The extremal values of the space charge density may greatly exceed its mean value. Although the probability of occurrence of space charges decreases rapidly with increasing space charge, these charges can nevertheless exceed 1 esu/m^3 in not less than 40% of the cases, and exceed 2×10^{-1} esu/m^3 in approximately 75% of the cases.

The connection between the dimensions of the zone where space charge of particular magnitude occurs and the extremal values of these space charges is shown in Fig. 26. Each point corresponds to a measured value of the space charge in a zone of given size. In the upper and lower parts of the figure are shown the absolute values of the space charge. In the zone where the clouds are inhomogeneous, however, one encounters both positive and negative space charges, so that usually the average space charge in the layer is much less than the sum of its absolute extremal values.

As can be seen from the data of Fig. 26, larger space charges do exist in smaller zones. Space charges reaching 10—17 esu/m^3 were noted, but they usually occupy a zone extending not more than 50 meters. A large space charge in a zone of considerable dimensions cannot exist, first because charges cannot accumulate at the rate at which they are generated in the clouds, if the fields that draw the charges out are on the increase, and second because the large zones are rapidly broken up by the large-scale turbulent movements in convective clouds.

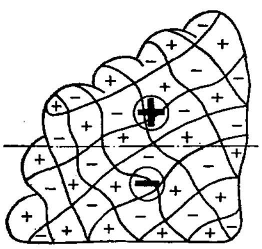

FIG. 28. Diagram illustrating the electric structure of a cumulus cloud.[92]

It must be noted that clouds lying below the zero isotherm and clouds whose tops lie above this isotherm have a similar structure, so long as icing or growing of particles does not begin in them.

The role that convective motion plays in the appearance of inhomogeneities is seen by comparing the probability distribution of the dimensions of the zones with field extrema (Fig. 27, curve 3) with the distribution of the jet dimensions (Fig. 27, curve 1), determined in the same flights by means of an accelerograph registering the airplane bumps. Curves 1 and 3 are similar in many respects. They show approximately the same limiting dimensions of the zones and the same distribution of the maxima.

The similarity between the dimensions of the zones with extremal field values and the jet dimensions can be apparently ascribed to the inhomogeneities in the particle dimensions and concentration distributions in the jets, and to the associated difference in space charge density. This was confirmed by measurement of the electric charge acquired by the airplane.

Curve 2 of Fig. 27 has been plotted for the same regions as curves 1 and 3 and shows the probable distribution of the dimensions of the extremal values of the airplane charge. Curve 2 of Fig. 27 is most similar to curves 3 and 1. Consequently, in jets that pass through the cloud, the concentration distribution and the particle-spectrum distribution can change appreciably from jet to jet, and this manifests itself in the value of the space charge and consequently the field in the jets.

The relatively narrow spectrum of sizes of the inhomogeneities allows us to assume that the inhomogeneity-zone dimensions should have a spectrum similar to that obtained in all convective clouds at moderate latitudes. Thus, for example, a jet dimension spectrum very close to that considered here was obtained by N. I. Vul'fson in investigations of the temperature pulsations in convective clouds at an altitude of 3,000 meters (curve 4 on Fig. 27).[100]

The research results show that cumulus congestus clouds, as well as simple cumulus clouds, are bipolar. As a rule, the positive charge is on top and the negative one on the bottom (Fig. 28). Against the background of these relatively small charges, with a volume density on the order of several tenths or hundredths of an esu/m^3, the cloud contains randomly scattered regions with negative and positive space charges of high density, amounting on the average to several tenths or even units of esu/m^3. The length of these regions varies from several tens to several hundreds of meters and is closely connected with the convective streams in the clouds, in which both the spectra and the dimensions of the particles should vary greatly.

Table VI

Form of cloud	Average space charge density, esu/m³	Average rate of accumulation of space charge, esu/m³ sec
Cumulus	10^{-2}–$5 \cdot 10^{-1}$	10^{-5}–10^{-3}
Cumulus congestus	10^{-2}–1	10^{-5}–10^{-3}
Cumulus congestus clouds that change over into thunderstorm or shower clouds	1–30	10^{-3}–10^{-1}
Thunderstorm clouds in the active stage	10–100	1–10^{2}

These results explain the fact noticed by Reynolds et al [107] and by Moore et al [108] that the electrification of convective clouds is closely connected with the convective motions of the air in these clouds.

The rate of accumulation of charges in cumulus and cumulus congestus clouds can be calculated from data obtained in investigation of intra-mass clouds. Since no noticeable increase in the space charge density is noticed as the clouds develop, it can be assumed that the total amount of free charge accumulated by the cloud is proportional to the volume of the cloud. For all stages of development of cumulus congestus clouds, the rate of buildup of the main space charge ranges between 10^{-5} and 10^{-3} esu/m^3 sec.

It is of interest to compare these data with the rate of accumulation of charges in the subsequent stages of development of cumulus congestus clouds. The corresponding data from [93,95,23,102] are listed in Table VI.

It is seen from Table VI that the rates of growth of space charge are more descriptive of the different types of clouds than the space charges themselves.

The foregoing data show that the fraction of charges first accumulating in a cumulus congestus cloud and then appearing in the thunderstorm is so small, that it can be reliably stated that these charges do not play any role in the thunderstorm processes. The altitude variation of the electric field for cumulus clouds is in many respects similar to that observed for stratocumulus clouds. A field maximum is observed under the lower boundary of the clouds, along with a negative space charge at the earth's surface. Above the clouds the electric field is positive.

The charges of the drops in convective clouds may reach hundreds of elementary charges. Furthermore, in individual parts of a cumulus cloud the field may reach values at which the effectiveness of coagulation of the drops noticeably increases. [152] Calculations of the effect of charge of the drops on the coagulation are given in [154]. Calculations of the effective coagulation on the charge are made in [33a,50a].

9. STRUCTURE OF SHOWER AND THUNDERSTORM CLOUDS

If a cumulus congestus does not dissipate, it turns into a shower or thunderstorm cloud. The development of the thunderstorm part of the cloud [111] consists of three stages: growth, the main stage, and disintegration. The growth stage includes a period when the cumulus congestus cloud grows vigorously and changes from a cumulus cloud into a shower or thunderstorm cloud. Ascending air currents prevail in the cloud during this stage. The main stage is characterized by maximum electrification and is associated with the presence of strong descending air currents along with the ascending ones. Finally, in the disintegration stage, the electrification attenuates greatly (although the field may remain quite large in the cloud, owing to the undissipated space charges), and the entire cloud as a whole comprises a single powerful descending stream. The thunderstorm processes may occur at different times in individual parts of the thunderstorm cloud, the so-called "cells," and even though the entire life cycle of one cell is about an hour long, the thunderstorm cloud may produce lightning for hours. The horizontal linear dimensions of the cells range from 1.5 to 10 km. [111]

The transformation of the cumulus clouds begins in a region where the particles begin to grow; the horizontal dimensions of this region are about 500 meters. In strong current streams, the speed of which may reach 15 m/sec, the particle growth is very fast. The top of the cloud is usually already at below-zero temperature and icing sets in. At approximately the same time, the electric field near the cloud begins to grow rapidly. Simultaneously with the increase in the field,

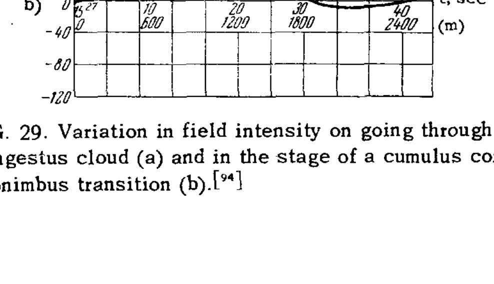

FIG. 29. Variation in field intensity on going through a cumulus congestus cloud (a) and in the stage of a cumulus congestus – cumulonimbus transition (b).[94]

the entire volume becomes uniformly charged. Figure 29 shows the variation of the electric field on the top of a cumulus congestus cloud at this stage.[112] Measurements made in flight through the top of a cumulus congestus cloud (Fig. 29a) disclosed average fields of about 10 V/cm, with amplitude not exceeding 25 V/cm. The space charges occupied regions with linear dimensions on the order of 100 meters.

To fix the exact instant when icing begins, the cloud, was seeded with dry ice. Four minutes after the start of seeding, the entire cloud was charged and the field intensity grew to 100 V/cm (Fig. 29b). A similar process was observed in the natural development of a cloud.[94,113] The growth stage may last from 10 to 30 minutes.

The most completely investigated were the clouds during the thunderstorm (main) stage. It was already shown by Wilson,[14] in an investigation of the change in field produced by lightning strokes, that thunderstorm clouds have a dipole structure. Investigations by Simpson et al[15-17] have shown in addition that the clouds have a certain excess positive charge. The measured values of the fields and the charges have a considerable dispersion. Positive charges predominate in the upper part of the cloud at altitudes above 7 km at temperatures lower than −20°C, and at any rate not higher than −10°C. Negative charges are located at altitudes between 2 and 7 km; their centers usually lie somewhat above the region of the zero isotherm. The lower positive charge is connected with the zone of intense precipitation and is usually located in a region of positive temperatures. A schematic model based on the analysis of all the measurements (Fig. 30) is given in [16]. Later works have shown that the charge distribution pattern is more complicated. Workman and Holzer have shown by measurements on the earth's surface that the center of the upper positive charge is displaced relative to the center of the lower one in the direction of the wind, and the centers themselves are located at 2.5 and 4 km. According to Barnard,[114] who investigated the variations of the field in three land stations, the distances between the centers of the main positive and negative charges is on the average 5.2 km and ranges from 2.5 to 8.7 km. According to data by Gunn,[96] obtained above the USA with direct measurements of the field in the clouds, this distance is about 3 km. At the same time Malan and Schonland[115,116] have reached the conclusion, on the basis of surface measurements of the field, that the negative charge in the thunderstorms of south Africa is located in a vertical column bounded by the 0 and 40°C isotherms, and this column is discharged by successive lightning strokes, starting at the base. The charges in the clouds differ greatly in value, according to various authors. Thus, according to Workman and Holzer, the charge carried by lightning ranges from 10 to 190 Coulombs, and values between 20 and 50 Coulombs are the most frequent. A

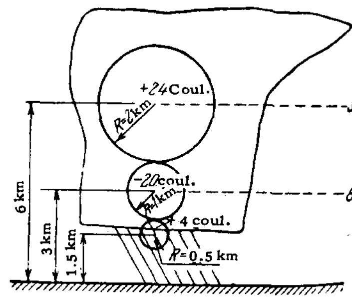

FIG. 30. Electric structure of thunderstorm cloud, after Simpson.

range of charges from 4 to 40 Coulombs is given in [114] (the average change in the electric moment of the cloud was 182.5 Coulomb-km). In [96] the cloud charge is estimated at 20 Coulombs. The values of the field intensity given in [15,16] have later on been shown[117] to be highly underestimated, and the average charges obtained by Simpson should be at least doubled. In addition to the cloud polarity shown in Fig. 30, an opposite polarity is also possible in shower and thunderstorm clouds. This is noted particularly frequently in shower clouds. Measurement of the electric fields made on an airplane[118] above the tops of about 100 shower and thunderstorm clouds has shown that approximately in 40% of the cases the clouds are negatively polarized, and usually shower clouds are negatively polarized.

Depending on the activity of clouds, they may yield discharges that follow each other with intervals ranging from several seconds to several times 10 seconds. Some clouds produce only one or two lightning bolts, which may furthermore occur inside the cloud. The clouds stretching along a thunderstorm front frequently have alternating polarities; such an arrangement of the clouds may lead to the appearance of a lightning longer than 50 km[119] and even 150 km.[120] The lifetime of the thunderstorm cell in the main stage is 20—25 minutes. During this stage the cells grow to the sizes indicated above, and heavy precipitation flows from the cloud. Investigations made in thunderstorm clouds in a high-mountain station by Kuettner[121] have shown that solid precipitation in the form of snowflakes or soft hail is observed in 93% of the cases near the zero isotherm. The role of the solid phase in the generation of thunderstorm electricity will be discussed later; we point out for the time being that some observers[122] report thunderstorms occurring in warm clouds, i.e., clouds whose tops lie below the zero isotherm. In the main stage a strong ascending air current flows through the cell as a whole, with a speed of about 10 m/sec, along with descending currents that appear in the upper part of the cloud. In strong thunderstorms, the current speed may be considerably higher. Thus, according to a rough estimate, the speed of vertical air currents in a strong storm on 14 August 1961, which resulted in considerable damage in Voronezh, reached 40 m/sec. This high speed of the ascending currents may be the reason why a negative charge column, rising to the

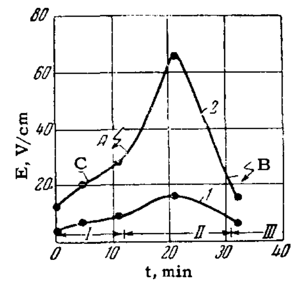

FIG. 31. Time variation of field intensity above the cloud at three stages of development of thunderstorm clouds.[118] A and B – Instants of start and termination of thunderstorm discharges, C – instant of start of icing in the top of the cloud and growth of the drops in it. Growth stage – I, main stage – II, disintegration stage – III. 2 – Maximum field intensity, 1 – average.

−40°C isotherm, appeared in thunderstorms in south Africa.[115,116]

The end of the discharges is followed by the disintegration stage, when the field intensity and the intensity of the precipitation greatly decrease. Frequently the field reverses sign, apparently because of the removal of negative charges from the cloud by the particles. Some 15—30 minutes following the end of the thunderstorm, the cloud is "washed out," and only the "anvil" remains—an elongated strip of ice crystals in the upper part of the cloud. The electric charges and hence the electric fields in the "anvils" are small.[94] Figure 31 shows the time variation of the average (1) and maximum (2) values of the field intensity[118] during the life of a single cell (or the variation of the electric moment of the cloud).

The development of one cell can apparently contribute to the development of new cells. Ice crystals from the icing top of the cell may enter the cupola of cumulus congestus clouds during the main or last stage. These crystals accelerate the icing of the cupola and the start of the new stage. A certain role in the acceleration of the development of the new cell may be played by the electric fields of the developed cells, if the coagulation of the drops or the electrification processes in the clouds are connected with the action of the electric field; this is suggested, for example, by Moore et al.[108] The distribution of the electric fields above a cloud, in the initial stage was measured by many researchers.[32,33,118] The intensity of the electric fields above the clouds amounts on the average to about 100 V/cm. The field frequently increases and decreases smoothly. This makes it possible to attempt to determine the magnitude and distribution of the charges producing the field, but such calculations are not very reliable in view of the uncertainty in the determination of the distribution of the charges from the given distribution of field intensity. In some simplest cases, however, such a solution is possible. It must be borne in mind in these calculations that the field intensity at a given point depends not only on the magnitude of the charges but also on the distribution of the conductivity,[123] since a quasi-static field distribution is established as a result of the current flow. In the central part of thunderstorm clouds the field intensity is on the order of[96] 1,000 V/cm and does not exceed 2,000 V/cm; directly under the thundercloud, at a level of 200—300 meters, the field intensity is approximately 200 V/cm, whereas at the earth's surface it does not exceed 100 V/cm. This decrease in field near the earth's surface, by 100 V/cm in a layer of 200 meters, is due to the action of the space charge produced by brush discharge from sharp points on the earth's surface in the field of the thunderstorm and shower clouds. The average density of this space-charge amounts thus to about 3 esu/m^3.[124]

The conductivity above thunderstorm clouds is close to the value normally prevailing at this height. Calculation of the effective conductivity inside thunderstorm clouds from data on the rate of variation of the field after the lightning stroke gives grounds for assuming that the conductivity inside the cloud is greater than in the surrounding atmosphere, amounting to about 10^{-2} esu.[23]

The charges of the drops in the clouds were hardly ever measured. According to [104] these charges are quite large (see Table IV) amounting on the average to 270 elementary charges per drop of five micron radius. The charges of the individual particles in the precipitation, measured at the earth's surface, are on the average[125] $+6.9 \times 10^{-3}$ esu and -7.3×10^{-3} esu, while [126] cites values of -2×10^{-2}—-3×10^{-2} esu. It should be noted that both positively and negatively charged drops are observed in measurements made on the earth's surface. The predominant sign of the charge carried by the precipitation at a given instant of time is the inverse of that of the field intensity, if the positive direction is taken to be the direction of the good weather field. This so-called "mirror" effect was observed and explained by Simpson[127] (see also [128–130]). In his opinion the drops falling from the clouds exchange charges in the appreciable space charge produced under the clouds by corona from sharp points. If the field is negative, then the space charge is positive and the drops acquire a positive charge, and vice versa. Since the field under the thunderstorm clouds is essentially negative, the drops under the clouds bring to the earth a positive charge.

Measurements of charges of precipitation drops in clouds and directly under the clouds show an essentially different picture.[131,132,89] Charged particles of a single polarity were observed in regions several kilometers long. The average charge of the particle in thunderstorm rain[131] ranged from 50×10^{-3} to 150×10^{-3} esu. Even in shower rains the average charge per drop under the clouds ranges from 30 to 50×10^{-3} esu, and the maximum charge exceeded 130×10^{-3} esu in many cases.[89] If the current carried by the precipitation from the cloud is measured at the earth's surface, it is found to be about 10^{-2} A/cm^2, and if the current is calculated from data on the particle charges, it reaches 0.1 A/km^2 even on the periphery of the thunderstorm.[95,89]

The considerable distortion that the space charge produced at the earth's surface introduces into the magnitude of the field, the particle charges, and the precipitation current, have stimulated Gish and Wait [32] and Sturges et al [33] to determine the currents flowing from thunderstorm clouds using data on the field intensity and the conductivity above the thunderstorm clouds. Starting with the premise that the current remains constant with altitude, they have assumed that the measured current is equal to the current flowing to the earth. The currents [32] ranged from zero to 1.4 A per cloud, with 0.5 A as an average. According to Sturges et al, who made their measurements closer to the equator, this average current was 0.8 A per thunderstorm. As already indicated, by using the data on the number of thunderstorms occurring simultaneously on the earth's sphere (about 1800), these figures can be used to calculate the current balance between the earth and the atmosphere. Holzer points out [132] that these current values are slightly exaggerated. In view of the possibility that some of the field lines from the upper part of the cloud can terminate on earth and on the lower charge of the cloud, it becomes necessary to reduce the values given by 15%. Taking account of the fact that clouds of opposite polarity also exist,[118] it must be noted that there are no grounds at present for stating that the "good weather current" is balanced by the thunderstorm current.

10. ACCUMULATION OF CHARGES IN THUNDERSTORM CLOUDS

For lightning to occur, the following three conditions must be satisfied.

1. The thunderstorm cloud should have a sufficient number of charges.

2. The oppositely charged particles should be at a considerable distance from each other.

3. The foregoing two conditions must be satisfied within a sufficiently short time interval, to allow the generation and separation of the charges in the clouds to proceed more rapidly than the recombination and association of the charges before the critical values of the charge and field intensity are reached.

Let us examine the scheme by which an electric moment is produced in a thunderstorm cloud (Fig. 32). Let the intensity of generation of particles with charge q in the cloud be I; we denote by W the relative velocity of particles of opposite signs. Then obviously, for the charge Q accumulated in a column of unit cross sections in regions I and II we obtain

$$\frac{dQ}{dt} = IqW - 4\pi Q\lambda - p\,\frac{Q}{h}\,. \tag{20}$$

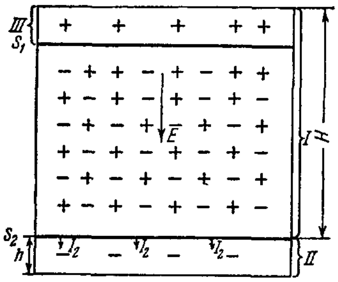

FIG. 32. Scheme showing the creation of electric moment in a thunderstorm cloud. H – thickness of cloud; I, II, and III – zone of separating negative and positive charges.

It is assumed here that the cloud is equivalent to a parallel plate capacitor, in which the field is $4\pi Q$, and that the turbulence carries away a charge $p\rho = pQ/h$ (ρ — space charge density, p —coefficient of turbulence). If $dQ/dt > 0$ prior to the equalization $Q = Q_{cr}$ at which the lightning discharge occurs, then the cloud turns into a thunderstorm cloud; if $dQ/dt \le 0$ prior to reaching the value $Q = Q_{cr}$, we have a shower cloud. The charges in the cloud will increase as

$$Q = \frac{IqWh}{4\pi\lambda h + p}\left(1 - e^{-\frac{4\pi\lambda h + p}{h}}\right). \tag{21}$$

From (21) it follows in particular that the turbulence in the cloud influences the variation in this charge in a manner similar to the conductivity. We can introduce an arbitrary effective relaxation time

$$\tau_{\text{eff}} = \frac{h}{4\pi\lambda h + p}\,, \tag{22}$$

which characterizes the rate of growth of the charges and fields in the clouds. In a real cloud all our assumptions are of course most relative. This scheme, however, presents the main features of the process quite satisfactorily.

Even Wilson [14] noted that the sharp change in the field due to the lightning bolt is followed by a relatively slow recovery of the field, lasting for several seconds, and he assumed that this recovery process represents the restoration of the electric moment M of the cloud. We note that the relative change in the field is $\Delta E/E \sim \Delta M/M$. These changes were investigated in detail by Wormell,[133] Smith,[134] and many others. It was found that when measurements are made on earth near the thunderstorm cloud, the observed field changes are affected by the space charge due to brush discharge near the earth. To eliminate the influence of this charge, the recovery times were measured on airplanes.[23] It was found that the field variations are usually exponential, and the relaxation time ranges from 0.5 to 33 sec.[92] The average value is $\tau = 3.6$ sec; the fraction of the cases with $\tau > 10$ sec is only 5% of the total number of cases, and the fraction of cases with $\tau > 15$ sec is only about 3%.

Thus, within a time on the order of 10 sec after the lightning bolt, the electric moment is restored in the

Table VII. Change in electric state of cumulus congestus clouds by artificial seeding

Date (1953)	Prior to seeding			After seeding			Time of growth of field, seconds	Total growth, %	
	Time (hours and minutes)	Field intensity V/cm		Time (hours and minutes)	Field intensity V/cm			Average	Maximum
		Average	Maximum		Average	Maximum			
17.07	13.57	3	5	14.02	20	—36	300	660	720
21.07	15.23	10	24	15.27	50	108	240	500	450
24.07	14.06	16	20	14.30	46.5	70	1440	300	350
				14.32	54	131.5	1560	350	700

Note: Precipitation on earth started at 14:32.

cloud. The electric moment of the cloud, neutralized by the lightning, is on the average 100 C-km. The charge neutralized by the lightning is on the average 20 Coulombs. The changes in the dipole moment of the cloud after the stroke of lightning should be due either to the increase in the number of separated charges, or to an increase in the dipole length. If it is assumed that the separation of charges of opposite signs is brought about by the force of gravity, then the separation speed W could hardly exceed 10 m/sec even for large particles. Thus, within a time $\tau = 10$ sec the charges producing the dipole can move about 0.1 km. Thus, the recovery of the field is due essentially to charges amounting to about 20 Coulombs appearing on the top and on the bottom of a layer not thicker than about 100 meters (see Fig. 32, regions II and III). In order for these charges to appear it is necessary that unseparated charges of equal density exist over *the entire volume of the cloud* (see Fig. 32, region I). If the section of the thunderstorm cell has an area of about 10 km^2, and the distance between the centers of the main charges is 5 km, then about 100 Coulombs of electricity distributed among the particles, or 20 Coulomb/km^3, must be present in the cloud to restore the electric moment. The natural question arises—were these charges brought to the cloud earlier or must they be produced within a time comparable with the relaxation time of the electric moment.

It is usually assumed [102] that all the charges are acquired by the cloud during the preceding stage. But we have seen that during the preceding stage the charges of the cloud are several orders of magnitude less than the required value. In addition, it can be assumed that, under conditions when the oppositely charged particles have a higher concentration, the recombination of the particles of opposite signs rapidly neutralizes all the "imported" charges if the particles are intensely mixed. Charges of opposite signs can therefore exist in the cloud only if they are continuously generated at a rapid rate. This explains the fast rate of charge generation and high values of the space charges themselves in thunderstorm clouds, as listed in Table VI.

As seen from formula (21), in those cases when the field drops to zero following a bolt of lightning and when one can be assured that the field has been produced only by the charges in the investigated cloud, it is possible to determine the charging current of the cloud by measuring the rate of recovery of the field at instants directly following the lightning bolt. Mason estimates this current to be approximately 3 A. [102]

It can be assumed that the charges of the cloud are not separated by gravity, but by rising air currents, which lift the positive charges, and descending currents which bring the negative charge down. [108] Since the air can attain velocities of 30—40 m/sec, this immediately reduces the amount of charge that must be accumulated in the cloud. So far, however, no one has succeeded in observing charges of opposite signs in oppositely flowing streams. In addition the foregoing estimated required charge density would remain the same for clouds where the air streams have speeds of about 10 m/sec.

*It is interesting to cite the results of direct meas*urements of the existing charges. To estimate the charges accumulated during precipitation, we can use the data given in [89]. The field intensity values measured at two altitudes in shower rains were used to determine the total average space charge of the air, which is equal to several tenths of an esu/m^3, whereas the charge on the drops in the precipitation reached 7 esu/m^3. Thus, the space charge in the air and on the small particles is approximately 7 esu/m^3. The separation of these charges would bring about conditions close to those of thunderstorms (see Table VI).

Thus, even during showers the precipitation and the surrounding air contain charges close in magnitude to those that should exist were the separation due to the force of gravity. To choose correctly those processes which create thunderstorms from among the dozens of possible mechanisms of elementary electrification, it is necessary to know not only the intensity of electrification but also the conditions under which these processes occur. In particular, it is very important to be able to state at what time during the life of the cloud does the intense charging, characteristic of thunderstorm clouds, begin. Usually the intensified charging of the cloud is noticed at a time coinciding with the *start of the growth of the particles in the cloud*, when their dimensions reach 100 microns and above. Such a growth follows directly the icing of the tops of the clouds (see Fig. 31); it remains unclear which factor plays the main role in the electrification of the cloud, the fast coagulation and the precipitation of minute drops of the same charge, or the electrification connected with the two-aggregate state of the cloud. As was already shown, at the initial stage of the growth the space charges are small, and consequently the coagulation mechanism cannot lead to a rapid buildup of charge as the particles increase in size, since the coagulation in the presence of oppositely charged particles leads to a relative decrease in the charge of the large particles. An attempt was therefore made to seed the cloud with dry ice at precisely this stage, thus creating conditions for rapid appearance of a two-aggregate state and a determination of its role in electrification.[112] The results of these experiments are summarized in Table VII and illustrated in Fig. 29.

As can be seen from Table VII, the creation of the ice phase in the clouds within a time on the order of several hundred seconds has brought about an intensified electrification of the clouds. Thus, the role of the icing in the electrification of the clouds can be regarded as demonstrated.

Unfortunately, there is no information whatever on the conditions under which charges are generated in "warm" clouds, i.e., pure water clouds, located below the zero isotherm. We shall therefore not discuss the generation of charges in such clouds. We mention only that these were observed[122] over the ocean in the subtropics during evening hours, i.e., in places with strongly developed convection, high humidity, and the specific conditions of nighttime thunderstorms.

Table VII also answers the interesting question: can thunderstorm activity be regulated artificially? As can be seen, the electric state of the cloud responds to external action. The change in potential difference on the boundaries of the clouds resulting from such action can be estimated at approximately 25 million volts. The possibility of controlling thunderstorm activity was pointed out by Langmuir.[135]

Several dozens elementary mechanisms can be suggested for the electrification of thunderstorm particles. Each has served inevitably as a basis for a theory of thunderstorm electricity. We shall not discuss these mechanisms in detail. Some are considered in detail in the book by Mason.[102] We shall only attempt to compare the possible rate of creation of charges in thunderstorm clouds called for by some of these mechanisms with the observed rate of generation of charges in thunderstorm clouds. Several elementary charging processes are connected with the capture of ions from the surrounding air by the cloud particles. This capture may be due to the difference in the recombination energies of the positive and negative ions, as suggested by Frenkel,[8] owing to the difference in the diffusion velocities of the ions towards the surfaces of the drop,[8] to the difference in the fluxes of positive and negative ions moving in the electric field directed along the direction of motion of the falling drop (the Wilson mechanism),[136] etc. The maximum charge that the particles can capture in this case within a time t is obviously

$$q = q_0 + It, \quad (23)$$

where q_0 is the number of ions of given polarity participating in the exchange at the time $t = 0$, and I is the ionization intensity.

No electrification mechanism connected with this process can produce a charge greater than that indicated. Figure 33 (curve I) shows the time buildup of the particle charge in 1 km^3 for the limiting case of unipolar charging [Eq. (23)] and the Wilson mechanism (curve II) in a cloud that produces precipitation at a rate of 24 mm/h, with an average drop radius 1.5 mm and an average field intensity 500 V/cm. The shaded area in the figure corresponds to the relaxation time of the electric moment in the thunderstorm cloud. The intersection of this region by the line showing the electricity per cubic kilometer required for the thunderstorm processes, delineates the region (shown cross hatched in Fig. 33) of the required electrification velocities. Curves III show the rate of charge buildup caused by the Elster and Geitel mechanism,[137] in which electrification is produced by collision with the small drops, which carry away the charge induced by the field in the upper parts of the larger drops.

Curve IIIa gives the rate of charge growth when the field itself depends on the size of the charge, while curve IIIb is constructed for the rate of growth of the charges in a field having an intensity 500 V/cm. New ideas concerning the possibility of this mechanism were recently developed by Sartor,[151] but its action is appreciably limited by the intensifying coalescence of the drops in strong electric fields:[152] Curve IVa has been constructed for electrification due to the ball effect of water;[138,155] curve V is the same for the ball effect of snow.[139] Curve VI shows the growth of the electric charge when the drops are disintegrated in the electric field, an effect investigated by V. M. Muchnik.[140] Curve VIa gives the growth of the charge under the assumption that the field is first equal to 1 V/cm, and then grows as a result of the disintegration of the drops. Curve VIb is constructed under the assumption that the drops are disintegrated in a field of 500 V/cm.

The effect of the mechanism analyzed by Mason and first observed by Findeisen[142,102] is represented by curve VII. This mechanism is connected with the electrification occurring when minute supercooled drops strike an ice surface and freeze on it. The physics of this mechanism, based on different rates of displacement of the ions H^+ and OH^- in the presence of temperature gradients, was considered in detail in [153].

Point VIII corresponds to electrification based on

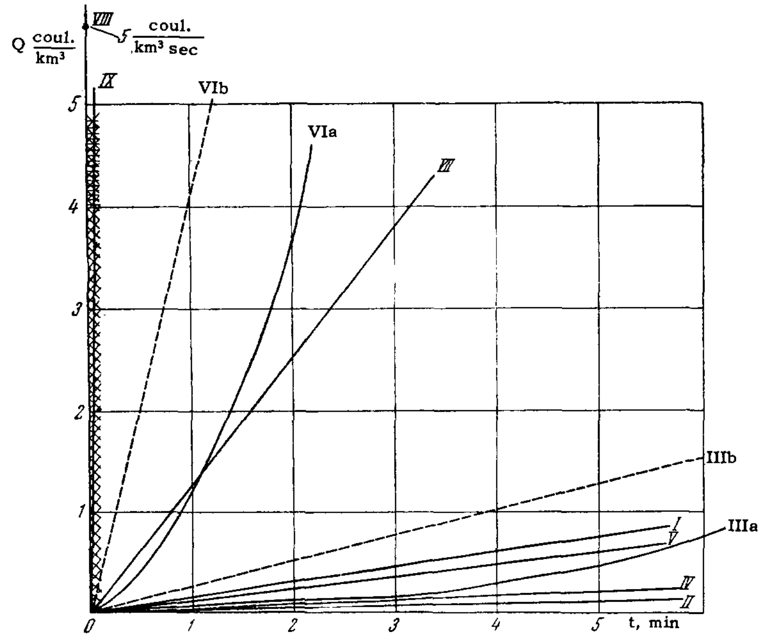

FIG. 33. Effect of elementary mechanisms of electrification in thunderstorm clouds. All the calculations are made for clouds which produce precipitation at a rate of 24 mm/h with an average drop radius 1.5 mm. I – Electrification due to unipolar capture of ions; II – electrification by the Wilson mechanism, III – electrification by the Elster and Geitel mechanism; IIIa – *initial field intensity 1 V/cm*; IIIb – *in field of* intensity 500 V/cm; IV – electrification due to the ball effect of water; V – electrification due to the ball effect of ice; VI – electrification due to disintegration of drops in electric fields; VIa – initial field intensity 1 V/cm; VIb – in field of intensity 500 V/cm; VII – electrification by elastic impact of supercooled drops against an icy surface; VIII – electrification by the Workman and Reynolds mechanism; IX – electrification by contact potential difference between water and ice.

the mechanism of Workman and Reynolds,[143] which consists of charging the solid and liquid phases when weak aqueous solutions of salts and acids freeze. The potential difference between the water and the ice may exceed 100 V. The maximum rate of charge production that this mechanism is capable of may reach 100 C/km^3-sec. The effective electrification mechanism was considered in [144].

This mechanism consists in the fact that if small drops of water make contact and jump away from ice particles or if these particles melt and water drops subsequently break away from their surfaces, the ice particles can be rapidly charged to considerable potentials because of the contact potential difference between the water and the ice. Under these conditions, approximately 1 C/sec can be produced in 1 km^3 (curve IX).

It must be noted that Fig. 33 does not show the limiting values. In thicker clouds with more intense precipitation and stronger fields the amount of electricity generated with the aid of these mechanisms can increase. Thus, for example, V. M. Muchnik[141] assuming the intensity of the precipitation in the clouds to be ~ 170 mm/h and the initial field intensity to be about 1,000 V/cm, found that the rate of charge generation in these clouds, accompanying the disintegration of the drops in the electric field, may reach several tens of C/km^3 sec. However, the initial data that he assumed are patently too high. Mason[102] assuming a higher number of ice particles (compared with that observed) in the cloud, also found that the mechanism investigated by him can yield five times more electricity per unit time than that shown in Fig. 33. Many of the mechanisms concerned give a polarization with direction opposite to that observed under real conditions. This pertains to the ball effect in water and in part to the Elster and Geitel effect. Other mechanisms, even some very powerful ones, cannot come into play effectively under thunderstorm cloud conditions. This pertains, in particular, to the mechanism of Workman and Reynolds.[102] However, an analysis of the data of Fig. 33 suggests that the most effective mechanisms are essentially connected with electrification occurring in a two-aggregate cloud on the water-ice interface. This circumstance agrees with the known facts that the greatest electrification begins at the instant when the ice phase occurs in the cloud and that the main electric charges are located in those zones of the cloud, where the water and ice particles exist simultaneously. It must be noted that most electrification processes noticed on the water-ice boundary actually reduce to only two or three physical processes. Workers investigating this type of electrification[102] usually describe, and use as the basis of classification, the conditions under which the electrification appears, and not the physical process which causes the electrification. The electrification of drops disintegrated in an electric field may turn out to be highly effective. In tropical thunderstorms, possibly, it may be the cause of lightning observed in warm clouds.

A detailed investigation of the macro and micro processes in thunderstorm clouds should permit us to resolve the question of what electrification mechanisms act in thunderstorm clouds and how they do so.

Among the least understood questions in the physics of thunderstorms is how the lightning is maintained. The electric field intensity in thunderstorm clouds does not exceed 2,000 V/cm, whereas the development of a spark at an altitude on the order of several kilometers calls for an intensity of about 10,000 V/cm. On the other hand, the discharge conditions in the lightning should be difficult compared with discharge from metallic electrodes connected to a relatively powerful source of supply, for which the foregoing value of breakdown voltage was obtained. To clarify the role of the singularities of the drops, an investigation was made of the behavior of the drops in strong electric fields.[145] It was found that drops become strongly stretched in the field and corona from them can be initiated. Macky[145] obtained the following equation for the critical field intensity E_{cr} at which the drops begin to elongate

$$E_{cr} = \frac{3875}{\sqrt{R}} \ [\mathrm{V/cm}],$$

where the radius of the drop R is in centimeters. Thus, the elongation of the drops and corona from them[146] can start in fields having intensity 7,000–10,000 V/cm, and there are no such fields in thunderstorm clouds. It is equally unclear how the discharge of the lightning is maintained. During the lifetime of the lightning, i.e., within a time on the order of milliseconds, the field of the cloud can diminish to zero. Thus, all the charges contained in a region with volume of 1 cubic kilometer on the drops located on an average at distances of about 10 cm and consequently well isolated from each other are gathered together by this lightning.

How this aggregate of isolated drops is suddenly converted into a single association is quite unclear. The lightning has even in its main channel a diameter of about 1 meter, and in the branches the diameter is even less. Lobe[147] suggests that positive streamers are produced in the cloud at the instant of discharge, and thus discharge the cloud. However, the existence of such streamers has not yet been observed, although radar measurements should be able to show the instant of time at which the entire volume of the cloud is ionized.

It is still unclear at present whether the earth or other celestial bodies are neutral or electrically charged.

The nature of ball lightning has not yet been made clear. It can be assumed that a solution of this problem can yield information of importance not for atmospheric electricity alone.

A study of a considerable portion of the phenomena considered in the present review is still at the initial stage of clarification of the main facts. The investigations became especially fruitful in recent years, when they have begun to be performed in the free atmosphere. We can relate this circumstance not only with the obvious progress in technology, but also with the stimulating influences which were exerted on these researches by the ideas of J. I. Frenkel.

[1] M. V. Lomonosov, in: Torzhestvo Akademii nauk ... noyabrya, 26 dnya, 1753 goda (Festival of the Academy of Sciences, November 26, 1753), St. Petersburg, Acad. Sci. Press, 1753, p. 1.

[2] L. Lemonnier, Mem. Acad. Sci. **2**, 223 (1752).

[3] G. Simpson, Meteorology (Calcutta) **1**, 302 (1919).

[4] S. Mauchly, Res. Dept. Terr. Magn. **5**, 387 (1926).

[5] H. Swerdrup, Res. Dept. Terr. Magn. **6**, 425 (1927).

[6] F. Whipple and F. Scrase, Geophys. Mem., No. 68, 1 (1936).

[7] H. Isräel, Wiss. Abhandl. Reichsamt für Wetterdienst (Berlin) **5**, No. 12 (1939).

[8] J. I. Frenkel, Teoriya yavleniĭ atmosfernogo élektrichestva (Theory of Phenomena of Atmospheric Electricity), Gostekhizdat, 1949.

[9] I. M. Imyanitov, Pribory i metody dlya izucheniya élektrichestva atmosfery (Instruments and Methods for the Study of Atmospheric Electricity), Gostekhizdat, 1957.

[10] P. N. Tverskoĭ, Atmosfernoe élektrichestvo (Atmospheric Electricity), Gidrometeoizdat, 1949.

[11] N. A. Paramonov, DAN SSSR **61**, 661 (1950).

[12] P. Idrac, Mêm. off. Nat. met. Fr., No. 18, 1 (1928).

[13] E. Everling und A. Wigand, Ann. Physik **66**, 261 (1921).

[14] C. Wilson, Proc. Roy. Soc. **A92**, 555 (1916).

[15] G. Simpson and F. Scrase, Proc. Roy. Soc. **A161**, 309 (1937).

[16] G. Simpson and G. Robinson, Proc. Roy. Soc. **A177**, 281 (1941).

[17] G. Simpson, Quart. J. Roy. Met. Soc. **68**, 1 (1942).

[18] N. A. Paramonov, Dissertation (Main Geophysical Observatory, Leningrad, 1953).

[19] L. G. Makhotkin and V. A. Solov'ev, Tr. GGO (Transactions, Main Geophysical Observatory) No. 97, 63 (1960).

[20] G. Coulomb, Mêm. l'Acad. Sci. (Paris), 1785.

[21] E. Pierce, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 5.

[22] O. Gish and K. Sherman, Nat. Geogr. Soc. Techn. Papers (Washington), Strat. Ser., No. 2 (1936).

[23] I. M. Imyanitov, DAN SSSR **109**, 77 (1956).

[24] H. Isräel, Ann. geophys. **10**, 93 (1954).

[25] H. Lettau, Beitr. Geophys. **57**, 365 (1941).

[26] P. N. Tverskoĭ and M. P. Timofeev, Izv. AN SSSR, ser. geofiz. **12**, 377 (1948).

[27] T. Wormell, Proc. Roy. Soc. **A115**, 443 (1927).

[28] B. Schonland, Proc. Roy. Soc. **A118**, 252 (1928).

[29] I. Chalmers and E. Little, Terr. Magn. and Atm. Electr. **52**, 239 (1947).

[30] T. Wormell, Proc. Roy. Soc. **A127**, 567 (1930).

[31] V. V. Zykova, Tr. GGO, No. 110, 3 (1960).

[32] O. Gish and G. Wait, J. Geophys. Res. **55**, 473 (1950).

[33] Stergis, Rein, and Kangas, J. Atm. and Terr. Phys. **11**, 83 (1957).

[33a] I. J. Frenkel and N. S. Shishkin, Izv. AN SSSR, ser. geofiz, **10**, 301 (1946).

[34] C. Brooks, Geophys. Mem. **3**, 145 (1925).

[35] E. Schweidler, Conservation of Electric Charge of the Earth, (Russ. Transl.) ONTI 1936.

[36] I. M. Imyanitov, UFN **63**, 267 (1957).

[37] C. Wilson, Phil. Trans. **A221**, 73 (1920).

[38] H. Isräel, Atmosphärische Elektrizität, Bd. I, Leipzig, 1957.

[39] H. Israël and H. Kasemir, Ann. geophys. **5**, 313 (1949).

[40] H. Kasemir, Arch. Met. (Wien) **A3**, 84 (1950).

[41] K. Stewart, Quart. J. Roy. Met. Soc. **86**, 399 (1960).

[42] I. M. Imyanitov, Inf. sb. komiteta GUGMS po provedeniyu MGG (Information Collection of the Committee of the Main Administration for Hydrometeorological Service on the IGY), No. 5, 12 (1958).

[43] I. M. Imyanitov and E. V. Chubarina, Tr. GGO, No. 110, 7 (1960).

[44] I. M. Imyanitov, Tr. GGO, No. 35, 3 (1952).

[45] L. Koenigsfeld, Thunderstorm Electricity, Chicago. 1953.

[46] S. Venkiteschwaran and P. Huddes, Ind. J. Met. Geophys. **7**, 61 (1956).

[47] S. Venkiteschwaran, et al, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 89.

[48] I. Lugeon and M. Bohkelbust, Ann. Stant. Cent. Met. Suisser, 1956, I (1957).

[49] Stergis, Rein, and Kangas, J. Atm. and Terr. Phys. **11**, 77 (1957).

[50] Hatakeyama, Kobajashi, Kitaoka, and Ushikawa, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 119.

[50a] N. S. Shishkin, Oblaka, osadki, grozovoe élektrichestvo (Clouds, Precipitation, and Thunderstorm Electricity), Gostekhizdat, 1954.

[51] F. Clark, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 61.

[52] A. L. Dergach, Tr. GGO, No. 105, 30 (1960).

[53] K. Dreisbach, Arch. Met., Geophys. und Bioklimat. **A9**, 36 (1956).

[54] R. Sagalyn and G. Faucher, J. Atm. and Terr. Phys. **5**, 253 (1954).

[55] C. Stergis et. al, Proc. Conf. Atm. Electr. Geoph. Res. Papers **42**, 43 (1955).

[56] R. Sagalyn, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 21 and 235.

[57] Bowen, Milliken, and Neher, Phys. Rev. **52**, 80 (1937); Phys. Rev. **51**, 1005 (1937).

[58] H. Curtis and M. Hyland, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 111.

[59] E. S. Selezneva and M. I. Yudin, Tr. GGO, No. 105, 37 (1960).

[60] J. Kraakevik, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 75.

[61] F. Rossman, Dtsch. Wetterdienst in der US-Zone, Berichte No. 15 (1950).

[62] A. M. Izmerin, Izv. AN SSSR, ser. geofiz. No. 6, 919 (1959).

[63] I. M. Imyanitov and E. V. Chubarina, Collection: Materialy Konferentsii po itogam MGG (1960) i meteorologii Antarktidy (Materials of the Conference on the Progress in the IGY (1960) and the Meteorology of the Antarctic) (1959), Gidrometeoizdat, 1961, p. 225.

[64] T. V. Lobodin, Tr. GGO No. 110, 27 (1960).

[65] I. M. Imyanitov, Collection: Issledovanie oblakov, osadkov, i grozovogo élektrichestva (Investigation of Clouds, Precipitation, and Thunderstorm Electricity), Moscow, AN SSSR, 1961, p. 225.

[66] H. Israël und A. Kunkis, Über einige luftelektrische Erfahrungen in Mittelamerika (preliminary communication).

[67] A. Chauveau, Recherches sur l'electricite atmospherique, Paris, I (1899); II (1900).

[68] I. M. Imyanitov and E. V. Chubarina, DAN SSSR **132**, 104 (1960).

[69] I. M. Imyanitov and E. V. Chubarina, op. cit. [65], p. 239.

[70] O. Gish, Terr. Magn. and Atm. Electr. **49**, 159 (1944).

[71] V. D. Reshetov, Tr. TsAO (Transactions of the Central Astronomical Observatory) No. 30, 54 (1959).

[72] V. D. Reshetov, ibid, No. 30, 62 (1959).

[73] V. I. Kraav, Tr. GGO, No. 120, 73 (1961).

[74] R. Mühleisen, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 213.

[75] I. M. Imyanitov and E. V. Chubarina, Tr. GGO, No. 136, (1962), in press.

[76] I. M. Imyanitov and E. V. Chubarina, Collection: Doklady na Vsesoyuznom meteorologicheskom soveshchanii (Transactions of the All-Union Meteorological Conference), Gidrometeoizdat, in press.

[77] P. Allee and B. Phillips, J. Meteor. **16**, 405 (1959).

[78] P. Pluvinage, Ann. geophys. **2**, 31 (1956).

[79] N. V. Krasnogorskaya, Izv. AN SSSR, ser. geofiz, No. 4, 527 (1958).

[80] L. G. Makhotkin and V. A. Solov'ev, Tr. GGO No. 97, 51 (1960).

[81] A. P. Sersheva, Izv. AN SSSR, ser. geofiz, No. 3, 347 (1958).

[82] G. D. Petrov, ibid, No. 11 (1959).

[83] Katsyka, Makhotkin, Petrov, and Chao, ibid No. 1, 162 (1961).

[84] S. Twomey, Tellus **8**, 445 (1956).

[85] V. Ya. Nikandrov, Tr. GGO, No. 57, 37 (1956).

[86] P. Gschwend, Jahrbuch d. Radioaktivität **17**, 62 (1920).

[87] J. Chalmers and F. Pasquill, Proc. Phys. Soc. **50**, 1 (1938).

[88] I. S. Anikiev, Meteor. i gidrol. (Meteorology and Hydrology), No. 4, 37 (1951).

[89] I. M. Imyanitov and V. V. Mikhaĭlovskaya, Tr. GGO, No. 97, 16 (1960).

[90] J. McClelland and J. Nolan, Proc. Roy. Irish Acad. **A29**, 81 (1912); **A30**, 61 (1918).

[91] J. McClelland and A. Gilmour, Proc. Roy. Irish Acad. **A35**, 13 (1920).

[92] I. M. Imyanitov, Tr. GGO, No. 97, 5 (1960).

[93] I. M. Imyanitov and A. P. Chuvaev, Meteor. i gidrol. No. 2, 15 (1956).

[94] Imyanitov, Kulik, and Chuvaev, Tr. GGO, No. 67, 3 (1957).

[95] I. M. Imyanitov and A. P. Chuvaev, op. cit. [65],

Gidrometeoizdat 1957, p. 13.
[96] R. Gunn, J. Appl. Phys. **19**, 481 (1948).
[97] E. M. Sal'man, Tr. GGO, No. 72, 46 (1957).
[98] N. F. Kotov, Tr. GGO, No. 102, 63 (1960).
[99] E. S. Selezneva, Tr. GGO, No. 93, 3 (1959).
[100] N. I. Vul'fson, DAN SSSR **97**, 77 (1954).
[101] D. Fitzgerald and H. Byers, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 245.
[102] B. Mason, Cloud Physics (Russ. transl.), Gidrometeoizdat 1961.
[103] R. Gunn, J. Meteor. **9**, 397 (1952).
[104] B. Phillips and G. Kinzer, J. Meteor. **15**, No. 14 (1958).
[105] E. K. Fedorov, DAN SSSR **78**, 1131 (1951).
[106] J. Chalmers, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 309.
[107] Reynolds, Brook, and Gourley, Thunderstorm Electricity Report. 9, New Mexico Inst. Min. Tech. Socorro, 1955 (see [108]).
[108] Moore, Vonnegut, and Bojka, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 333.
[109] Rayleigh, Proc. Roy. Soc. **28**, 406 (1879).
[110] J. I. Frenkel and G. P. Vacher, Izv. AN SSSR, ser. geofiz, **12**, 3 (1948).
[111] H. Byers and R. Braham, Thunderstorm, U.S. Weather Bureau, Washington, 1949.
[112] Imyanitov, Kulik, and Chuvaev, Tr. GGO, No. 67, 33 (1957).
[113] E. Reynolds and H. Neill, J. Meteor. **12**, 1 (1955).
[114] V. Barnard, J. Geophys. Res. **56**, 33 (1951).
[115] D. Malan and B. Schonland, Proc. Roy. Soc. **A206**, 145 (1951).
[116] D. Malan and B. Schonland, Proc. Roy. Soc. **A206**, 158 (1951).
[117] S. Chapman, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 227.
[118] I. M. Imyanitov and T. V. Lobodin, Tr. GGO, No. 136, (1962), in press.
[119] I. M. Imyanitov, Priroda (Nature) No. 7, 110 (1960).
[120] M. Ligda, J. Atm. and Terr. Phys. **9**, 329 (1956).
[121] J. Kuettner, J. Meteor. **7**, 322 (1950).
[122] B. Moore et al, J. Geophys. Res. **65**, 1907 (1960).
[123] H. Holzer, J. Geophys. Res. **57**, 207 (1952).
[124] I. M. Imyanitov, op. cit. [65], 1957, p. 159.
[125] S. K. Banerje and S. Lele, Natura **130**, 998 (1932).
[126] V. P. Kolokolov and K. A. Semenov, Tr. GGO, No. 97, 43 (1960).
[127] G. Simpson, Geophys. Mem. Met. (London) **4**, No. 84 (1949).
[128] T. Ogawa, J. Geomagn. and Geoelectr. **12**, 21 (1960).
[129] M. Sivaramakrischnan, Ind. J. Meteor. and Geophys. **11**, 258 (1960).
[130] F. Whipple and I. Chalmers, Quart. J. Roy. Met. Soc. **70**, 103 (1944).
[131] R. Gunn, Phys. Rev. **71**, 181 (1947).
[132] R. Gunn, J. Geophys. Res. **55**, 171 (1950).
[133] T. Wormell, Philos. Trans. **A238**, 249 (1939).
[134] L. Smith, Recent Advances in Atmospheric Electricity, Pergamon Press, London, 1958, p. 299.
[135] I. Langmuir, Science **112**, 35 (1950).
[136] C. Wilson, J. Franklin Inst. **208**, 1 (1929).
[137] I. Elster and H. Geitel, Z. Phys. **14**, 1287 (1913).
[138] G. Simpson, Philos. Trans. **A209**, 379 (1909).
[139] G. Simpson, Quart. J. Roy. Met. Soc. **68**, 1 (1942).
[140] V. M. Muchnik, JETP **26**, 109 (1954).
[141] V. M. Muchnik, Izv. AN SSSR, ser. geofiz, No. 4, 626 (1960).
[142] W. Findeisen, Z. Met. **57**, 201 (1940).
[143] E. Workman and S. Reynolds, Phys. Rev. **A78**, 254 (1950).
[144] I. M. Imyanitov, DAN SSSR **121**, 93 (1958), Soviet Phys. Doklady **3**, 815 (1959).
[145] W. Macky, Proc. Roy. Soc. **A133**, 565 (1931).
[146] W. English, Phys. Rev. **74**, 179 (1948).
[147] L. Loeb, Atmospherical Exploration, Cambridge, Mass. Technol. Press, New York, 1958, p. 46.
[148] G. Freier, J. Geophys. Res. **66**, 2695 (1961).
[149] R. A. Allik, Trudy NIU GUGMS (Transactions, Main Administration of Hydrometeorological Service) Series I, No. 4 (1941).
[150] H. Isräel, Atmosph. Elektrizität, Bd. II, Leipzig, 1961.
[151] I. Sartor, J. Geophys. Res. **66**, 831 (1961); **66**, 3070 (1961).
[152] Goyer, McDonald, Baer, and Braham, J. Meteor. **17**, 442 (1960).
[153] J. Latham and B. Mason, Proc. Roy. Soc. **A260**, 1303 (1961).
[154] L. M. Levin, Issledovaniya po fizike grubodispersnykh aérozoleĭ (Research on the Physics of Coarsely-dispersed Aerosols), AN SSSR, 1961.
[155] V. I. Arabadzhi, Groza i grozovye protsessy (Thunderstorms and Thunderstorm Processes), Minsk, 1960.

Translated by J. G. Adashko