Inadvertent modification of atmospheric electricity

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Human activities on different scales of space and time cause a change in electrical state of the atmosphere or cloud electrification. Ionization and nuclei introduced into the atmosphere by human activities may contribute to such modification. Urbanization, desertification and air pollution, which modify cloud electrification characteristics, can influence the evolution of precipitation and dynamics of clouds.

Like inadvertent modification of weather and climate, some activities of man cause modification of atmospheric electricity on different scales of space and time[1]. The global electric circuit reflects world-wide events happening at the same time and influencing the magnitude of parameters measured at any place. Local processes also shape the spatial and temporal variations of these parameters. We need to understand how the global and local components have contributed and will continue to contribute in future to shape various atmospheric electric parameters at different places. We

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Table 1. Human activities causing modification of atmospheric electricity

Distortion of electric field	Change in conductivity: Decrease	Change in conductivity: Increase	Change in charge generation: At earth's surface	Change in charge generation: In cloud	Triggering of lightning
High towers and tall buildings	Aerosols produced due to:	Krypton-85	Oil slicks on sea surface	Gaseous pollutants	Aircraft and rockets
		Atomic explosions	Dust storms due to desertification	Weather-modification activities	Ships
Aircraft and rockets	Automobile exhaust	Nuclear power plant accidents			High towers and tall buildings
	Industrialization	VLF radiations	Point discharge from high towers and tall buildings		Artificial triggering of lightning
	Change of land-use patterns				
			High-tension lines		

also need to know how the electrification in clouds is influenced by human activities. To answer such questions it is necessary to identify the activities of man which can modify the electrical state of the atmosphere, on local, synoptic and global scale.

Because of the short relaxation time of the atmosphere to electrical input any space charge generated at a particular place in the atmosphere will have a life only of a few minutes or hours. Activities causing generation of space charge and its introduction into the atmosphere are therefore expected to affect the atmospheric electrical state only on a local scale.

On the other hand, activities that cause a change in nuclei content of the atmosphere or in redistribution of ionizing agents over the whole globe, or modify the cloud electrification will cause longer time changes. The purpose of this article is to identify such human activities which may cause local or global modification of the electrical state of the atmosphere. The effects that such modification will have on certain meteorological processes are briefly pointed out.

Change of land-use patterns

With the progress of human civilization, man has preferred to live in villages, towns and cities. He has built long roads and highways and cultivated large areas for agriculture. Large areas of forest have been replaced by roads and large cities. Man's activities have resulted in deforestation and desertification on a large scale in some areas. We have seen how the increased cultivation activity in 1930s and 1950s in the southwest United States had changed the region into a dust-bowl where dust storms occur more frequently. Blowing dust in the dust storms causes large charge transfers in the atmosphere[2]. Potential gradients of many kilovolts per metre associated with space charge densities of 10^{-7}–10^{-8} C m^{-3} have been observed close to ground in dust storms occurring in southwestern United States. Significance of charge transfers taking place below dust storms can be appreciated when one considers that negative charge transferred to earth's surface by point discharge alone below dust storms in northwest India is reported to be as large as 1177 C km^{-2} yr^{-1} compared to 248 C km^{-2} yr^{-1} below thunderstorms in the same area[3].

Cities and towns change the albedo, increase the surface roughness, release carbon dioxide by the fossil-fuel burning, and introduce particulate matter and gaseous pollutants into the atmosphere. As a result, heat islands develop, low-level lapse rates are steepened, horizontal winds slowed, and up- and downdrafts induced. Such regions will thus modify the development and vertical growth of the mixing layer which substantially contributes to the columnar resistance of the atmosphere. These changes will therefore modify the local and synoptic electric climate of the region. These changes in land-use patterns and in atmospheric conditions are also likely to produce major changes in the electric current flowing from ground to the bases of the clouds developing in those regions. This will modify the electrical properties of these clouds.

There is ample evidence[4] to support that urban areas modify the cloud coverage and rainfall patterns. In the vicinity of some large cities, it has been reported that turbulence and cloud formation increase and rainfall is enhanced. Findings of the research project 'Metromex'[5] support some of these earlier results. It is not surprising that some of the clouds growing in unstable polluted air over heat islands of the urban areas grow into thunderstorms. For example, Changnon[6] reports an increase in thunderstorm frequency of 6% for Chicago, 11% for St Louis and 7% for Urbana. There are several reports that such thunderstorms increase rainfall in urban areas. For example, in one case, mesoscale

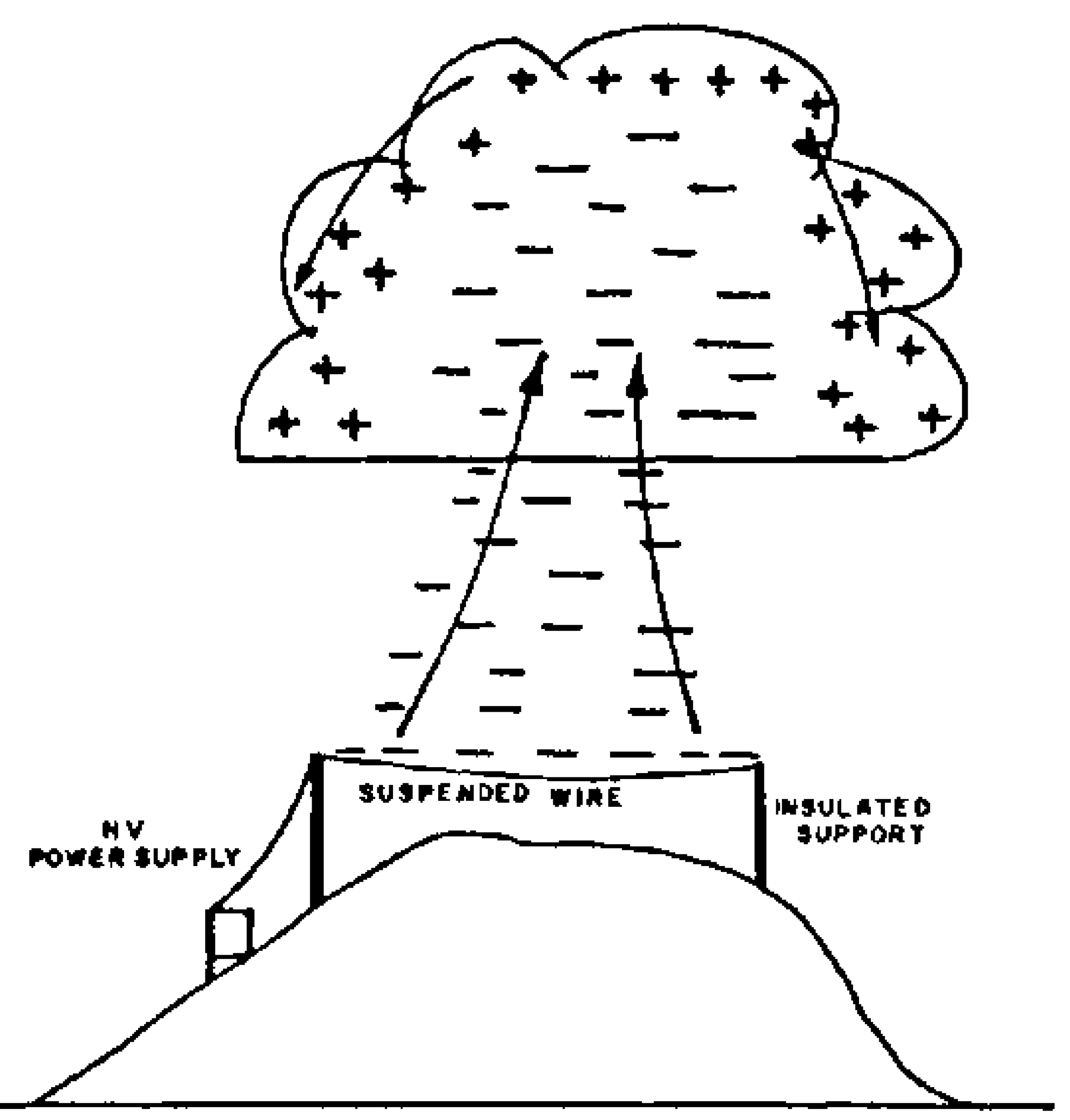

Figure 1. Charge generated in air under a cumulus cloud may enter the cloud with convection currents and determine the cloud's polarity of electrification, Aircraft measurements in experiments conducted by Charles B. Moore and Bernard Vonnegut in Central Illinois and New Mexico, USA, show that charges released in air by a wire connected to a high-voltage power supply are carried upwards through the cloud. Reversing the polarity of the power supply reverses the cloud's polarity.

analysis[7] showed that the London city received 68 mm of rain from a thunderstorm while all of southeastern England had no more than 3 mm on that particular day. Similarly, in another case, London had about 10 times as much rain as the surroundings. The storm formed about 30 km upwind of London and had radar echoes to 6.5 km. Radar echoes increased to 9.5 km height over the city. In a review Changnon[6] arrives at 5% urban increase in annual precipitation for both Urbana and Chicago. Such increase in thunderstorm frequency and the rainfall will certainly modify the supply current of global condenser.

Induction of charged and uncharged aerosol particles

Industrialization, including automobile exhaust, adds large quantities of particulate material into the atmosphere. The suspended particles are largely in the size range 2×10^{-3} to $10\,\mu m$ in radius and will influence the local electric climate of the region. A large fraction of smaller man-made particles results from gas-to-particle conversion from gases emitted into the air, mainly in the presence of sunlight[8], and these submicron particles are of major concern on the global scale. These have low terminal velocities and can be transported to great heights and distances. Although a large fraction of submicron particles is rained out, the theory suggests that the scavenging efficiency by precipitation for particles in the size range of 0.1 to $1\,\mu m$, which shows a maximum in the background particle concentration, is relatively low. Moreover, particles injected into upper troposphere or stratosphere require time to mix down to rain-bearing layers. These particles decrease the electrical conductivity of the atmosphere by getting attached to small large-mobility ions and changing them to large low-mobility ions. Electrical conductivity in the North Atlantic showed a 20% decrease[9] in 1967 compared to that observed in Carnegie expedition during 1910–29. Similar decrease in electrical conductivity was not observed in South Pacific. Decrease in conductivity in North Atlantic has been suggested as an index of the increase of fine particle aerosol pollution in Northern Hemisphere.

Exhaust from aircraft is the other source which introduces particulate material into the atmosphere. Past few decades have seen a manifold increase in military activity. Of particular importance is the supersonic transport, which adds particles to the atmosphere at stratospheric levels. This factor is of major concern when one considers the large residence time of these particles in the stratosphere.

Addition of aerosol particles to the atmosphere by different means, as discussed above, reduces not only the electrical conductivity of the atmosphere on global scale but also increases the columnar resistance of the atmosphere. This factor is therefore of major concern to cause a change in electrical state of the atmosphere on a global scale.

Introduction of ions

High voltage power lines stretched over long distances over earth's surface can introduce large number of ions into the atmosphere. Power lines carrying high DC voltage will produce ions of a single polarity and introduce space charge into the atmosphere. Ions produced in foggy weather from these high voltage power lines can affect the electric field on ground over long distances downwind of these lines[10]. Further, the space charge released from wires raised to high potential can enter the cloud bases and influence the polarity of electric dipole in such clouds[11,12]. Electrical contribution of such clouds to global electric circuit will be much different from the normal ones.

Tall structures such as high towers for TV transmission and communication, chimneys, tall buildings and lightning conductors significantly affect the electrical state of the atmosphere in their surroundings. Besides, atmospheric ions concentrated around these tall objects under electrode effect are blown off downwind of such objects[13,14]. These tall structures also produce small ions by point discharge occurring from them even in fair weather electric fields and thus act as a source for continuous supply of ions in the atmosphere. These tall structures also influence the occurrence of cloud-to-ground lightning discharges below thunderclouds[15,16]. Enhancement of electric field and the increased ionization produced around such objects may initiate the electrical breakdown process at such structures instead of in the cloud and thus may cause a lightning discharge which otherwise might not have occurred. It has been observed[16] that lightning can strike tall structures even when the thundercloud is at a significant distance from the structure and that the charge transfer characteristics of such discharges are much different from that of a natural one. For example, their results show that about 21% of lightning flashes strike the towers in absence of large electric fields ($<2\,kV\,m^{-1}$) and these flashes tend to be shorter and more intense which carry less charge.

Weather modification activities

With the discovery of silver iodide as freezing nuclei by Vonnegut[17] in 1947, more and more countries are involved in weather-modification activities. As a result, a large number of ice-forming nuclei are introduced into the atmosphere from ground generators and from aeroplanes. These ice-forming nuclei modify the initiation and development of rain in clouds by changing their ice-nucleation characteristics. These ice-forming nuclei, long after their release into the atmosphere, keep affecting the glaciation of clouds developing in the atmosphere. Since, for many processes of charge generation in clouds, presence of ice is essential, such modification of glaciating characteristics of clouds will no doubt affect the electrical characteristics of such clouds.

Transfer of charge by lightning discharges is one of the main factors for charge transfer in global electric circuit. Artificial triggering of lightning by firing wire-trailing small rockets below electrified clouds is now practised[18] at several places to investigate lightning characteristics. On the other hand, in some weather-modification efforts, it has been tried to suppress the lightning activity in clouds to prevent forest fires[19,20]. As mentioned in the last section, tall structures and lightning conductors also modify the occurrence of lightning in their surroundings. However, the total charge transferred during such activities is of little significance on global scale.

Bursting bubbles on sea surface

Laboratory experiments show that positive charge is introduced into the atmosphere because of bursting bubbles on sea surface[21]. A positive current of about 450 A has been estimated to flow from the world oceans to the atmosphere. Large quantities of oil and other surface-active materials are spilled over the sea surface and brought into the sea by various rivers that flow and collect pollution over long stretches of land. This charge transfer is greatly modified[21] by the organic surface-active material on the water surface. Therefore the presence of such materials on sea surface will decrease the flux of charge from sea to the atmosphere by this process.

Current flowing from sea surface to the atmosphere owing to bursting bubbles is determined by the surface area covered by the bursting bubbles. In recent times, man has significantly increased transport activities over sea. Large number of vessels move across the world oceans at all times. Area covered by the bursting bubbles in the wake of boats and ships adds to the area of bubbling activity on the sea surface and consequently affects the transfer of charge from sea surface to the atmosphere.

Aviation and navigation

Aeroplanes flying in thunderclouds cause concentration of the electric fields around their conducting bodies. Sometimes it results in triggering of a lightning discharge by the aeroplane[22]. Radar echoes of lightning strikes to NASA F-106B from a UHF-band radar that tracked the airplane during storm penetrations have been analysed[23] and a physical model for such lightning strikes is proposed[24]. The Thunderstorm Research Aircraft, NASA-106B, has intercepted about 700 lightning strikes, most of which have been determined to be triggered by the aircraft itself[25]. Data from UHF-band radar tracking the airplane showed that every echo from a lightning strike to the airplane started on top of airplane echo and propagated outward. Analysis of Apollo-12 lightning incident by NASA shows that lightning discharges hitting the Apollo-12 36 and 52 seconds after its take-off were triggered because of introduction of an electrical perturbation caused by the rocket and its trail. Analysis of several other incidents[26] confirms that aircraft and space vehicles can trigger the lightning.

Ships sailing below thunderstorms provide an electrical anomaly on the open sea surface. It is possible that these ships may trigger a lightning discharge below a thundercloud. Since the screening effect due to space charge generated by point discharge from different points on land is absent on the water surface, electric field as high as $130\,kV\,m^{-1}$ exists over lakes during thunderstorms[27]. Although point discharge characteristics from ships or other objects on sea surface are not well studied, they are likely to generate much higher currents compared to similar isolated points on land surface.

Gaseous air pollutants

Laboratory experiments[28] on the charge separation on freezing of water have shown that such charge transfers are highly sensitive to small traces of ammonia in atmospheric air. Even small concentrations of some substances such as halides and sulphates of the alkaline metals and surface-active organic compounds can not only influence the magnitude but also the polarity of charge being separated. A small fraction of gases released from stacks and chimneys of industries will bé convected up to the level of clouds and affect the charge-separating processes in clouds. Also, because of mixing of these gases by the general circulation of the atmosphere, this process may be significant on global scale. Moreover, atmospheric ions can get attached to large molecules of these gases released into the atmosphere by man's activities, thereby reducing the electrical conductivity of the atmosphere. It is worth noting that very small concentrations, as low as 1 in 10^{10}, of certain gaseous molecules containing halogens such as sulphur hexafluoride can significantly modify dielectric breakdown processes in air.

This problem has been discussed in terms of the existence of double electric layers at the air–water, ice–air and water–ice interfaces. Electric properties of these double layers are strongly influenced by the gases and surface-active materials released into the atmosphere by various air-pollution sources. Thus the charge-generating processes in clouds will be modified. Moreover, it has been suggested[29] that the substances which change the properties of the interfaces may become active agents in lightning suppression.

Release of krypton-85

Krypton-85 is a radioactive by-product of nuclear reactors and is released into the atmosphere. Krypton-85 is a chemically inert gas and has a half-life of 10.76 years and can therefore be dispersed throughout the atmosphere by its general circulation. It has no significant removal mechanism other than radioactive decay. So its concentration is determined by the balance of its annual radioactive decay and the annual release rate. The background concentration of krypton-85 has increased from a near-zero value prior to the utilization of nuclear fission in the 1940s to a value of about 15 $pCi\,m^{-3}$ at sea level in 1972 (refs. 30, 31). The future trends of krypton-85 concentration in atmosphere are difficult to predict in view of large political and sociological factors on the decisions about nuclear power policies of different nations.

Ionization in the atmosphere produced by the decay of krypton-85 will increase the total production rate of ions in the atmosphere. Increase in ionization rate due to this factor may be about 0.86 ion pairs cm^{-3} and it may cause a decrease of total resistance of global circuit[32] by about 10%. The vertical ionization profile of the atmosphere will also be modified by the decay of this isotope.

All theories to explain cloud electrification are affected by the flux of charge to the cloud. Thus any change in the state of ionization of the air in which the cloud grows will influence the growth of electrical activity and occurrence of lightning in the cloud. For example, in a model[33] of thundercloud electrification which includes effects due to the presence of radioactive aerosol particles resulting from fresh debris from a nuclear explosion, an ion pair generation rate of $\geq 10^{12}\,m^{-3}\,s^{-1}$ will prevent significant electric field growth in the cloud.

Since the global electrical circuit is likely to be influenced by the release of this isotope, its monitoring in the atmosphere is very much desirable to check its trend in the future.

Fallout from nuclear explosions

Ionizing radiations from radioactive fallout of nuclear explosions produce additional ionizations in the atmosphere. Following the test series of nuclear explosions in 1950s and 1960s, there are several reports from different locations of the effect of explosions on atmospheric electric parameters. For example, following a nuclear explosion in Nevada desert, the atmospheric conductivity at Tucson increased by about ten-fold and the potential gradient decreased[34] by a factor of 6. Similarly, the secular variation of potential gradient at Eskdalemuir, Scotland, showed a decrease in potential gradient[35]. Following a nuclear explosion in USSR at Novaya Zyemlya on 13 October 1961, Huzita[36] observed an increase in atmospheric conductivity at ground level at Kyoto during 1961–63. Perturbations caused in atmospheric electric parameters by nuclear explosions are quite strong on local or synoptic scales and will spread over a large area with the passage of time.

Nuclear power plant accidents

After the accident in the nuclear power plant at Chernobyl, USSR, pronounced influence on the atmospheric electric parameters has been observed[37] even 1300 km away at Uppsala, Sweden. Following a rainfall, they observed that conductivity increased by about 11 times, atmospheric electric field decreased about 10 times and space charge density decreased about 10 times of the normal values. Similar changes in atmospheric electric parameters have also been observed at Swider[38], Poland, 600 km away and at Athens[39], Greece, 1500 km away from Chernobyl. These observations are supported by large increase in radioactive fallout at these places. Areas with high radioactive fallout experience[40,41] an increase in lightning activity in thunderstorm season in Sweden. Thus radioactive materials introduced into the atmosphere by such incidents of nuclear power plants can spread over large areas by atmospheric circulation and make large changes in atmospheric electrical state.

VLF radiations

Low frequency radiations from high power VLF transmitters or emissions from power lines may enhance[42] the precipitation of electrons in the stratosphere. This will consequently increase the ionization of that region and to some extent decrease the columnar resistance of the atmosphere. This additional ionization may however significantly increase the electrical conductivity of the clear air around a thunderstorm and thereby increase the conduction current flowing to the upper part of a cloud.

Interactions of telluric currents with man-made systems

Natural telluric currents are caused by electromagnetic induction of the time-varying geomagnetic field of external origin. They are also caused when a conducting body, such as seawater, moves across the earth's permanent magnetic field[43]. Natural telluric currents are strongly affected by man-made systems such as communication cables, power lines, long pipelines carrying gas, railways, etc. Severe corrosion has been reported from man-made telluric currents when the conductors are buried close to DC electric railways or tramways. Natural telluric currents may often be many times larger than the currents flowing in the global atmospheric circuit and are no doubt part of the earth's electrical environment. However, the exact interaction, if any, of the two phenomena and, therefore, any possible influence of man-made telluric currents on global atmospheric current are at present not clearly defined and deserve further investigation.

Work done in India

Several studies conducted in India point to various activities of man that can modify the electrical state of the atmosphere. For example, atmospheric electricity measurements made in 1964–65 at Poona show an increase in electric field and a corresponding decrease in electrical conductivity and small ion number density compared to their values for the period[44,45] 1930–38. These changes have been associated with the increased atmospheric pollution due to increase in industrialization, urbanization and traffic at Poona during this period of about 30 years[44]. Measurements taken over the ocean in Bay of Bengal where there are no local sources of pollution show that conductivity values near the land are about half of that in the unpolluted air over the ocean[46]. Values of potential gradient over ocean were found to be much lower than over land and of the same order as those obtained during the Carnegie cruises in the Indian Ocean[46]. Some measurements made in the vicinity of thermal power plants show that emissions from these plants may cause large anti-fair weather electric field up to several hundred metres downwind of the plants[47]. Sometimes these electric fields are large enough to cause point discharge currents from points raised above the earth's surface[47].

Deforestation of land causes an increase in frequency of dust storm occurrence in that region. Large values of anti-fair weather potential gradients have been observed at the earth's surface in dust storms occurring at Roorkee in north-west India[48]. These electric fields are often large enough to cause point discharge currents from points raised above the ground surface[49] and the contribution of charge transferred to earth's surface by point discharge under these dust storms may be significant on global scale[3].

Measurements made at various places in India of ground deposition and airborne fallout of fission products from nuclear-test explosions conducted during 1953 to 1956 show large increase in ground deposition and a decrease in airborne fallout in the rainy season[50,51]. Such changes in concentration of radioactive products will change the conductivity of the air in that region. Increase in ground deposition of radioactive material will cause an increase in rate of ionization in the lower atmosphere which can enhance the rate of gas-to-particle conversion[52].

As mentioned earlier, change in rainfall patterns from clouds grown from urban air may change the transfer of charge by precipitation. An analysis[53] of rainfall data in the coastal region of Bombay has indicated significant increase of about 15% downwind of the urban industrial complexes during the period of increased industrialization during 1941–69. Some changes in electrical and microphysical characteristics of clouds have also been reported in the upwind and downwind regions of a thermal power plant[54] and in clouds growing in maritime and urban environment[55]. Changes in electrical properties of clouds may affect the microphysical[56,57] and dynamical[58] properties of the clouds.

Conclusions

It can be concluded from the above that man inadvertently modifies the electrical state of the atmosphere on different scales of space and time.

There is every reason to believe that the ionization and nuclei introduced into the atmosphere by human activities will modify the electrical processes taking place in the atmosphere which constitutes the dielectric of the giant spherical capacitor comprising the conductive solid and liquid earth and the conductive ionosphere. Evidence for decrease in electrical conductivity as a result of increase in air pollution owing to growing industrialization in Northern Hemisphere is quite convincing[10]. This decrease in conductivity will somewhat be counterbalanced by the additional ionization caused by the release of krypton-85 and its mixing throughout the atmosphere by its general circulation. Outbursts of very large quantities of radioactive material into the atmosphere, as in case of a nuclear explosion or a nuclear power station accident, produce pronounced effects in electrical parameters along its plume for thousands of kilometres and even after a few weeks.

In addition, there is good evidence to support that some human activities such as urbanization, desertification, releasing ice-forming nuclei into the atmosphere, etc. will influence the development of clouds and precipitation in them. Enhanced rainfall over large cities seems to be well documented. Also, some activities of man such as releasing ions, ice-forming nuclei, gaseous pollutants into the atmosphere, and erecting tall objects will modify the charge-generating processes, distribution of charges and lightning activity in clouds and charge-transfer processes from these clouds to the giant spherical capacitor. Experiments[12,13] convincingly demonstrate that polarity of electric dipole in a cloud is influenced by the space charge that is generated at the ground and enters the cloud bases. Moreover, recent experiments leave no doubt about man's capability to artificially trigger lightning discharge from thunderclouds.

It is worth mentioning here that inadvertent modification of atmospheric electric environment can cause changes in some meteorological processes. For example, changes in water drop charges or electric fields in a thundercloud can significantly modify the collision–coalescence characteristics[59], terminal velocities[60,61] and shape[56] of the water drops. Such changes might significantly accelerate or modify the evolution of precipitation and thus influence the dynamics of clouds[58,62,63]. Moreover, the efficiency with which aerosol particles are scavenged in subcloud layer by cloud and raindrops is enhanced by the presence of charge on drop or aerosol particles and external electric fields[59].

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