4.6 Monitoring Atmospheric Electricity in Mountain Areas

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1. What is atmospheric electricity?

A wide range of electromagnetic phenomena are observed on Earth. An electromagnetic layer known as the ionosphere extends from the Earth's surface to an altitude of 100 to 1000 km. This region is dominated by a plasma that is partially ionized by solar radiation such as ultraviolet rays. Next, turning to the zone beneath the Earth's surface, given the slightly electrically conductive nature of the Earth's surface, induced currents arise from changes in the magnetic field in the ionosphere and generate electricity through the movement of ion-containing fluids such as groundwater. Naturally, the movement of seawater, which contains vast quantities of ions, also brings about electromagnetic changes.

What, then, is the first thing that comes to mind when thinking of familiar atmospheric electrical phenomenon? Many people would probably say lightning or the static electricity that often builds up when you wear a sweater in the winter. Lightning is one of the most extreme natural phenomena and is the focus of much research in the field of atmospheric electricity. The main areas of research in this field include not only lightning but also various other phenomena that are closely related to weather. Such phenomena include the electric field that, similar to the geomagnetic field, forms at the global scale during fair weather, and high-altitude transient luminous events (TLEs) such as sprites and elves that have recently garnered much attention and are generated by the interaction of thunderclouds and the ionosphere.

Atmospheric electricity has a long history as a scientific discipline. One of the earliest studies in the field was conducted by Benjamin Franklin, a politician involved in drafting the United States Declaration of Independence. Franklin is famous for flying a kite into a thundercloud and demonstrating that lightning is an electrical phenomenon. Considering that this experiment was conducted in the 1750s, we can indeed say that the field has a long history. Yet, we have only recently learned many things. One example is the aforementioned high-altitude TLEs. These phenomena, which sailors and pilots have frequently reported witnessing, were only discovered in the scientific sense in the 1990s. The radiation generated by lightning discharges and thunderclouds was also only discovered in the 1990s. Both of these were major scientific discoveries that were made relatively recently in the field's long history.

One reason for the slow pace of discovery despite the proximity of the phenomena has to do with the difficulty of measurement, stemming from the transient nature of these phenomena, the challenge of getting physically close to them, and other phenomena obscuring them. Thus, numerous unexplored areas remain.

How can we easily study such phenomena now that advanced instruments have been developed? One possibility is mountain monitoring.

2. Advantages of mountain atmospheric monitoring

Atmospheric electrical phenomena occur as a result of interactions between the ionosphere and the Earth's surface. Thunderclouds, a frequent research topic, occur at altitudes of several kilometers up to 20 km, so it is necessary to approach these altitudes. While airplanes and weather balloons are used for observation, it is not possible to carry out fixed point observation inside thunderclouds using these methods. More importantly, floating observations do not allow for ground contact, making it difficult to deploy measures for lightning protection.

Mt. Fuji's summit, with an altitude of just under 4 km, reaches the bottoms of thunderclouds, making it possible

Fig. 4.6-1: The isolated peak of Mt. Fuji

to place instruments inside them. It is also possible to deploy acceptable lightning protection measures. For mountain monitoring, an isolated mountain with a pointed peak is desirable, because such peaks do not change the shape of thunderclouds as they pass. When a thundercloud collides with a mountain range, it changes shape. Mt. Fuji is the only high-altitude, cone-shaped peak in Japan (Fig. 4.6-1). As a member of NPO Mt. Fuji, we can use the weather station on Mt. Fuji. The weather station was a manned station used for year-round monitoring by the Japan Meteorological Agency (JMA) until 2004. As such, it was equipped with a commercial electricity supply, and the entire structure was enveloped in metal to protect it from frequent lightning strikes (Fig. 4.6-2). Accordingly, the station became a state-of-the-art facility for atmospheric electricity research.

Fig. 4.6-2: Lightning striking immediately in front of the weather station

3. Radiation from thunderclouds

There are only two types of naturally occurring radiation on Earth: radiation emitted from minerals containing natural radioisotopes and radiation from outer space known as cosmic rays. The importance of these discoveries has yielded numerous Nobel Prize winners, including Marie Curie. The discovery of a third type of radiation generated by lightning discharge or thunderclouds has attracted much attention.

The impetus for this discovery came from the identification of high-energy radiation coming from Earth in data collected by a satellite that was launched to detect high-energy radiation (gamma rays) from celestial bodies. It was found that this radiation coincides with lightning strikes on the Earth's surface. This new type of natural radiation has become an active topic of discussion in the scientific community and has been given the name terrestrial gamma rays. Furthermore, it is becoming clear that radiation arising from thunderstorm activity is not limited to radiation generated by lightning; it has also been detected in thundercloud activity that is not accompanied by lightning discharge. Whereas the duration of radiation bursts associated with lightning is on the order of milliseconds, the duration of the high-energy radiation associated with thundercloud activity is much longer and can last several minutes.

This phenomenon was discovered in the Hokuriku (northwest) region of Japan, where numerous nuclear power plants are located. In the winter, transient radiation of unknown origin was recorded by radiation monitoring stations in the region that had been set up to detect radiation leaks from the power plants. After much study, it was found that these radiation bursts occurred when winter thunderclouds approached. In Japan, the bottoms of winter thunderclouds are much lower than those of summer thunderclouds. Since radiation is absorbed by the atmosphere, it makes sense that radiation generated by winter thunderclouds, whose bottoms are close to the ground, could be detected at the Earth's surface.

If this is indeed a real phenomenon, is radiation universally generated by summer thunderclouds around the world? The bottoms of summer thunderclouds are somewhere in the vicinity of 4 km, one order of magnitude higher than those of winter thunderclouds. This means that radiation from summer thunderclouds cannot be detected at the Earth's surface due to atmospheric attenuation. Making observations closer to the altitude of the summer clouds would be better. In other words, Mt. Fuji, an isolated peak with a summit elevation of almost 4 km, provides ideal conditions for such observations (Fig. 4.6-3).

We began monitoring at the JMA weather station in 2008 and wait each summer for thunderclouds to collide with the summit. Monitoring at the weather station can be carried out in the summertime only, and the actual observation window is around 1 month. Nonetheless, the summit is covered by thunderclouds at least several times during that window, and radiation is frequently detected. At present, we are continuing to take various measurements to elucidate the mechanism by which the radiation is generated.

Fig. 4.6-3: A hailstorm near the bottom of a thundercloud. Such storms can occur even in the middle of summer (Photograph by Toshio Yamamoto, one of the mountain crew of NPO Mt. Fuji Research Station)

4. High-altitude TLEs

There are TLEs that occur at the boundary between the atmosphere and space, which lies at an approximate altitude of 100 km, and TLEs that occur at the tops of thunderclouds, which can reach as high as 20 km. The electrical discharges that everyone is familiar with are discharges between thunderclouds and the Earth's surface, which we see as lightning, or intra-cloud discharges, which we hear as thunder. These occur at altitudes below the tops of thunderclouds. However, some of these discharges are immediately followed by lightning flashes above the thunderclouds. Although this phenomenon was theoretically predicted more than a century ago by C.T.R. Wilson, who received a Nobel prize for his invention of the cloud chamber, it was only scientifically verified in the 1990s. The scientific discovery of these high-altitude luminous events was delayed until recently because that they give off less light and are of shorter duration than lightning discharges. The scientific novelty, brilliant colors, and rarity of this phenomenon immediately drew the attention of scientists, leading to substantial advances in research. In Japan, a monitoring network has been established involving high schools across the country. At the university level, efforts are being made to elucidate this phenomenon by equipping satellites and the International Space Station with measuring instruments.

Given their rarity, TLEs are not easy to observe in practical terms. Also, because the events occur above thunderclouds, they are often obscured by lower cloud layers. Although this problem can be overcome by using low-orbit satellites, weather balloons, or airplanes, satellites and the International Space Station are unable to stay in same position, making it impossible to carry out fixed-point monitoring. Similarly, the limitation of weather balloons and airplanes is their inability to carry out long-term fixed-point monitoring. Mountain monitoring is carried out above lower cloud strata and enables long-term fixed-point monitoring (Fig. 4.6-4).

We studied the conditions under which sprites occur in mesoscale convection systems comprising multiple thunderclouds, discovering that sprites occur only when multiple thunderclouds successively grow large and the entire system reaches maturity. A key to this research is also knowing the conditions when TLEs do not occur, so that it is possible to determine the conditions under which TLEs are likely to occur. This research truly takes full advantage of mountain monitoring.

Fig. 4.6-4: Photograph of a high-altitude transient luminous event in Iwate Prefecture

5. Measurement of the fair-weather atmospheric electric field

Downward-pointing vertical electric fields exist in the atmosphere and are referred to as “atmospheric electric fields.” These electric fields have a strength of approximately 100 V/m. Given that the potential of a single dry cell battery is 1.5 V, it is evident that these fields are fairly strong.

Electric fields surround electric charges, but what is the source of atmospheric electric fields? From the existence of a downward-pointing vertical electric field, we can infer that the source is a global-scale capacitor comprising the positively charged ionosphere and the negatively charged surface of the Earth. How, then, does electrical charge accumulate in this capacitor? Also, as is described in the article by Professor Miura in Chapter 4.4, it is known that the atmosphere contains ions formed through ionization by cosmic rays or natural radioisotopes and that an air-to-Earth current of several picoamperes per meter squared is carried by these ions.

Some may wonder why the charge stored in the global-scale capacitor would not be discharged by this air-to-Earth current. To answer this question, we must turn our attention to the diurnal variation in the atmospheric electric field during fair weather. The atmospheric electric field is affected by the electrification of cloud droplets in even small clouds. For this reason, we focus on the atmospheric electric field under fair-weather conditions when there is no wind (or very slight wind) and no clouds.

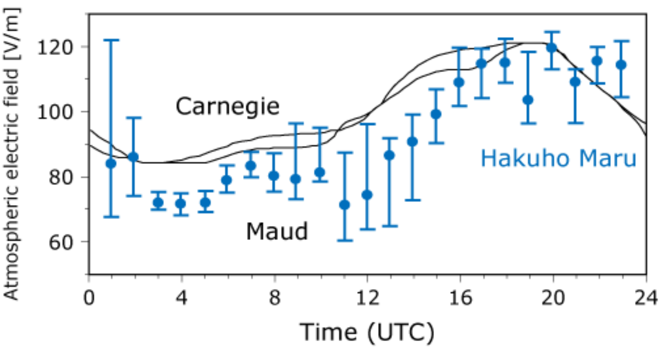

Fig. 4.6-5: The Carnegie Curve. Measurements by the research vessel Hakuho Maru were obtained as part of collaborative research with Professor Miura of the Tokyo University of Science

When we statistically analyze the diurnal variation in the atmospheric electric field recorded over a certain period of fair weather, a characteristic variation emerges. In a graph with the fair-weather atmospheric electric field plotted on the vertical axis and the coordinated universal time (UTC) plotted on the horizontal axis, it is apparent that the atmospheric electric field peaks at around 20:00, regardless of where in the world the measurement is taken (Fig. 4.6-5).

In other words, the same change is observed around the world, regardless of the local time at each monitoring location. This fact was discovered approximately a century ago based on measurements taken by the research vessel Carnegie. subsequent investigation has led to the interpretation that charge is transferred by global thunderstorm activity and rainfall (i.e., recharge the capacitor) such that the earth’s surface and ionosphere accumulate a negative and positive charge, respectively. The diurnal variation in the fair-weather atmospheric electric field is understood as reflecting the change in overall charges. This understanding of the global atmospheric electric circuit (global circuit theory) explains the recharge mechanism and reason why the atmospheric electric field does not dissipate even when there is discharge via the air-to-Earth current (Fig. 4.6-6). Even today, it remains difficult to directly verify this theory through measurements (by continuously monitoring the difference in electrical potential of the ionosphere and the Earth’s surface). That said, given that indirect measurements obtained using various methods are, for the most part, not inconsistent with this theory,

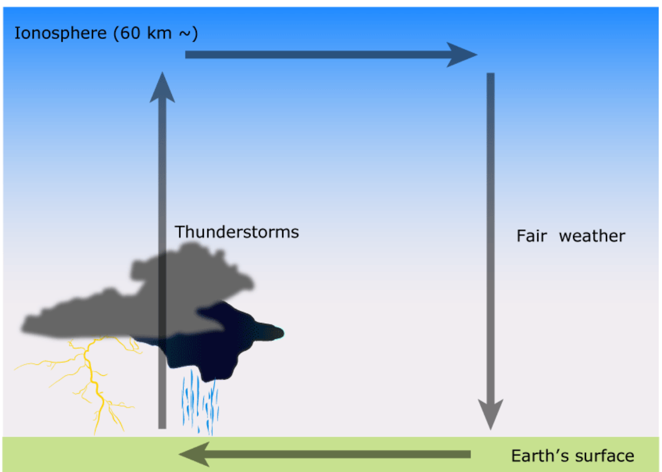

Fig. 4.6-6: Conceptual diagram of the atmospheric global electric circuit

the concept of the global circuit is used to explain the global electric field (which we often refer to as the Earth field), in much the same way that geomagnetism is used to explain the global magnetic field.

What, then, do measurements of the fair-weather atmospheric electric field taken in mountains reveal? Do they follow the Carnegie curve? This question captured the interest of atmospheric electric field researchers for a long time.

However, the results of such measurements, in many cases, exhibited a dependence on local time; that is, the atmospheric electric field increased as the sun rose and decreased as the sun set. Given that similar results were reported around the world, researchers at the time were troubled that observations in mountains did not yield a Carnegie curve consistent with the explicit predictions of global circuit theory. One of the main researchers focusing on this particular topic was Professor Seki, who was then at the Department of Physics, Tokyo University of Science. Professor Seki conducted year-round monitoring at the Mt. Fuji summit in the latter half of the 1960s. The conclusion drawn from the results was that the diurnal variation differs by season. It was found that in all seasons except for winter, the diurnal variation did depend on the local time, with the atmospheric electric field increasing as the sun rise and decreasing as the sun sets. In winter, the diurnal variation was found to follow a Carnegie Curve completely dependent on the UTC. Although many hypotheses to explain this seasonal difference were proposed by Professor Seki and others in the 1950s, no definitive conclusion was reached and the phenomenon remained shrouded in mystery until recently.

The mystery was finally unraveled through collaborative research conducted by the author and members of NPO Mt. Fuji, including the research group of Professors Miura (TUS) and Okochi (Waseda). Our measurements of the fair-weather atmospheric electric field taken at the summit exhibited the same diurnal variation reported by Professor Seki, and we found ourselves face to face with this unsolved mystery. Our monitoring methods differed from those used by Professor Seki insofar as we were able to use cameras to monitor clouds and were therefore able to easily measure a wide range of parameters in addition to the atmospheric electric field. From the diverse data generated, we identified a notable characteristic. In the summer, even when the summit was experiencing fair-weather conditions (negligible winds and clear skies), a robust field of clouds formed and existed at altitudes below the summit, but only during the daytime (Fig. 4.6-7). Even in clouds not of the cumulonimbus type that generates lightning, a weak charge develops in the stratified clouds of the type that form a cloud field. The weak charge integrated over the expansive area of the cloud field was measured as a discrete change in the atmospheric electric field at the summit. Based on measurements taken on the Mt. Fuji slope and at Tarobo (the southeastern foot of Mt. Fuji) as well as simulations, we concluded that the formation of cloud fields affects atmospheric electric field measurements and that the local time dependence of cloud field formation brings about local time-dependent changes in the atmospheric electric field.

In the discussion above, I introduced one aspect of atmospheric electricity research based on mountain monitoring. My hope is that this example demonstrates the potential for mountain monitoring to dramatically increase our ability to conduct research and to study previously inaccessible phenomena. Mountain monitoring is a treasure trove of research whose value cannot be fully described. It is my sincere hope that researchers will avail themselves of the opportunities presented by the Mount Fuji Research Station.

Fig. 4.6-7: A cloud field as seen from the summit of Mt. Fuji