Lightning

Physics and Effects

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1 Introduction

An electrically active thundercloud may be regarded as an electrostatic generator suspended in an atmosphere of low electrical conductivity. It is situated between two concentric conductors, namely, the surface of the earth and the electrosphere, the latter being the highly conducting layers of the atmosphere at altitudes above 50 to 60 km.

D.J. Malan (1967)

In this chapter, we introduce the basic lightning terminology (Section 1.2) and summarize the available quantitative information on various aspects of lightning in tabular form (Section 1.3). Additionally, we give a historical overview of the mythology and science of lightning covering the period from ancient times to the mid twentieth century (Section 1.1) and briefly discuss the global electric circuit that is generally thought to be energized by thunderstorms (Section 1.4). Finally, we consider whether the energy of lightning can be utilized and show that this is impractical (Section 1.5).

1.1. Historical overview

It is likely that lightning was present on Earth long before life evolved on our planet about three billion years ago. Further, it is possible that lightning played a role in producing the organic molecules necessary for the formation of every life form (Oparin 1938; Section 15.9 of this book). Harland and Hacker (1966) reported on a fossil glassy tube, referred to as a fulgurite, created by lightning 250 million years ago. Encounters of early humans with lightning undoubtedly were frightening and fascinating. All ancient civilizations incorporated lightning and thunder in their religious beliefs. Schonland (1964), Prinz (1977), Tomilin (1986), Wahlin (1986), Uman (1987, 2001), and Gary (1994) have reviewed mythological views of lightning in different cultures.

In ancient Egypt, the god Typhon (Seth) hurled the thunderbolts (lightning). A roll seal from Mesopotamia dated about 2200 BC shows a goddess standing on the shoulders of a winged creature and holding a bundle of thunderbolts in each hand (Prinz 1977, Fig. 1). Behind her, in a four-wheeled cart, is a weather god generating thunder with a whip. The similarly equipped weather god Teschup is seen on a Hittite relief found in northern Syria and dated about 900 BC. The thunderbolt is also the emblem of the goddess Tien Mu in Chinese mythology. Tien Mu is among the five dignitaries of the "Ministry of Thunderstorms", which is chaired by Lei Tsu, the God of Thunder, aided by Lei Kung, the drum-beating Count of Thunder. The ancient Vedic books of India describe how Indra, the son of Heaven and Earth, carried thunderbolts on his chariot. Many early statues of Buddha show him carrying in his right hand a thunderbolt with prongs at each end.

According to Prinz (1977), around 700 BC the ancient Greeks began using the lightning symbols of the Middle East in their art, attributing them primarily to Zeus, their supreme god. A lightning flash was one of the chief signs of the displeasure of Zeus in ancient Greece and of Jupiter in ancient Rome. In Rome, the laurel bush was considered, according to Pliny, to be immune from lightning. For this reason, the emperor Tiberius wore a wreath of laurel during thunderstorms. A very powerful political body, the College of Augurs, was formed about 300 BC to determine the views of Jupiter regarding Roman State affairs. This task was accomplished by making observations of three classes of objects in the sky: birds, meteors, and lightning.

In ancient Scandinavia, lightning was believed to be produced by the magic hammer Mjollnir of the god Thor, who hurled it from a chariot rolling thunderously upon the clouds. The Buryats, living in the area of Lake Baikal (Russia), believed that their god produced lightning by throwing stones from the sky. Some Indian tribes of North America, as well as certain tribes in southern Africa, hold the belief that lightning is produced by a magical thunderbird, which dives from the clouds to earth.

There exists a long record of lightning damage to tall structures, particularly churches, covering the period from the Middle Ages to the modern era. For example, the Campanile of St. Mark in Venice, which is about 100 m high, was damaged or destroyed by lightning in 1388, 1417, 1489, 1548, 1565, 1653, 1745, 1761, and 1762. In 1766, a lightning protective system, invented in 1752 by Benjamin Franklin and often referred to as a Franklin rod system, was installed and no further lightning damage has occurred since. In 1718, 24 church towers along the Brittany coast of France were damaged by lightning, apparently during the same storm. In 1769, the Church of St. Nazaire in Brescia, Italy, was struck by lightning. About 100 tons of gunpowder had been placed in the vaults of the church for safekeeping, and when the lightning discharge caused it to explode, about one-sixth of the city was destroyed, more than 3000 people being killed.

There are, however, many historic buildings which have never been seriously damaged by lightning, apparently because they had, in effect, a lightning protective system equivalent to that proposed later by Franklin. For example, the Temple in Jerusalem, originally built by Solomon, experienced no apparent damage from lightning over a period of a thousand years. Other examples are the 62 m high monument erected in 1677 in commemoration of the Great Fire of London and the cathedral of Geneva, the most prominent building in that city. This cathedral was immune from lightning damage for 300 years prior to being equipped with a Franklin rod system. In 1773, Franklin pointed out that "buildings that have their roofs covered with lead or other metal, and spouts of metal continued from the roof into the ground are never hurt by lightning; as whenever it falls on such a building, it passes in the metal and not in the walls" (Schonland 1964, p. 14). More information on the lightning protection of buildings, including historical aspects, is found in Section 18.3.

The practice of ringing church bells during thunderstorms in an attempt to disperse lightning existed for many centuries in Europe. Since bell towers are usually preferred targets for lightning because of their relatively large height (see Section 2.9), this practice caused the deaths of many of those pulling the ropes. In fact, over a period of 33 years, lightning struck 386 church towers and killed 103 bell-ringers, as reported in a book by Fischer published in Munich in 1784 (Schonland 1964, p. 9).

Many ships with wooden masts have been severely damaged or totally destroyed by lightning, as discussed in subsection 18.4.1. Harris (1834, 1838, 1839, 1843) reported that from 1799 to 1815 there were 150 cases of lightning damage to British naval vessels. One ship in eight was set on fire, nearly 100 lower masts were destroyed, about 70 sailors were killed, and more than 130 people were wounded. In 1798, the 44-gun ship *Resistance* exploded as a result of a lightning discharge.

Systematic studies of thunderstorm electricity can be traced back to 10 May 1752 in the village of Marly-la-Ville, near Paris. On that day, in the presence of a nearby storm, a retired French dragoon, acting on instructions from Thomas-François Dalibard, drew sparks from a tall iron rod that was insulated from ground by wine bottles. The results of this experiment, proposed by Benjamin Franklin, provided the first direct proof that thunderclouds contain electricity, although several scientists had previously noted the similarity between laboratory sparks and lightning (Prinz 1977; Tomilin 1986). The Marly experiment was repeated thereafter in several countries including Italy, Germany, Russia, Holland, England, Sweden, and again France. Franklin himself drew sparks from the probably moist hemp string of a kite after the success at Marly, but before he knew about this (Cohen 1990). Not only kites but also balloons, mortars, and rockets were used to extend conducting strings into the electric field of the cloud (Prinz 1977, Fig. 5). In all these experiments, the metallic rod (such as in the experiment at Marly) or the conducting string was polarized by the electric field of the cloud, so that charges of opposite polarities accumulated at the opposite ends of the conductor. As the gap between the bottom end of the conductor and ground was decreased, a spark discharge to ground occurred. The scale and effect of this spark discharge are orders of magnitude smaller than those of lightning. In designing his experiments, Franklin did not consider the possibility of a direct lightning strike to the rod or the kite. Such a strike would almost certainly have killed the experimenter. Thus all those who performed these experiments risked their lives, but there is only one case on record in which a direct strike did occur in such experiments. This happened on 6 August 1753 in St. Petersburg, Russia when Georg Richmann, who had previously done Franklin's experiment, was killed by a direct lightning strike to an ungrounded rod. Interestingly, Richmann was not in contact with the rod, and what caused his death appeared to be a ball lightning that came out of the rod and went to his forehead. This accident is discussed further in Section 20.1.

Franklin also showed that lightning flashes originate in clouds that are "most commonly in a negative state of electricity, but sometimes in a positive state" (Franklin 1774). Even before the experiment at Marly, Franklin had proposed the use of grounded rods for lightning protection. Originally, he thought that the lightning rod would silently discharge a thundercloud and thereby would prevent the initiation of lightning. Later, Franklin stated that the lightning rod had a dual purpose: if it cannot prevent the occurrence of lightning, it offers a preferred attachment point for lightning and then a safe path for the lightning current to ground. It is in the latter manner that lightning rods, often referred to as Franklin rods, actually work (Section 18.3), as suggested by Lomonosov in 1753 (Tomilin 1986); a lightning rod cannot appreciably alter the charge in a cloud. One convincing demonstration of the effectiveness of Franklin rods took place in Siena, Italy, on 18 April 1777. On that day, a large number of people gathered near the 102 m tower of the city hall, which had been repeatedly struck and damaged by lightning prior to the installation of lightning rods in 1777. A thunderstorm rumbled into the area, and the crowd saw lightning strike the lightning protective system without damaging the tower. More information on the contributions of Benjamin Franklin to the study of lightning and lightning protection is found, for example, in Dibner (1977) and Krider (1996b).

In 1876, James Clerk Maxwell suggested that Franklin rod systems attracted more lightning strikes than the surrounding area. He proposed that a gunpowder building be completely enclosed with metal of sufficient thickness, forming what is now referred to as a Faraday cage. If lightning were to strike a metal-enclosed building, the current would be constrained to the exterior of the metal enclosure, and it would not even be necessary to ground this enclosure. In the latter case, the lightning would merely produce an arc from the enclosure to earth. The Faraday cage effect is provided by all-metal cars and airplanes. Modern steel-frame buildings with reinforcing metal bars in the concrete foundation connected to the building steel provide a good approximation to a Faraday cage. As the spacing between conductors increases, however, the efficiency of the lightning protection decreases. In practice, a combination of the Franklin rod system concept and the Faraday cage concept is often used. Modern lightning protection schemes for structures containing computers or other sensitive electronics employ a technique known as topological shielding with surge suppression (subsection 18.3.6), which can be viewed as a generalization of the Faraday cage concept.

In the following, we briefly review the history of lightning research from the latter part of the nineteenth century to the middle of the twentieth century. In the late nineteen century, photography and spectroscopy became available as diagnostic tools for lightning research. Among the early investigators of the lightning spectrum were Herschel (1868), Gibbons (1871), Holden (1872), and Clark (1874). It was Herschel who first identified a nitrogen line as being the brightest in the visible spectrum and who noted that the relative intensities of the lines change from spectrum to spectrum. Schuster (1880) made the first systematic identification of the lines in the spectrum of lightning. Dufay (1949) and Israel and Fries (1956) were the first to consider the spectrum of lightning as a source of quantitative information about the physical conditions in and around the lightning channel. Slipher (1917) obtained the first photographic record of the spectrum of lightning and noted that there were both line and continuum emissions. Spectroscopic studies of lightning are reviewed by Uman (1969, 1984, Chapter 5) and Orville (1977).

Among the early investigators who used stationary or moving photographic cameras were Hoffert (1889), Weber (1889), Walter (1902, 1903, 1910, 1912, 1918), and Larsen (1905). Time-resolved photographs showing that lightning flashes often contain two or more strokes, similar to that shown in Fig. 4.1a, were obtained. The invention of the streak camera (Boys 1926) and its further improvement (Boys 1929; Malan 1950, 1957) facilitated the major advances in lightning research made by B.F.J. Schonland, D.J. Malan, and their co-workers in South Africa during the 1930s. For example, it was shown conclusively by the South African researchers that lightning strokes lowering negative charge to ground are composed of a downward leader and an upward return stroke and that the first-stroke leader is stepped (see Fig. 4.2). Schonland (1956) summarized the main results of the South African studies. (Much of the presently used lightning terminology was introduced by the South African researchers.) The results obtained in South Africa have been confirmed and extended by investigators using streak cameras in the United States, Russia, France, Japan, and Switzerland. A review of photographic studies of lightning through the 1960s is found in Uman (1969, 1984, Chapter 2).

The first estimates of lightning peak current, inferred from the residual magnetization of pieces of basalt placed near the strike object, were made by Pockels (1900). Further information on the estimates of lightning currents obtained using magnetizable materials is found in Uman (1969, 1984, Chapter 4). The first oscillographic recordings of lightning current waveforms were obtained using tethered balloons in Russia (Stekolnikov and Valeev 1937) and in England (Davis and Standring 1947), and on the Empire State Building in New York City (McEachron 1939, 1941; Hagenguth and Anderson 1952). The most comprehensive data on lightning current waveforms to date were acquired by K. Berger and his associates on two instrumented towers on Monte San Salvatore in Switzerland, as discussed in Chapters 4, 5, and 6.

C.T.R. Wilson, who received a Nobel Prize for his invention of the cloud chamber to track high-energy particles, was the first to use electrostatic field measurements to infer the charge structure of thunderclouds (subsection 3.2.2) as well as the charges involved in the lightning discharge. Simpson and Scrase (1937) and Simpson and Robinson (1941) made the earliest measurements of electric fields inside thunderclouds and used these measurements to infer cloud charge structure (subsection 3.2.3). The first multiple-station measurements of the electromagnetic fields on ground from relatively close lightning were performed by Workman *et al.* (1942) and Reynolds and Neill (1955). Early measurements of the electric fields of distant lightning in the frequency range from a few to a few tens of kilohertz, called atmospherics, are discussed in Section 13.3. Austin (1926), Appleton *et al.* (1926), Wattson-Watt (1929), Norinder (1936), and Chapman (1939) were among the first to study atmospherics. Norinder and Dahle (1945) made an attempt to relate lightning magnetic field measurements to the current in the lightning channel. The modern era of electric and magnetic field measurements relating to lightning can be traced to the 1970s, when the first field records on microsecond and submicrosecond time scales were reported (see Chapters 4 and 9). More information on the early measurements of the electric and magnetic fields due to lightning is found in Uman (1969, 1984, Chapter 3).

1.2. Types of lightning discharge and lightning terminology

Lightning, or the lightning discharge, in its entirety, whether it strikes ground or not, is usually termed a "lightning flash" or just a "flash". A lightning discharge that involves an object on ground or in the atmosphere is sometimes referred to as a "lightning strike". A commonly used non-technical term for a lightning discharge is "lightning bolt". The terms "stroke" or "component stroke" apply only to components of cloud-to-ground discharges. Each stroke involves a downward leader and an upward return stroke and may involve a relatively low level "continuing current" that immediately follows the return stroke. Transient processes occurring in a lightning channel while it carries continuing current are termed M-components. First strokes are initiated by "stepped" leaders while subsequent strokes following previously formed channels are initiated by "dart" or "dart-stepped" leaders.

From the observed polarity of the charge effectively lowered to ground and the direction of propagation of the initial leader, four different types of lightning discharges between cloud and Earth have been identified. The term "effectively" found here and elsewhere in this book in a similar context (although often it is omitted for simplicity) is used to indicate that individual charges are not transported all the way from the cloud to ground during the lightning processes. Rather, the flow of electrons (the primary charge carriers) in one part of the lightning channel results in the flow of other electrons in other parts of the channel, as discussed by Uman (1987, 2001). For example, individual electrons in the lightning channel move only a few meters during a return stroke that transfers a coulomb or more of charge to ground.

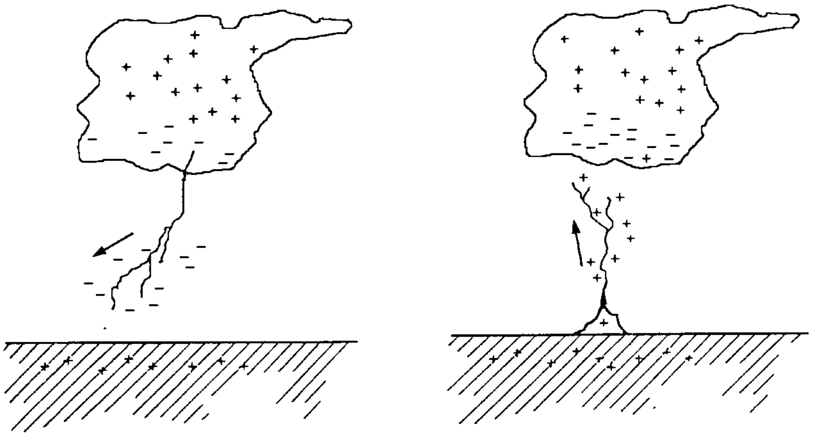
The four types of lightning, illustrated in Fig. 1.1, are (a) downward negative lightning, (b) upward negative lightning, (c) downward positive lightning, and (d) upward positive lightning. Discharges of all four types can be viewed as effectively transporting cloud charge to the ground and therefore are usually termed cloud-to-ground discharges (sometimes referred to as CGs). It is believed that downward negative lightning flashes, type (a), account for about 90 percent or more of global cloud-to-ground lightning, and that 10 percent or less of cloud-to-ground discharges are downward positive lightning flashes (type (c)). Upward lightning discharges, types (b) and (d), are thought to occur only from tall objects (higher than 100 m or so) or from objects of moderate height located on mountain tops (Chapter 6). Rocket-triggered lightning, discussed in Chapter 7, is similar in its phenomenology to the upward lightning initiated from tall objects. The term "initial continuous current," as differentiated from continuing current, is used to denote the relatively low-level current flowing during the initial stage of upward (Chapter 6) and rocket-triggered (Chapter 7) lightning. The downward negative lightning discharge is considered in Chapter 4 and the positive lightning discharge in Chapter 5. Additionally discussed in Chapter 5 are lightning flashes that transfer both negative and positive charges to ground. The majority of lightning discharges, probably three-quarters, do not involve ground. These are termed cloud discharges and sometimes are referred to as ICs. Cloud discharges include intracloud, intercloud, and cloud-to-air discharges and are considered in Chapter 9. Unusual forms of lightning and lightning-like discharges (including ball lightning) are discussed in Chapter 20.

There are three possible modes of charge transfer to ground in lightning discharges. It is convenient to illustrate these for the case of negative subsequent strokes. In negative subsequent strokes these three modes are represented by (a) dart-leader–return-stroke sequences, (b) continuing currents, and (c) M-components. Figure 1.2 schematically shows current profiles corresponding to these three modes, which we now discuss.

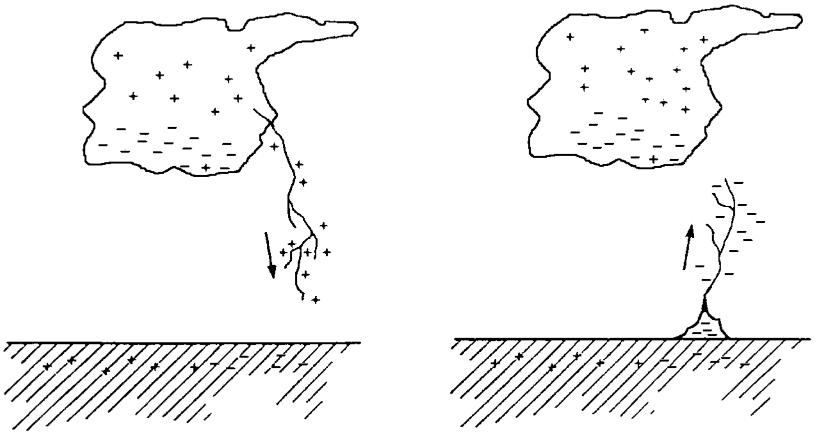
(a) In a leader–return-stroke sequence, the descending leader creates a conductive path between the cloud charge source and ground and deposits negative charge along this path. The following return stroke traverses that path, moving from ground toward the cloud charge source, and neutralizes the negative leader charge. Thus, both leader and return-stroke processes serve to transport effectively negative charge from the cloud to ground.

(b) The lightning continuing current can be viewed as a quasi-stationary arc between the cloud charge source and ground. The typical arc current is tens to hundreds of amperes, and the duration is up to some hundreds of milliseconds.

(c) Lightning M-components can be viewed as perturbations (or surges) in the continuing current and in the associated channel luminosity. It appears that an M-component involves the superposition of two waves propagating in opposite directions (see Fig. 1.2). The spatial front length for M-component waves is of the order of a kilometer (shown shorter in relation to the cloud height in Fig. 1.2, for illustrative purposes), while for dart-leader and return-stroke waves the spatial front lengths are of the



(a) Downward negative lightning (b) Upward negative lightning



(c) Downward positive lightning (d) Upward positive lightning

Fig. 1.1. Four types of lightning effectively lowering cloud charge to ground. Only the initial leader is shown for each type. In each lightning-type name given below the sketch, the direction of propagation of the initial leader and the polarity of the cloud charge effectively lowered to ground are indicated.

order of 10 and 100 m, respectively. The M-component mode of charge transfer to ground requires the existence of a grounded channel carrying a continuing current that acts as a wave-guiding structure. In contrast, the leader–return-stroke mode of charge transfer to ground occurs only in the absence of such a conducting path to ground. In this latter mode, the wave-guiding structure is not available and is created by the leader. For all the processes shown in Fig. 1.2, the channel conductivity is of the order of 10^4 S m^{-1}, except for the channel section between the dart-leader tip and ground shown by a broken line. For this latter channel section, the conductivity is about 0.02 S m^{-1} (Rakov 1998). Thus, the primary distinction between the leader–return-stroke and M-component modes is the availability of a conducting path to ground. It is possible that, as the conductivity of the path to ground decreases, the downward M-component wave can transform to a dart leader.

We now define the terms "leader" and "streamer", as they are used in this book. Any self-propagating electrical discharge creating a channel with electrical conductivity of the order 10^4 S m^{-1} (comparable to that of carbon) is called a leader. Streamers, on the other hand, are characterized by much lower electrical conductivity; the air behind the streamer tip remains essentially an insulator (e.g., Bazelyan *et al.* 1978). A corona or point discharge consists of numerous individual streamers. Corona discharge is confined to the immediate vicinity of an "electrode" such as a grounded object, a leader tip, the lateral surface of the leader channel,

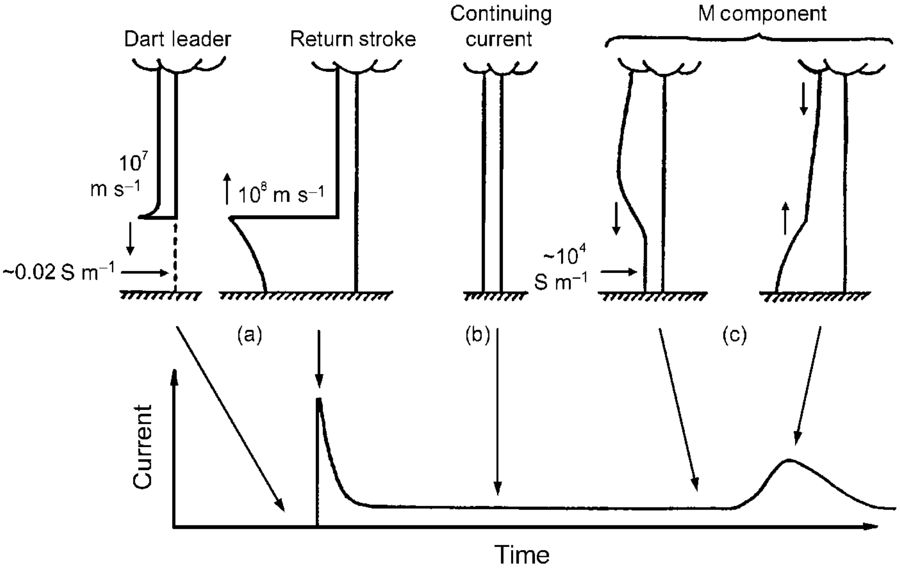


Fig. 1.2. Schematic representation of current versus height profiles for three modes of charge transfer to ground in negative lightning subsequent strokes: (a) dart-leader–return-stroke sequence, (b) continuing current, and (c) M-component. The corresponding current versus time waveform represents the current at the ground.

or a hydrometeor, that is, it is not a self-propagating discharge. It is worth noting that the terms leader and streamer in the lightning literature are sometimes used interchangeably, the term streamer in most cases being used to denote a low-luminosity leader, particularly the upward connecting leader (Section 4.5).

1.3. Summary of salient lightning properties

The salient properties of downward negative lightning discharges, the most common type of cloud-to-ground lightning, are summarized in Table 1.1. Negative lightning is discussed in detail in Chapter 4. Properties of positive and bipolar lightning are discussed in Chapter 5 and those of cloud discharges in Chapter 9. Characteristics of microsecond-scale electric field pulses associated with various lightning processes are summarized in Table 1.2.

Various lightning processes emit electromagnetic signals with a peak in the radio-frequency spectrum at 5 to 10 kHz when observed at distances beyond 50 km or so. At frequencies higher than that of the spectrum peak, the spectral amplitude is approximately inversely proportional to the frequency up to 10 MHz or so and inversely proportional to the square root of frequency from about 10 MHz to 10 GHz (Cianos *et al.* 1973). The mechanisms of radiation in the high-frequency (HF) region of the spectrum, 3–30 MHz, and above are not fully understood. It is thought that this radiation is caused by numerous small sparks occurring during the formation of new channels, that is, by the electrical breakdown of air rather than by high-current pulses propagating in pre-existing channels.

1.4. The global electric circuit

Shortly after the experiment at Marly that confirmed Franklin's conjecture regarding the electrical nature of thunderstorms (Section 1.1), Lemonnier (1752) discovered atmospheric electrical effects in fair weather. Further research established that the Earth's surface is charged negatively and the air is charged positively, the associated vertical electric field in fair weather being about 100 V m^{-1} near the Earth's surface.

1.4.1. Conductivity of the atmosphere

The atmosphere below about 50 km is conducting, owing to the presence of ions created by both cosmic rays and the natural radioactivity of the Earth. Small ions, those with diameters of 0.1 to 1 nm and lifetimes of about 100 s, are the primary contributors to the conductivity of the lower atmosphere. Free electrons at these heights are attached to neutrals on time scales of the order of microseconds, and their contribution to the conductivity of the atmosphere below about 50 km can be neglected (Gringel *et al.* 1986; Reid 1986). Above 60 km or so, free electrons become the major contributors to the atmospheric conductivity. The average production rate of ions at sea level is one to 10 million pairs per cubic meter per second. Cosmic rays and natural radioactivity contribute about equally to the production of ions at the land surface. Since large water surfaces have no

Table 1.1. *Characterization of negative cloud-to-ground lightning*

Parameter	Typical value[a]
Stepped leader	
Step length, m	50
Time interval between steps, µs	20–50
Step current, kA	> 1
Step charge, mC	> 1
Average propagation speed, m s^{-1}	2×10^5
Overall duration, ms	35
Average current, A	100–200
Total charge, C	5
Electric potential, MV	~ 50
Channel temperature, K	$\sim 10\,000$
First return stroke[b]	
Peak current, kA	30
Maximum current rate of rise, kA µs^{-1}	$\geq$10–20
Current risetime (10–90 percent), µs	5
Current duration to half-peak value, µs	70–80
Charge transfer, C	5
Propagation speed, m s^{-1}	$(1\text{–}2) \times 10^8$
Channel radius, cm	$\sim$ 1–2
Channel temperature, K	$\sim 30\,000$
Dart leader	
Speed, m s^{-1}	$(1\text{–}2) \times 10^7$
Duration, ms	1–2
Charge, C	1
Current, kA	1
Electric potential, MV	~ 15
Channel temperature, K	$\sim 20\,000$
Dart-stepped leader	
Step length, m	10
Time interval between steps, µs	5–10
Average propagation speed, m s^{-1}	$(1\text{–}2) \times 10^6$
Subsequent return stroke[b]	
Peak current, kA	10–15
Maximum current rate of rise, kA µs^{-1}	100
10–90 percent current rate of rise, kA µs^{-1}	30–50
Current risetime (10–90 percent), µs	0.3–0.6
Current duration to half-peak value, µs	30–40
Charge transfer, C	1
Propagation speed, m s^{-1}	$(1\text{–}2) \times 10^8$
Channel radius, cm	$\sim$ 1–2
Channel temperature, K	$\sim 30\,000$
Continuing current (longer than $\sim$ 40 ms)[c]	
Magnitude, A	100–200
Duration, ms	~ 100
Charge transfer, C	10–20
M-component[b]	
Peak current, A	100–200
Current risetime (10–90 percent), µs	300–500
Charge transfer, C	0.1–0.2
Overall flash	
Duration, ms	200–300
Number of strokes per flash[d]	3–5
Interstroke interval, ms	60
Charge transfer, C	20
Energy, J	$10^9 - 10^{10}$

[a] Typical values are based on a comprehensive literature search and unpublished experimental data acquired by the University of Florida Lightning Research Group.

[b] All current characteristics for return strokes and M-components are based on measurements at the lightning channel base.

[c] About 30 to 50 percent of lightning flashes contain continuing currents having durations longer than $\sim$ 40 ms.

[d] About 15 to 20 percent of lightning flashes are composed of a single stroke.

significant radioactive emanation, the production of ions over oceans is about one-half of that over land. At altitudes of roughly 1 km and greater, cosmic rays are responsible for most of the ions in the fair weather atmosphere, regardless of the presence of land below. The ionization rate depends on magnetic latitude and on the solar activity.

The electrical conductivity of the air at sea level is about 10^{-14} S m^{-1}, and it increases rapidly with altitude. A diagram illustrating conductivity variations up to an altitude of 120 km is shown in Fig. 1.3. The various regions of the atmosphere are named in Fig. 14.1, and typical values of electron density and collision frequency as a function of height are found in Figs. 13.5 and 13.6, respectively.

At a height of 35 km, where the air density is about one percent of that at the Earth's surface, the electrical conductivity is greater than 10^{-11} S m^{-1}, which is more than three orders of magnitude higher than at sea level. For comparison, the average electrical conductivity of the Earth is about 10^{-3} S m^{-1}. As seen in Fig. 1.3, a considerable variation of conductivity exists at the same altitude for different measurements, about six orders of magnitude at 60 km. Above about 80 km, the conductivity becomes anisotropic because of the influence of the geomagnetic field (Section 13.2), and there are diurnal variations due to solar photoionization processes.

Blakeslee *et al.* (1989) reported, from high-altitude U-2 airplane measurements, that the conductivity near 20 km was relatively steady above storms, variations being less than ±15 percent. However, a number of balloon measurements of the electrical conductivity between 26 and 32 km over thunderstorms suggest that some of the time the storm may significantly (up to a factor 2) perturb the

Table 1.2. *Characterization of microsecond-scale electric field pulses associated with various lightning processes. Adapted from Rakov et al. (1996)*

	Dominant polarity[a]				
Type of pulses	Atmospheric electricity sign convention	Physics sign convention	Typical[b] total pulse duration, μs	Typical[b] time interval between pulses, μs	Comments
Return stroke in negative ground flashes	positive	negative	30–90 (zero-crossing time)	60×10^3	3–5 pulses per flash
Stepped leader in negative ground flashes	positive	negative	1–2	15–25	Within 200 μs just prior to a return stroke
Dart-stepped leader in negative ground flashes	positive	negative	1–2	6–8	Within 200 μs just prior to a return stroke
Initial breakdown in negative ground flashes	positive	negative	20–40	70–130	Some milliseconds to some tens of milliseconds before the first return stroke
Initial breakdown in cloud flashes	negative	positive	50–80	600–800	The largest pulses in a flash
Regular pulse burst in both cloud and negative ground flashes	Both polarities are about equally probable		1–2	5–7	Occur later in a flash; 20–40 pulses per burst
Narrow bipolar pulses	negative	positive	10–20	-	Probably associated with the initial breakdown in cloud flashes

[a] The polarity of the initial half cycle in the case of bipolar pulses.

[b] Typical values are based on a comprehensive literature search and unpublished experimental data acquired by the University of Florida Lightning Research Group.

conductivity (Bering *et al.* 1980b; Holzworth *et al.* 1986; Pinto *et al.* 1988; Hu *et al.* 1989). It is usually assumed that the atmosphere above a height of 60 km or so, under quasi-static conditions, becomes conductive enough to consider it an equipotential region. The electrical conductivity increases abruptly above about 60 km because of the presence of free electrons (Roble and Tzur 1986; Reid 1986). This region of atmosphere just above 60 km or so where free electrons are the major contributors to the conductivity is sometimes referred to as the electrosphere (e.g., Chalmers 1967) or "equalizing" layer (Dolezalek 1972). At 100 km altitude (in the lower ionosphere) the conductivity is about 12 ± 2 orders of magnitude (depending on the local time of the day) greater than the conductivity near the Earth's surface, that is, the conductivity at 100 km is comparable to the conductivity of the Earth, whether land or sea (Rycroft 1994).

1.4.2. Fair-weather electric field

As noted above, the electric field near the Earth's surface under fair-weather (also called fine-weather) conditions is about 100 V m^{-1}. The electric field vector is directed downward. This downward-directed field is defined as positive according to the "atmospheric electricity" sign convention. According to the alternative sign convention, sometimes referred to as the "physics" sign convention, a downward directed electric field is negative because it is in the direction opposite to that of the radial coordinate vector of the spherical coordinate system whose origin is at the Earth's center. We will use the physics sign convention in this chapter (both sign conventions are given in Table 1.2) and in Chapters 3 and 8. However, in order to minimize conflict with the existing literature, we will use the atmospheric electricity sign convention in Chapters 4, 5, 6, 7, and 12, and we will employ both the atmospheric electricity and physics

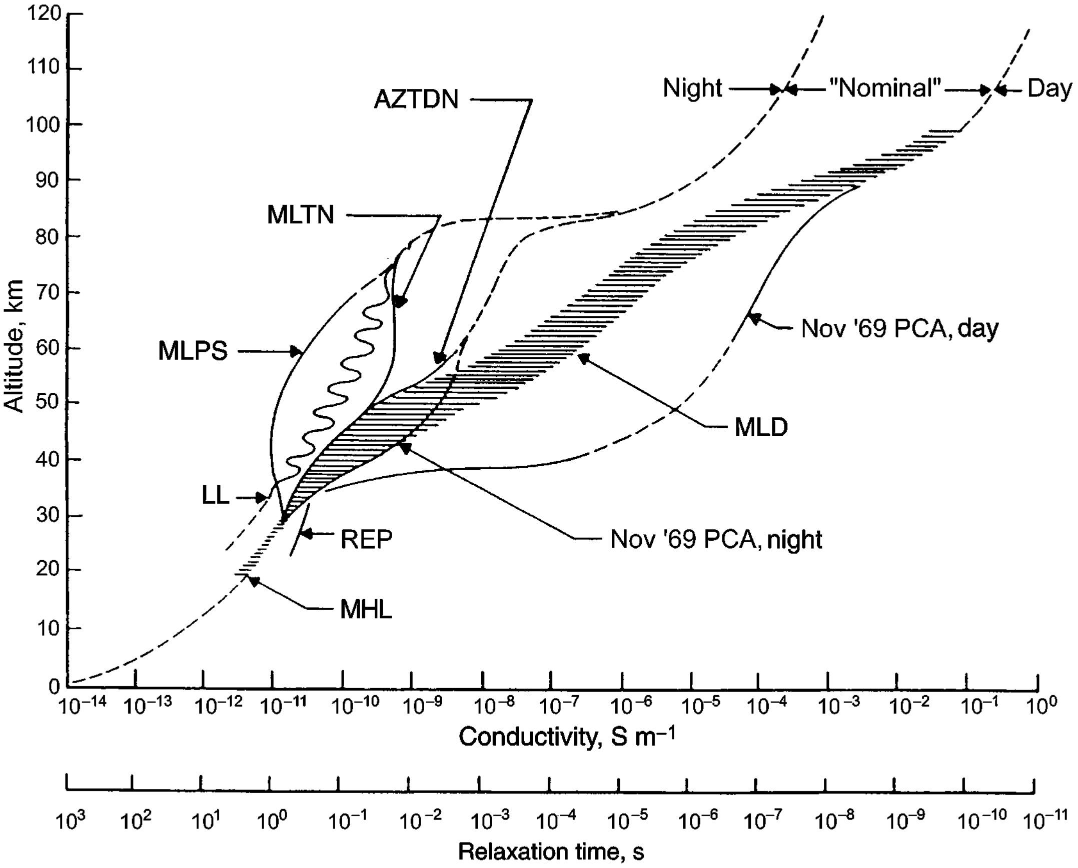


Fig. 1.3. Electrical conductivity σ and corresponding relaxation time $\tau = \varepsilon_0 \sigma^{-1}$, where $\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1}, versus altitude under a variety of geophysical conditions. LL, low latitude, "wavy"; MLPS, mid-latitude pre-sunrise (unusual); MLTN, mid-latitude typical night (high-latitude, quiet); AZTDN, auroral zone, typical disturbed night; MLD, mid-latitude day, quiet; MHL, mid-high-latitude, typical of $\sim$ 100 measurements; REP, relativistic electron (energy from a few MeV to 10 MeV) precipitation event (unusual); PCA, polar cap absorption event (an unusually large flux of energetic, $\sim$ 100 MeV solar protons within the polar cap). Adapted from Hale (1984).

sign conventions in Chapter 9. We will indicate explicitly the direction of the electric field vector when appropriate. The magnitude of the fair-weather electric field decreases with increasing altitude. For example, according to Volland (1984),

$$E(z) = -[93.8 \exp(-4.527z) + 44.4 \exp(-0.375z) + 11.8 \exp(-0.121z)] \qquad (1.1)$$

where $E(z)$ is the electric field in V m^{-1} (the negative sign indicates that the electric field vector is directed downward) and z is the altitude in kilometers. This equation is valid at mid-latitudes below about 60 km altitude and outside thunderstorms or cloudy areas. According to Eq. 1.1, the electric field at the ground is 150 V m^{-1} and at 10 km altitude decreases to about 3 percent of its value at the ground. The electric field magnitude normally drops to around 300 mV m^{-1} at 30 km at mid-latitudes (Gringel *et al.* 1986) and to 1 μV m^{-1} or so at about 85 km (Reid 1986).

1.4.3. "Classical" view of atmospheric electricity

The evaluation of the line integral of the electric field intensity from the Earth's surface to the height of the electrosphere yields the negative of the potential of the electrosphere, sometimes termed the ionospheric potential (e.g., Markson 1976), with respect to Earth potential. The potential of the electrosphere is positive with respect to the Earth and its magnitude is about 300 kV, most of the voltage drop taking place below 20 km where the electric field is relatively large. The overall situation is often visualized as a lossy spherical capacitor (e.g., Uman 1974), the outer and inner shells of which are the electrosphere and Earth's surface, respectively. According to this model, the Earth's surface is negatively charged, the total charge magnitude being roughly 5×10^5 C, while an equal positive charge is distributed throughout the atmosphere. Little charge resides on the electrosphere "shell". Further, most of the net positive charge is found within 1 km of the Earth's

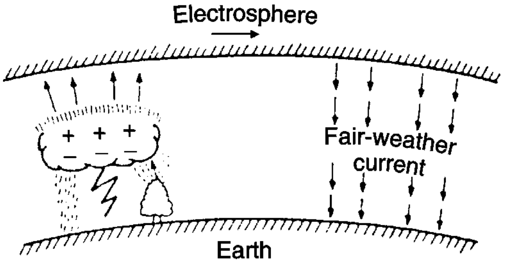


Fig. 1.4. Illustration of the global electric circuit. Shown schematically under the thundercloud are precipitation, lightning, and corona. Adapted from Pierce (1974).

surface, and more than 90 percent of this charge within 5 km (MacGorman and Rust 1998). Because the atmosphere between the capacitor "shells" is weakly conducting, there is a fair-weather leakage current of the order of 1 kA (2 pA m^{-2}; 1 pA = 10^{-12} A) between the shells that would neutralize the charge on the Earth and in the atmosphere on a time scale of roughly 10 minutes (depending on the amount of pollution) if there were no charging mechanism to replenish the neutralized charge. Since the capacitor is observed to remain charged, there must be a mechanism or mechanisms acting to resupply that charge. Wilson (1920) suggested that the negative charge on the Earth is maintained by the action of thunderstorms. Thus all the stormy-weather regions worldwide (on average, at any time a total of about 2000 thunderstorms are occurring, over about 10 percent of the Earth's surface) constitute the global thunderstorm generator, while the fair-weather regions (about 90 percent of the globe) can be viewed as a resistive load. Lateral currents are assumed to flow freely along the highly conducting Earth's surface and in the electrosphere. The fair-weather current, of the order of 1 kA, must be balanced by the total generator current, which is composed of currents associated with corona, precipitation, and lightning discharges. The total current flowing from cloud tops to the electrosphere is, on average, about 0.5 A per thunderstorm (Gish and Wait 1950). The global electric circuit concept is illustrated in Fig. 1.4. Negative charge is brought to Earth mainly by lightning discharges (most of which transport negative charge to ground) and by corona current under thunderclouds. The net precipitation current is thought to transport positive charge to ground, and its magnitude is comparable to the lightning current (Wahlin 1986). Positive charge is presumed to leak from cloud tops to the electrosphere. If we divide the potential of the electrosphere, 300 kV, by the fair-weather current, 1 kA, the effective load resistance is 300 Ω.

The diurnal variation of the fair-weather field as a function of universal time over the oceans, the so-called Carnegie curve, named after the research vessel *Carnegie* on which the measurements were made (Torreson *et al.* 1946), appears to follow the diurnal variation of the total worldwide thunderstorm area (Whipple and Scrase 1936). Both characteristics exhibit maximum values near 1900 UT and minimum values near 0400 UT. However, the annual variation of the fair-weather electric field is not in phase with the annual variation of thunderstorm activity throughout the world (Imyanitov and Chubarina 1967). Füllekrug *et al.* (1999) found that the hourly contribution of global cloud-to-ground lightning activity (as represented by magnetic field measurements in the frequency range 10–135 Hz) to the fair-weather electric field in the Antarctic during December 1992 was about 40 ± 10 percent, and that the contribution to hourly departures from the mean diurnal variation of the electric field was about 25 ± 10 percent. Holzworth *et al.* (1984) showed that significant time variations could occur in the global fair-weather current on time scales of 10 minutes to several hours.

According to the classical picture of atmospheric electricity, the layer of the atmosphere extending from about 15 to 200 km and including the stratosphere, mesosphere, and the lower portion of the thermosphere (Chapter 15 and Fig. 14.1), should be "passive". However, some rocket measurements indicate the existence of strong electric fields (in the volts per meter range, which is orders of magnitude higher than expected in the mesosphere, at altitudes of 50–85 km) of unknown origin (Bragin *et al.* 1974; Tyutin 1976; Hale and Croskey 1979; Hale *et al.* 1981; Maynard *et al.* 1981; Gonzalez *et al.* 1982). Interestingly, these abnormally strong electric fields are observed near the 60 to 65 km height region, where the "equalizing" layer (the electrosphere) is presumed to exist. Their origin remains a subject of controversy. Any plausible explanation of this phenomenon must involve either a local mesospheric field-generation mechanism or a dramatic local decrease in conductivity.

1.4.4. *Maxwell current density*

The Maxwell current density $\mathbf{J}_\mathrm{M}$ associated with a thunderstorm is defined as the sum of four terms (e.g., Krider and Musser 1982):

$$\mathbf{J}_\mathrm{M} = \mathbf{J}_\mathrm{E} + \mathbf{J}_\mathrm{C} + \mathbf{J}_\mathrm{L} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \tag{1.2}$$

where $\mathbf{J}_\mathrm{E}$ is the field-dependent current density, which may include both linear (ohmic, for which $\mathbf{J} = \sigma\mathbf{E}$ where σ is the electrical conductivity) components and nonlinear (corona) components, $\mathbf{J}_\mathrm{C}$ is the convection current density, which may include a contribution from precipitation, $\mathbf{J}_\mathrm{L}$ is the lightning current density, and the last term is the displacement current density. In planar geometry, the current density $\mathbf{J}_\mathrm{M}$ is the same at any height in the atmosphere, as required by the current continuity equation (e.g., Sadiku 1994). Krider and Musser (1982) suggested that the thundercloud, the postulated current source in the global electric circuit, can be viewed as producing a quasi-static Maxwell current density even in the presence of lightning. In this view, the thunderstorm generator in the global electric circuit can, in principle, be monitored through its Maxwell current density.

The total Maxwell current density under thunderstorms has been measured by Krider and Blakeslee (1985), Deaver and Krider (1991), and Blakeslee and Krider (1992). Krider and Blakeslee (1985) found that the amplitude of $\mathbf{J}_\mathrm{M}$ is of the order of 10 nA m^{-2} under active storms, while Deaver and Krider (1991) reported amplitudes of the order of 1 nA m^{-2} or less (in the absence of precipitation) under small Florida storms. Above thunderstorms, the convection and lightning terms, $\mathbf{J}_\mathrm{C}$ and $\mathbf{J}_\mathrm{L}$, in Eq. 1.2 are assumed to be negligible, and the Maxwell current density is expressed as the sum of only two terms:

$$\mathbf{J}_\mathrm{M} = \mathbf{J}_\mathrm{E} + \varepsilon_0(\partial \mathbf{E}/\partial t) \tag{1.3}$$

The Maxwell current density at altitudes of 16–20 km was measured by Blakeslee *et al.* (1989). They found that $\mathbf{J}_\mathrm{E}$ typically accounted for more than half $\mathbf{J}_\mathrm{M}$, while at the ground $\mathbf{J}_\mathrm{M}$ is generally dominated by the displacement current density during active storm periods, as long as the fields are below the corona threshold of a few kV m^{-1} and there is no precipitation current. It is thought that, under some conditions, the Maxwell current density may be coupled directly to the meteorological structure of the storm and/or the storm dynamics (Krider and Roble 1986, pp. 5–6). However, the lack of simultaneous Maxwell current measurements both on the ground and aloft has prevented the details of this relationship from being determined.

1.4.5. Modeling of the global circuit

Models that can be used to calculate the electric field or the potential distribution around the thundercloud and the current that flows from a thundercloud into the global electric circuit have been developed by Holzer and Saxon (1952), Kasemir (1959), Illingworth (1972a), Dejnakarintra and Park (1974), Hays and Roble (1979), Tzur and Roble (1985b), Nisbet (1983, 1985a, b), Browning *et al.* (1987), Hager *et al.* (1989a, b), Driscoll *et al.* (1992), Stansbery *et al.* (1993), Hager (1998), and Plotkin (1999). Both analytical and numerical models have been developed. Some models (e.g., Holzer and Saxon 1952; Hays and Roble 1979; Tzur and Roble 1985b) have been based on a quasi-static approximation, while others (e.g., Illingworth 1972a; Dejnakarintra and Park 1974; Driscoll *et al.* 1992) have been designed to describe a time-varying problem that includes the effects of lightning. Nisbet (1983) modeled the atmosphere by a network of resistors, capacitors, and switches, where the current through these circuit elements represents conduction, displacement, and lightning currents, respectively. Sometimes corona currents have been taken into account (e.g., Tzur and Roble 1985b). Convection currents, including those due to precipitation, have usually been neglected. These models provide a convenient means of examining, through numerical experiments, the various processes operating in the global circuit. Normally, heights up to 100–150 km are considered, and thunderclouds are represented by two vertically displaced point charges of opposite polarity maintained by a current source. The upward-directed current from thunderclouds is assumed to spread out in the ionosphere of the storm hemisphere and, in some models (e.g., Hays and Roble 1979; Tzur and Roble 1985b; Browning *et al.* 1987; Stansbery *et al.* 1993) to flow along the Earth's magnetic field lines into the conjugate hemisphere. According to Stansbery *et al.* (1993), approximately half the current that reaches the ionosphere flows into the conjugate hemisphere and the other half flows to Earth in the fair-weather regions of the storm hemisphere. Pasko *et al.* (1998d) developed an electrostatic coupling model to examine the effects of the relatively steady electric fields of thunderclouds on the lower ionosphere.

1.4.6. Alternative views of the global circuit

Wilson's suggestion that thunderstorms are the main driving element in the atmospheric global circuit has been questioned by, among others, Dolezalek (1972), Williams and Heckman (1993), Kasemir (1994, 1996), and Kundt and Thuma (1999). Dolezalek (1988) suggested that the net charge on the Earth may be zero or near zero, rather than the 5×10^5 C postulated in the classical model of atmospheric electricity. Kasemir (1994, 1996) proposed an alternative concept of the global circuit in which the only equipotential layer is the Earth. He assumed that the very high negative potential of the Earth with respect to infinity drives the fair-weather current; lightning discharges and corona at the ground are claimed to be "local affairs" that do not contribute to the global circuit. In Kasemir's view, there are two types of generator in the global circuit, convection, acting in both stormy and fair-weather regions, and precipitation, both generators being driven by non-electrical forces. Kundt and Thuma (1999), who estimated a relatively low cloud top voltage, 1 MV relative to the Earth, asserted that thunderstorms are not important in the global electric circuit. However, Marshall and Stolzenburg (2001), from 13 balloon soundings of electric field through both convective regions and stratiform clouds, reported cloud top voltages ranging from −23 to +79 MV, with an average of +25 MV. The average cloud top voltage for the nine cases with positive values was +41 MV. Marshall and Stolzenburg (2001) considered these voltage values as supporting Wilson's hypothesis that thunderstorms drive the global electric circuit. Further, they estimated an average cloud top voltage of +32 MV for electrified stratiform clouds, this finding suggesting that stratiform clouds may make a substantial contribution to the global electric circuit.

1.5. Regarding the utilization of lightning energy

It appears to be impractical to utilize lightning energy. Each cloud-to-ground lightning flash involves an energy of roughly 10^9 to 10^{10} J (Section 4.2). For comparison, the energy required to operate five 100 W light bulbs continuously for one month is

$$5 \times 100\ \text{W} \times 3600\ \text{s} \times 24\ \text{h} \times 30\ \text{days} = 1.3 \times 10^9\ \text{J}$$

or about 360 kilowatt hours (1 kWh = 3.6×10^6 J), which is comparable to the total energy of one lightning flash. Even if it were possible to capture all the energy of a flash (this is not possible since the bulk of this energy is not delivered to the strike point but, rather, is lost to heating the air and producing thunder, light, and radio waves), one would need to attract 12 flashes to the energy storage facility in order to operate the five light bulbs for one year. The probability of a lightning strike to a given point on ground is very low. For example, a 1 m^2 area in Florida is struck by lightning on average, once in 10^5 years. A grounded structure protruding above Earth's surface is more likely to be struck by lightning. A 60 m tower located in Florida is expected to be struck by lightning at a rate roughly between once every other year and once every year (subsection 2.9.2). Thus, one needs 12 to 24 such towers covering a large area of 1 km^2 or so to operate the five 100 W light bulbs, which is obviously impractical. Most of the United States experiences lightning activity that is a factor 2 to 3 lower than in Florida. As a result, the number of lightning-capturing towers needed to operate the five 100 W bulbs in areas of moderate lightning activity would be 24 to 72.

Thus the three main problems with the utilization of lightning energy (leaving aside the issue of energy storage devices) can be formulated as follows.

(i) The power associated with a lightning flash is very high, but it is released in pulses of very short duration (of the order of 10^{-4}–10^{-5} s). As a result, the lightning energy, the integral of the power over the short period of time, is moderate, comparable to the monthly energy consumption, 360 kilowatt hours, of five 100 W light bulbs.

(ii) Not all the lightning energy in a flash is delivered to the strike point. Using a typical value of energy per unit resistance (action integral) of 10^5 A s^2 (Table 4.4) determined from measurements of the current at the negative lightning channel base and an assumed range of resistances at the strike point of 10 to 100 Ω, we estimate the range of the lightning energy delivered to the strike point to be from 10^6 to 10^7 J, which is only 10^{-2} to 10^{-4} of the total energy.

(iii) The capturing of a sufficiently large number of lightning strikes would require the use of a large number of tall towers, which is impractical.

1.6. Summary

In ancient cultures lightning was viewed both as a weapon of the gods, used by them to punish humans, and as a message from heaven used to influence state affairs. Systematic studies of thunderstorm electricity began in 1752 when an experiment proposed by B. Franklin was conducted in France. The results of that experiment and similar following experiments in other countries showed conclusively that thunderclouds were electrified. In the same year that the first thunderstorm electricity experiment was carried out, fair-weather electricity was discovered. According to the "classical" view of atmospheric electricity, the potential of the electrosphere, located at an altitude of 60 km or so, with respect to the Earth's surface is about 300 kV. This potential difference drives a total conduction current of the order of 1 kA in all fair-weather regions on the globe. Thus, the global fair-weather load resistance is about 300 Ω. Thunderstorms are considered as the sources in the global electric circuit. Since there has been no experiment to confirm conclusively this classical picture of atmospheric electricity, it remains a subject of debate. The salient properties of downward negative lightning discharges, the most common type of lightning, are summarized in Table 1.1. It appears to be impractical to utilize lightning energy.

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