Chapter 6
Charge Generation in Thunderclouds and Different Forms of Lightning Flashes

6.1 Charge Generation in Thunderclouds

Many theories have been advanced to explain the generation of electrical charge in thunderclouds [1]. However, one theory has withstood the test of time, and the current consensus is that the mechanism proposed by this theory is the dominant one for charge separation in thunderclouds. This mechanism is based on the collision of graupel and ice crystals in the presence of super-cooled water drops in a cloud.

6.1.1 Ice–Graupel Collision Mechanism

The theory is based on experiments conducted in Japan by Takahashi [2] and in the UK by Jayaratne et al. [3]. In these experiments, a graupel particle, simulated by a riming target, was moved at a certain speed through a cloud of ice crystals and supersaturated water droplets. The charge generated during the collision of ice crystals and graupel particles was measured. Observations revealed that the magnitude and polarity of the charging process depend on the water content of the cloud and the ambient temperature. The results obtained by Takahashi [2] and Jayaratne et al. [3] are shown in Fig. 6.1a, b, respectively. According to Fig. 6.1a, during collisions graupel particles charge positively at higher temperatures, at both low and high water content, and they charge negatively at low temperatures and at intermediate water content. The results obtained by Jayaratne et al. [3] also show that there are two charging regimes, but the temperature and the water content where charges of a particular polarity are achieved are different (Fig. 6.1b). The difference could be due to the different experimental conditions used by the two research groups. Recent experimental data seem to suggest that the experimental conditions used by Takahashi [2] resemble more closely the physical conditions present in clouds [4].

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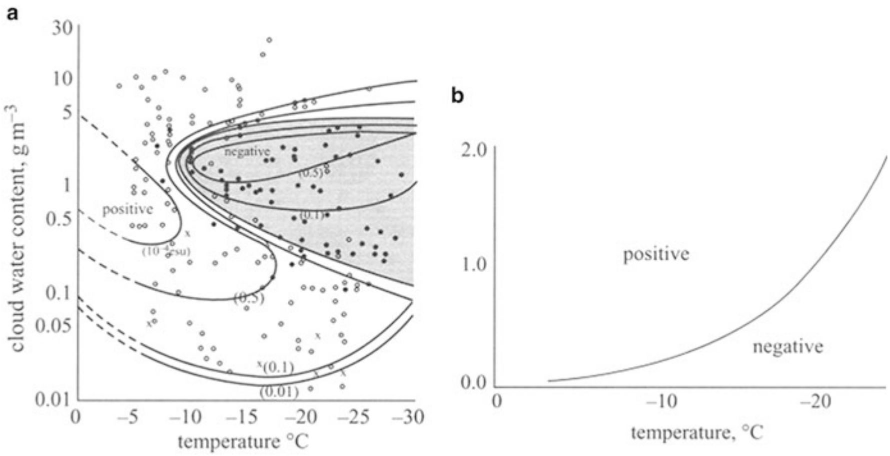

Fig. 6.1 (**a**) The polarity of the charged acquired by a graupel particle during collision with ice crystals as a function of water content and ambient temperature as determined by an experiment conducted by Takahashi [2] in Japan. (**b**) Results of a similar experiment conducted in the UK by Jayaratne et al. [3]. Note that whether a graupel particle achieves a charge of negative or positive polarity during collision with an ice crystal is determined by the temperature and the cloud water content

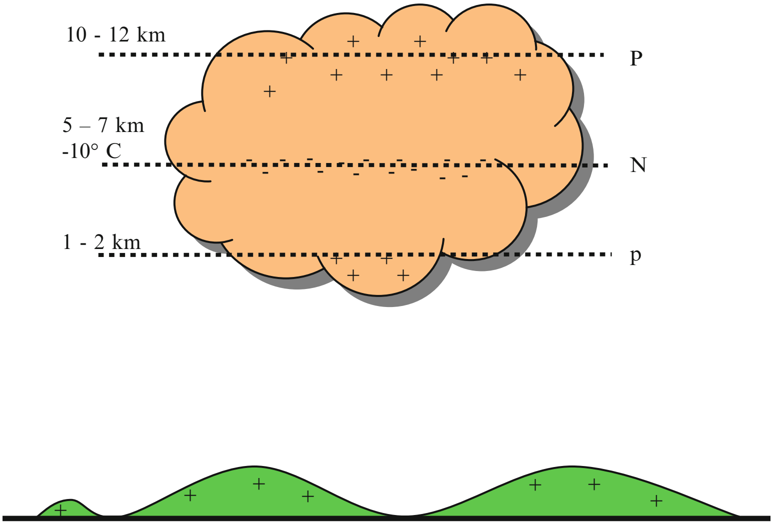

Fig. 6.2 An idealized tripole charge structure of a thundercloud. It contains three charged regions. The main positive charge center is located in the upper part of the cloud (P). The main negative charge center (N) is located below the main positive charge center and it is located in the region of the cloud where the temperature is somewhere between −15 °C to −10 °C. Below the main negative charge center is a positively charged region (*p*). In reality there could also be a screening layer of negative charge on the upper surface of the cloud formed by the attraction of negative charge to the upper surface of the cloud by the electric field produced by the positive charge (Figure created by author)

Consider a cloud water content of approximately 1 g/m^3, which is typical of most clouds. Then, according to Fig. 6.1a, at temperatures below approximately −10 °C, graupel particles receive a negative charge and at higher temperatures a positive charge during collisions. As we will show subsequently, this fact seems to explain the main characteristics of the location of charge centers in thunderclouds.

The exact mechanism through which a charge transfer takes place during graupel–ice collisions is not known at present. One theory, proposed by Baker et al. [5], is based on the temporal growth of the colliding particles. Both graupel particles and ice crystals can grow by accretion of water vapor and because of the riming of the particles by supercooled water droplets that condense on the colliding particles. According to the theory, during the collision of graupel particles and ice crystals, more rapidly growing particles charge positively. This is explained by the following facts. A growing particle transfers negative ions to the surface of the particle. At the ice surface (of both graupel particles and ice crystals) is a liquid layer that is in equilibrium with water vapor, and these negative ions migrate into the liquid layer. The thickness of the water layer increases with increasing surface temperature. As the particle grows by riming and accretion, the latent heat released by the water vapor and supercooled droplets increases the temperature of the surface. As a consequence, the growing particle maintains a thicker water layer on the surface. During collision water is transferred from the thick layer to the thinner one. Since the water contains negative ions, the negative charge is also transferred together with the water. This causes the growing particle to charge positively and the slower growing particle to charge negatively. The growth rate of the particles depends on the liquid water content, and the temperature and, hence, polarity and magnitude of the charge transfer depend on these parameters. As was mentioned earlier, this mechanism can explain some of the field observations on the location of charge centers in clouds. This point is discussed further in the next section.

6.1.2 Consequences of Ice–Graupel Collision Charging Mechanism

6.1.2.1 Tripolar Structure of Cloud Charge

Experimental observations show that a typical cloud contains two main charge centers, one positive and the other negative. An idealized charge structure of a thundercloud is shown in Fig. 6.2. The positive charge center is located above the negative one, and the negative one is very shallow, approximately 1 km in thickness, and located in a region of −15 to −10 °C isotherm. Below the negative charge center is a small positive charge pocket. The ice–graupel collision mechanism can explain this observation satisfactorily. Consider a typical cloud with a liquid water content of approximately 1 g/m^3. As the graupel particles fall from greater heights through the clouds, they collide with ice crystals that are being carried upward in

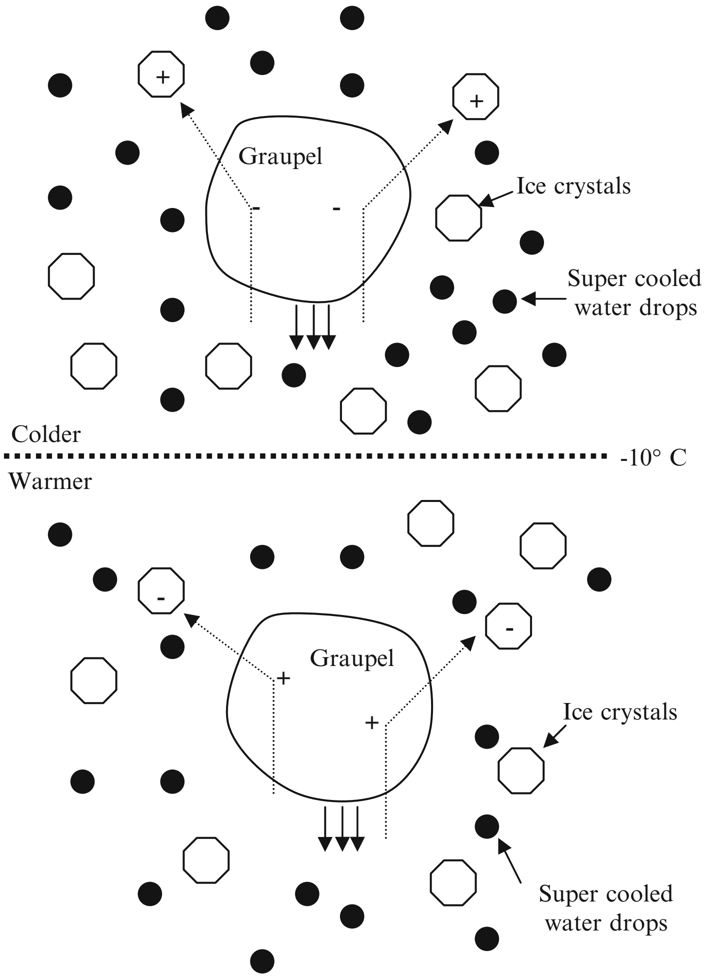

Fig. 6.3 At a temperature below approximately −15 °C to –10 °C graupel particles colliding with ice crystals achieve a negative charge (*the upper diagram*), whereas at temperatures above approximately −15 to –10 °C the graupel particles receive a positive charge (*the lower diagram*) (Figure created by author based on information available in literature)

updrafts. If the temperature is below approximately −15 to −10 °C, the graupel particles charge negatively and the ice crystals positively (upper part of Fig. 6.3). The light positively charged ice crystals travel upward along the updraft, leaving the positive charge at a higher location in comparison with the negatively charged falling graupel particles. As the graupel particles fall further, the temperature increases and the graupel particles start to charge positively (lower part of Fig. 6.3). Thus, there is a region below the height of the isotherms −15 to −10 °C where graupel particles are positively charged. This is the basis of the positive charge pocket located below the negative charge center. For example, the

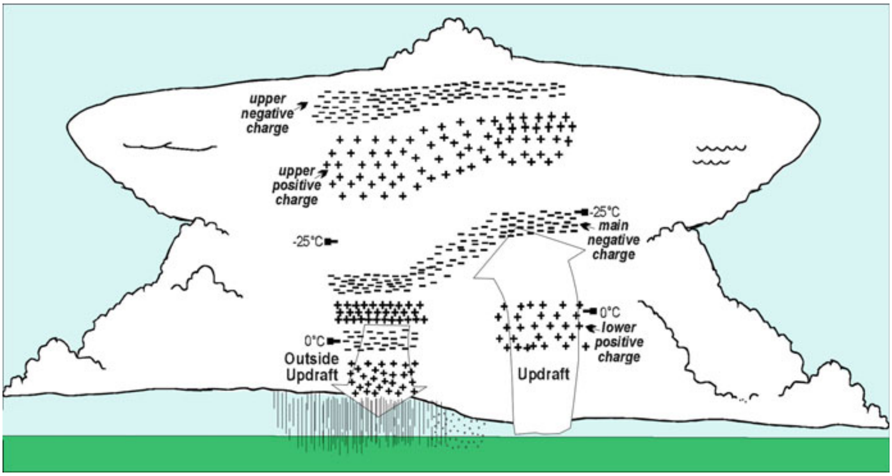

Fig. 6.4 A more detailed charge structure of a thundercloud created using in situ electric field measurements and other meteorological data. The upper negative charge region is probably generated by the flow of negative charges toward the top of the cloud under the influence of the electric field generated by the positive charges (The figure is from Stolzenburg et al. [6]). Note that the detailed charge structure of the cloud is significantly different from the tripolar structure assumed in various analyses (Adapted from Stolzenburg et al. [6])

ice crystals at higher levels of a cloud are positively charged, whereas falling graupel particles at temperatures below approximately -15 to -10 °C are negatively charged, and graupel particles that fell further in the cloud are positively charged. This creates the observed tripolar structure of the cloud. It also explains why the main negative charge center is located in the region of the -15 and -10 °C isotherm. Of course, in reality the charge structure is much more complicated than this simple picture suggests [6]. The charge structure of a thunderstorm created using electric field data is shown in Fig. 6.4. Note that even though the basic structure as explained previously is still there, the details of the charge distribution is more complicated. This can be expected because of the large variation in the cloud parameters in different regions of the cloud.

6.1.2.2 Charged Structure of Clouds in Different Geographical Regions

The heights at which different temperatures occur in the atmosphere vary in different geographical regions, and in the same geographical region it may change from one season to another. Since the charging mechanism is controlled by the ambient temperature, the location of charge centers in clouds also changes in different geographical regions. Figure 6.5 shows the location of charge centers in three regions, namely, Florida, New Mexico, and Japan (in winter) [7]. Note that the negative charge center is located in the vicinity of -15 to -10 °C isotherms in all clouds, but their heights are different because of the difference in the temperature profile.

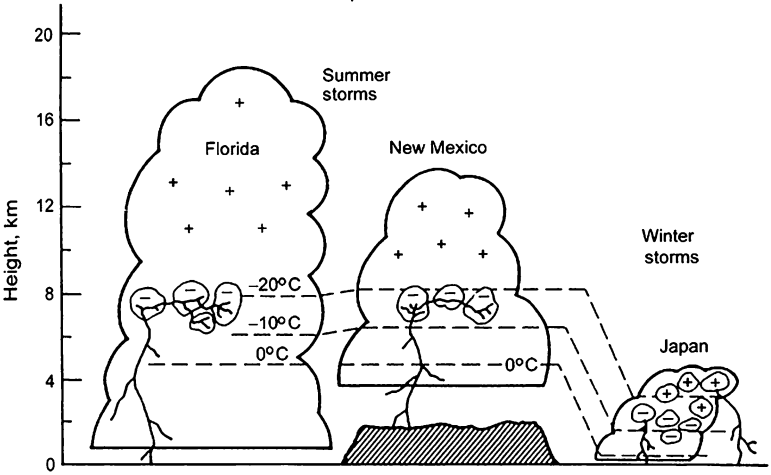

Fig. 6.5 The location of charge centers in thunderclouds is controlled by the ambient temperature, among other parameters. Since the height of a given temperature isotherm depends on the geographical region under consideration, the height of the charge centers in thunderclouds differ in different geographical regions. Figure shows the location of charge centers in summer storms in Florida and in New Mexico and in winter thunderstorms in Japan. Note that in all three regions the negative charge center is located in the vicinity of −15 and −10 °C isotherms (Adapted from Krehbiel [7])

6.1.2.3 Different Types of Clouds

What we saw earlier were typical clouds where the water content is approximately 1 g/m^3. However, according to experimental data, a variety of cloud charge structures may occur in nature depending on the liquid water content and the temperature in the cloud. The wind shear could also move charge centers with respect to each other. Four types of cloud that can arise due to this variability are shown in Fig. 6.6. The cloud in Fig. 6.6a is the most typical where a negative charge is located below a positive charge. These clouds produce predominantly lightning flashes that bring a negative charge to Earth. However, if there is wind shear, the positive charge center could be sheared away from the negative charge center, making it easier to produce lightning flashes that transport a positive charge to ground (Fig. 6.6b). If the meteorological conditions are such that the depletion of water content by a riming process and rain formation is suppressed, the charging process may take place under conditions of high liquid water content, and in this case it is possible to obtain a cloud with an inverted dipole that generates predominantly positive charges (Fig. 6.6c). Such clouds have been identified in Colorado in experiments conducted within STEPS (Severe Thunderstorm Electrification and Precipitation Study) [8]. When the meteorological conditions are such that less cloud water content is associated with laterally extensive weak updrafts, it is also possible to obtain clouds with an inverted charge dipole. Such meteorological conditions obtain in the stratiform precipitation regions of large mesoscale convective systems (Fig. 6.6d). Since the positive charge center in these clouds is closer to ground, these clouds generate predominantly positive ground flashes.

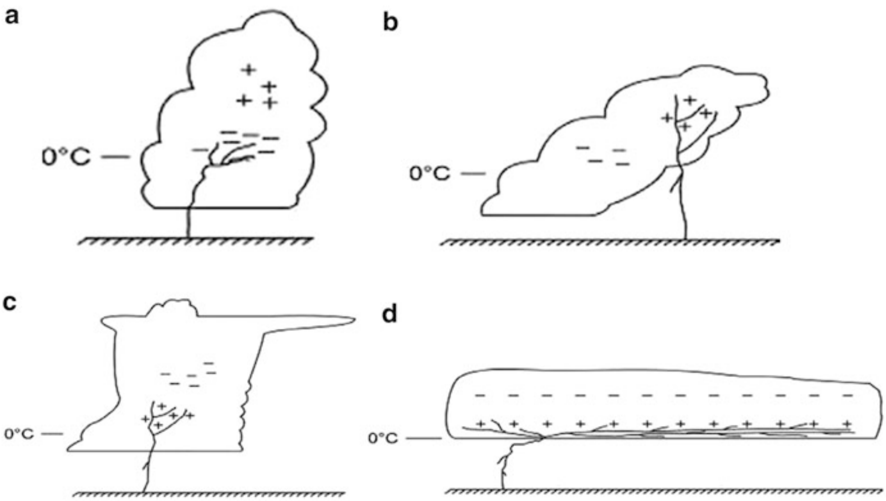

Fig. 6.6 Clouds with different charge structures caused by variation in water content, temperature, and wind shear. See text for explanation. Note that in (**c**) and (**d**) the polarity of the charge centers are inverted. This makes it easier for these clouds to generate positive ground flashes (Adapted from Williams and Yair [8])

6.2 Different Types of Lightning Flash

The basic structure of a lightning flash may be different depending on the two charged regions between which the lightning discharge takes place and the polarity of the charge transported from one region to another. The most common type of lightning flash is the one taking place between the two main charge centers inside a cloud, as depicted in Fig. 6.7a. These lightning flashes are called *intracloud lightning flashes*. Sometimes a lightning flash may take place between opposite charge centers of neighboring clouds. In such cases, they are called *intercloud lightning flashes*. Lightning flashes taking place between the negative charge center and ground (Fig. 6.7b) are called *negative ground lightning flashes*. The majority of lightning flashes that strike ground (90 %) take place between the negative charge center and the ground. A small proportion (10 %) of lightning flashes that strike the ground take place between the positive charge center and the ground (Fig. 6.7c). They are called *positive ground flashes*. It has also been observed that some lightning flashes emerge from a cloud but, instead of reaching the ground, terminate in a region near the base of the cloud (Fig. 6.7d). These types of lightning flash are called *air discharges*. Such lightning flashes might initiate in a manner similar to ground discharges but for some unknown reason could not complete the path to ground. Lightning flashes that strike the ground and those described previously originated inside a cloud. That is, they started in a cloud and ended up on ground. As we will see subsequently, under special circumstances, lightning flashes can also be triggered by tall structures at ground; these have their origin at ground level and

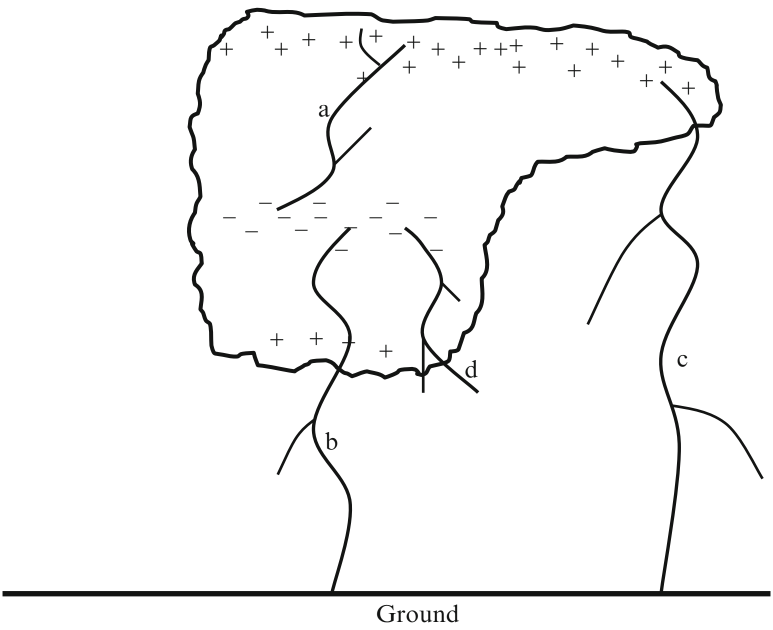

Fig. 6.7 Different types of lightning flash. (**a**) Cloud flash. (**b**) Negative ground flash. (**c**) Positive ground flash. (**d**) Air discharge. The wind shear can shift the upper part of the cloud and, hence, the positive charge center, making it possible for the positive leaders to travel to ground and giving rise to positive ground flashes without the downward moving positive leader being intercepted by the negative charge center and leading to a cloud flash (Figure created by author)

are called *upward initiated lightning flashes*. Depending on whether the upward initiated lightning flash transports negative or positive charge to ground they are called *negative* or *positive upward flashes*, respectively. Sometimes a lightning flash may start as a negative or positive ground flash but at a later stage make a connection to the opposite charge center and transport charge of opposite polarity to ground. These are called *bipolar lightning flashes*.

6.3 Global Distribution of Lightning Flashes

The global distribution of lightning flashes can be determined with satellites that record lightning flashes by using the light generated by them [9]. Since lightning channels are obscured by clouds, observations using satellites cannot distinguish ground flashes from cloud flashes. The latest distribution of lightning flashes obtained from satellite data is shown in Fig. 6.8. According to these observations, approximately 40–100 lightning flashes take place each second around the globe. Observe that most of the lightning flashes take place over land regions rather than over the sea. The reason for this is the less convective intensity in oceanic

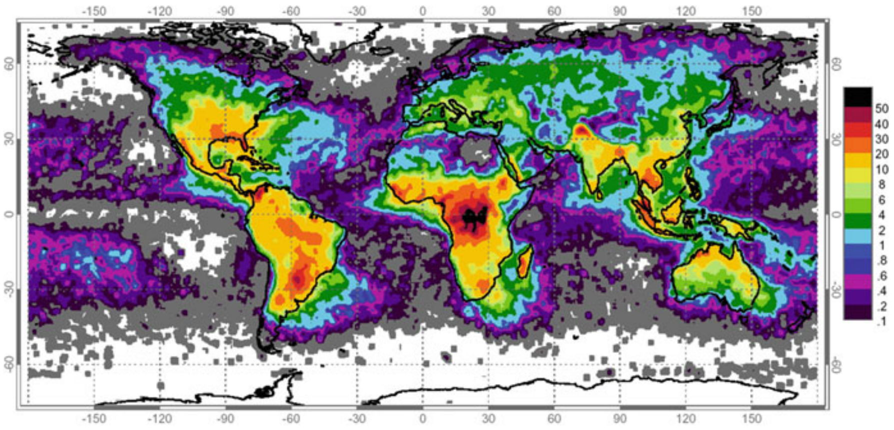

Fig. 6.8 Global distribution of lightning, April 1995–February 2003, from combined observation of NASA OTD (April 1995–March 2000) and LIS (January 1998–February 2003) instruments. The numbers on the color code refer to the annual number of lightning flashes per square kilometer [Courtesy NASA TRMM team]

thunderstorms compared to continental ones. For example, the updraft speeds of oceanic thunderstorms may reach a maximum of approximately 10 m/s, while in continental thunderstorms updraft speed may reach 50 m/s or greater. Updraft speed is closely related to the charging process of thunderstorms, and higher updraft speeds lead to vigorous charging. For this reason, the lightning activity over oceans is an order of magnitude lower than that over land. Furthermore, over land regions, most lightning activity is confined to the tropics.

6.4 Density of Lightning Flashes Striking Earth

In meteorological studies, it is the total number of lightning flashes taking place around the globe that is of interest. However, lightning protection engineers are interested in the number of lightning flashes striking in a given region over a given time interval. Usually, this number is given as the number of lightning flashes striking 1 km^2/year. This number can be obtained by directly locating the lightning flashes that strike in a given region [10]. However, such advanced lightning location systems are not available in many regions of the globe, and scientists have set about to obtain this parameter using what are known as *thunderstorm days*. A thunderstorm day is a day where thunder is heard. Records of thunderstorm days are available from many regions because the parameter is measured routinely by meteorological observations. Figure 6.9 shows the global distribution of annual thunderstorm days. Note again that the number of thunderstorm days is higher in tropical regions and can reach values as high as 150–200 days in certain regions in Asia, Africa and South America. By studying the number of lightning flashes

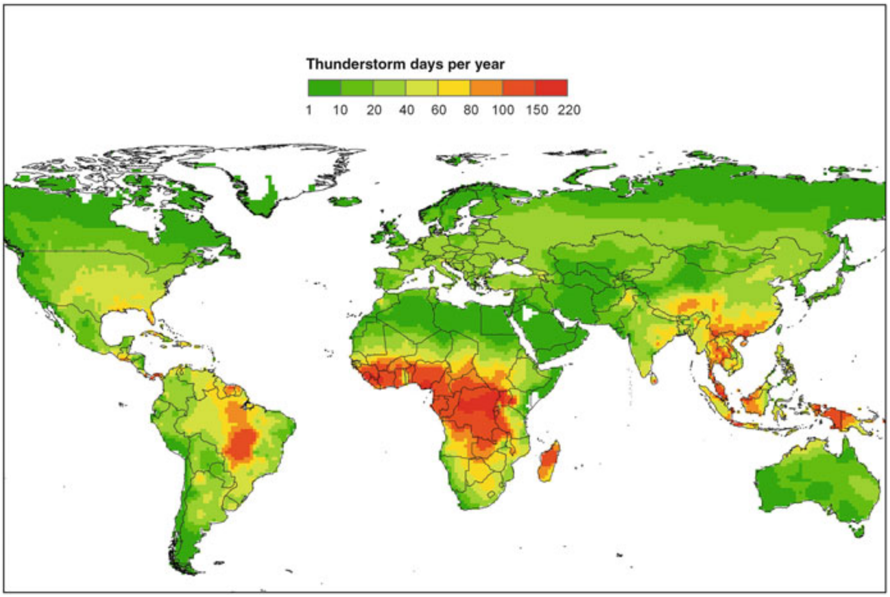

Fig. 6.9 Global distribution of thunderstorm days. (Adapted from [12])

striking in a given region using lightning location systems, scientists have come up with an equation to relate ground flash density to thunderstorm days. This relationship is not a universal one, and several relationships have been proposed for different regions. One equation frequently used by scientists is [11]

$$N_g = 0.04T_d^{1.25}, \tag{6.1}$$

where N_g is the ground flash density in flashes/km^2/year and T_d is the number of thunderstorm days. For example, according to the preceding equation, a region having 100 thunderstorm days/year is expected to receive approximately 13 lightning flashes in each square kilometer per year. Another parameter that is of interest is the annual number of thunderstorm hours. This is the number of hours of thunder activity in a given region in a year. This parameter, T_h, is related to the ground flash density by [13]

$$N_g = 0.054T_h^{1.1}. \tag{6.2}$$

As we will see in subsequent chapters, the ground flash density is one of the most important parameters in lightning protection.

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