Lightning

Synonyms

Cloud flash; Ground flash

Definition

- Lightning or lightning discharge. A series of transient and multiple electrical breakdown pulses producing high current channels (Uman 1987).
- Lightning flash. A luminous manifestation accompanying a sudden electrical discharge which takes place from or inside a cloud or, less often, from high structures on the ground or from mountains (WMO 2011).

Introduction

A lightning flash is a noncontinuous multi-scale physical process that ranges from the initial breakdown of air to the actual discharge propagation in discrete steps that can occur from cloud to ground (CG) or inside the clouds, i.e., intracloud (IC). In the case of CG lightning, the lightning channel formation is led by stepped leaders (that creates a conducting path between charge centers) and then followed by one or multiple return strokes that traverse the channel moving electric charges and neutralizing the leaders (Rakov and Uman 2003). These series of return strokes are the lightning flash, and each stroke is guided by the dart leaders that propagate downward on the track of a preceding return stroke. CG flashes are also classified by the polarity of lowered charge: negative and positive. Negative flashes are more common and exhibit several return strokes, while positive flashes have a single or very few return strokes, but higher current than the negative ones. These processes occur too rapidly for the human eye to distinguish, and the flash appears as a single channel lasting for less than a second. Lightning detection networks typically look for the electric field changes associated with such processes. In the case of IC lightning, recoil streamers propagate within the track of positive branches of a bi-leader carrying strong negative charges. The lightning flash is terminated when the electric field is reduced to the point where it cannot sustain the discharge’s propagation anymore.

The electromagnetic spectrum of lightning

The rapid release of electric energy inside the lightning channel generates a shock wave and electromagnetic radiation in a broad spectrum, qv Radiation, Electromagnetic. The shock wave rapidly decays into an acoustic wave we know as thunder. The electromagnetic radiation ranges from radio frequencies through visible to x-rays and gamma rays, composing the basis for ground-based lightning location systems (LLS) and remote sensing from satellites.

Each lightning component (stepped leaders, return strokes, recoil streamers) emits electromagnetic energy proportional to the charge carried and its derivative in time. Negative stepped leaders are associated with strong negative currents in very short pulses (1 ms), and are detectable in very high frequencies (VHF, 1–200 MHz), as well as the dart leaders and recoil streamers, but with a relatively lower electrical current (MacGorman and Rust 1998). The return strokes of a CG are high-energy discharges typically of the magnitude 10–100 kA in long pulses, and radiate from the very low to high frequency range (1 kHz to 10 MHz). Positive CG return strokes usually have continuous high current (>100 kA) and therefore are easily detected by VLF systems.

Radio emissions from lightning occur in the form of short pulses by accelerated charges during the fast changing current steps, while the optical emissions occur from ionized and dissociated gases by thermal radiation of the lightning channel (Goodman et al. 1988). The heating in the channel reaches temperatures above 20,000 K resulting in optical emissions primarily in discrete atomic lines with some continuum at shorter wavelengths. Several measurements of lightning emission in the cloud top have shown strongest emissions at the neutral oxygen (OI(l)) and neutral nitrogen (NI(l)) lines, i.e., 777.4 and 868.3 nm in the near infrared, respectively (Goodman et al. 1988).

The radio electromagnetic waves of the lightning processes described above travel through the atmosphere and then are likely to be dissipated, reflected, scattered, refracted, and absorbed. The main effect is the dissipation, reducing the amplitude of the signal inversely proportional to the square of the distance. Ionospheric reflection, where the energy from waves with frequency lower than 5 MHz is trapped in the atmospheric waveguide formed by the ionosphere and the ground, permits long-range propagation of waves from high-energy return strokes. In the optical spectrum, the scattered energy by the cloud particles is observed from satellites as a diffuse light source at cloud top (Christian et al. 1989).

Ground-based lightning location systems

Several instruments can be used to locate lightning flashes and more detail can be found at MacGorman and Rust (1998) and Betz et al. (2009). The main technique consists of a network of sensors that detect IC and/or CG lightning by recording the electromagnetic radiation from VLF to VHF continuously with time. The radiation detected by each sensor is then compared to other sensors in the network using two main location methods: the time-of-arrival and interferometer techniques. In the time-of-arrival method (TOA), time difference of lightning waveforms from several stations is computed and the location of lightning occurrence is given by the intersection of the hyperbolas for equal time differences. The interferometer method consists of determining the directions of the lightning waveform (azimuth and elevation) by analyzing the phase difference of an incident wave at several stations, and the intersection of these directions gives the location of the lightning source.

Today's operational lightning detection networks usually consist of different sensor types that use one or more location method for redundancy. These networks can be local, regional, or global depending on their operation baseline (distance between the sensors), and their detection efficiency and location accuracy are determined by the density of sensors and radio frequency used (Betz et al. 2009). Table 1 summarizes some of these more widely used lightning networks. The largest regional network is the US National Lightning Detection Network (NLDN) created in 1998, composed by 114 sensors operating in LF that locates mainly CG lightning in North America. Similar regional networks are found in Australia, Brazil, Canada, and Europe. Long-range networks operate in VLF and have been deployed worldwide in an attempt to locate lightning over remote areas like the oceans and the tropics. These networks operate with a sensor baseline of thousands of kilometers, which limits the detection efficiency to the stronger amplitude lightning signals (Cramer and Cummins 1999).

Table 1 Ground-based lightning location systems operating in the world

Network	Frequency used	Type of discharges detected	Coverage area	Website
NLDN (US National Lightning Detection Network)	LF	Mainly CG	United States of America	http://www.vaisala.com/
CLDN (Canadian Lightning Detection Network)	LF	Mainly CG	Canada	http://www.ec.gc.ca/foudre-lightning/default.asp?lang=En&n=D88E34E8-1
EUCLID (EUropean Cooperation for LIghtning Detection)	LF	Mainly CG	Europe	http://www.euclid.org
RINDAT (Rede Integrada Nacional de Detecção de Descargas Atmosféricas)	LF	Mainly CG	South-Southeast Brazil	http://www.rindat.com.br/

LINET (LIghtning location NETwork)	VLF, LF	Total lightning (IC + CG)	Europe	http://www.pa.op.dlr.de/linet/
LDAR (Lightning Detection and Ranging)	VHF	Total lightning (IC + CG)	Florida, USA	http://branch.nsstc.nasa.gov/PUBLIC/LDARII/
LMA (Lightning Mapping Array)	VHF	Total lightning (IC + CG)	USA-New Mexico, Oklahoma, Northern Alabama , Western Texas, Colorado, Atlanta, Washington DC, Spain	http://lightning.nmt.edu/nmt_lms/
ENTLN (EarthNetworks Total Lightning Networks)	ELF-HF	Total lightning (IC + CG)	Australia, Americas, Europe	http://www.earthnetworks.com/
		Mainly CG	Globe	
STARNET (Sferics Timing and Ranging NETwork)	VLF	Mainly CG	South America and East Africa	http://www.zeus.iag.usp.br/
WWLLN (World Wide Lightning Location Network)	VLF	Mainly CG	Globe	http://wwlln.net/
Vaisala GLD360 (Global Lightning Dataset 360)	VLF	Mainly CG	Globe	http://www.vaisala.com/
GLN (Global Lightning Network)	VLF	Mainly CG	Globe	http://www.uspln.com/gln.html
ATDnet (Met Office's Arrival Time Difference network)	VLF	Mainly CG	Globe	http://www.metoffice.gov.uk/

Total lightning (IC + CG lightning) is monitored using VHF and a combination of LF and VLF or VHF and LF. In the USA, total lightning is monitored by several VHF Lightning Mapping Array (LMA) research networks (Table 1) developed by New Mexico Tech (Rison et al. 1999). The individual LMA regional networks consist of ten or more stations extending ~80 km. The LMA measures the TOA of the magnetic peak signals at the different receiving stations to locate the source of impulsive VHF radio signals. Hundreds to thousands of sources per flash can be correlated in space and time, allowing a 3-D or 2-D lightning mapping of the channel over a regional domain of ~200 km.

Lightning detection from space

Several astronauts reported seeing lightning while looking down from space in the 1960s, describing flashes with hundreds of kilometers in extent and simultaneous flashes occurring between widely separated storms. Lightning was detected in early satellite imagery (Sparrow and Ney 1971), and in 1981, the space shuttle astronauts recorded lightning in a 16-mm movie camera (Goodman et al. 1993). Although it was not their primary objective, several instruments onboard of the U.S. Air Force DMSP (Defense Meteorological Satellite Program) satellites have also recorded lightning, providing the first global lightning distribution map as a bonus to the mission (Goodman et al. 1993).

The Optical Transient Detector (OTD) onboard of the Microlab-1 (later renamed as OrbView-1) satellite was the first instrument designed to measure lightning from space day and night with storm scale resolution. The OTD operated between 1995 and 2000 in a 70° inclination low Earth orbit (see Low Earth Orbit (LEO)) at an altitude of 740 km. From this altitude, the OTD observed an individual storm for about 3 min. The design concept was based on the earlier research on optical emissions of lightning at cloud top (Christian and Goodman 1987; Goodman et al. 1988). The OTD detected optical impulses with a 128 × 128 charge-coupled device (CCD) using a 1-nm narrow-band interference filter centered at 777.4 nm (Christian et al. 2003). Whereas the earlier satellite-based studies were limited to detecting visible lightning flashes during the darkness of night, the near-infrared wavelength combined with the use of spatial and temporal filtering used by OTD also allowed lightning detection during daylight. In 1997, the Lightning Imaging Sensor (LIS) onboard the Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al. 1998) was launched into a lower orbit inclination of 35° at an altitude of 350 km, later raised to 402 km in August 2001 to extend the mission lifetime. From this altitude, the LIS observed an individual storm for about 90 s.

The OTD was a flight qualified engineering model of the LIS, and thus, they share the same basic design heritage. In both OTD and LIS, the signal is read out from the focal plane into a real-time event processor for lightning event detection. The background scene is updated during each frame readout sequence and when a pixel's brightness compared to the prior background values exceeds a threshold, it is identified as a lightning event. The events are sent to the satellite ground station for geolocation processing in space and time, and an algorithm clusters the events into "flashes" (multiple CCD events grouped into time and space). The flash cannot be distinguished between CG and IC lightning, although in a statistical sense, the fraction of CG and IC flashes might be retrievable from a large sample of flashes (Koshak 2010).

OTD and LIS findings

The first global distribution of total lightning was derived from 5 years of OTD measurements by Christian et al. (2003), who found that the annual average global flash rate is 44 fl s^{-1}, with a maximum of 55 fl s^{-1} in the boreal summer and a minimum of 35 fl s^{-1} in the boreal winter. In Figure 1, we present the updated LIS/OTD climatology for 16 years of OTD (1995–2000) and LIS (1999–2010) combined observations of total lightning flash rate density (FRD, fl km^{-2} $year^{-1}$). The difference between land and ocean can be clearly observed, with lightning occurring more frequently over continental (>20 fl km^{-2} $year^{-1}$) regions having greater instability and stronger vertical motion than oceanic environments. However, some coastal regions presented moderate FRD (1–10 fl km^{-2} $year^{-1}$) associated with frequent synoptic scale extratropical cyclones and cold fronts (such as south-southeast coasts of Brazil, South Africa, Australia, and United States), and large-scale convergence zones (such as the South Atlantic, South Pacific, and the Intertropical Convergence Zones).

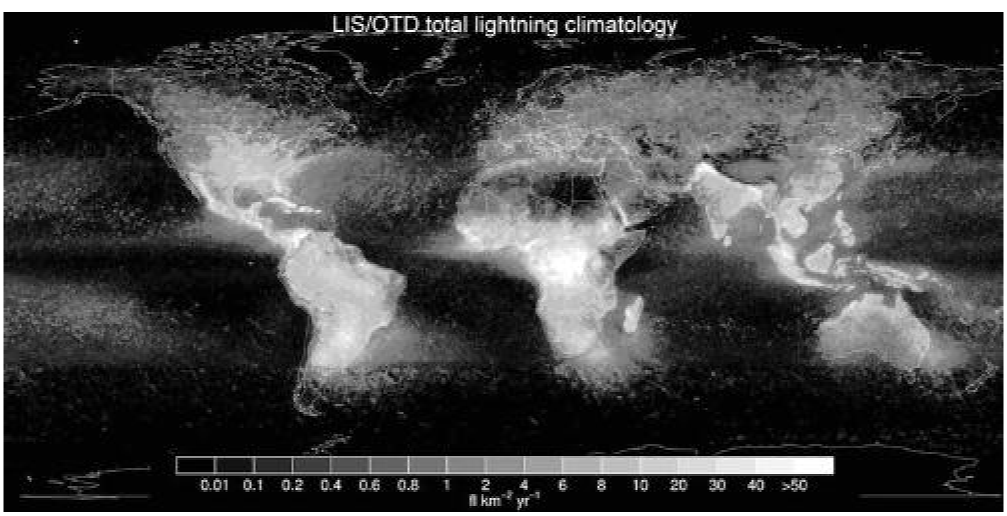

Figure 1 Total lightning climatology derived from OTD (1995–2000) and LIS (1998–2010)

High elevated and complex terrain regions over the tropics can be identified by high thunderstorm activity (>30 fl km^{-2}

year^{-1}) at the mountains foot (e.g., Andes, Himalayas, Sierra Madre Occidental, Cameroon Line, and Mitumba Mountains). Congo Basin is dramatically highlighted by its extensive area of large FRD (>50 fl km^{-2} year^{-1}), where the greatest annual number of individual thunderstorms is observed (Zipser et al. 2006). However, higher resolution (0.10°) LIS climatological maps highlighting topographical features and complex terrain indicate the Congo Basin has the second highest climatological FRD, with 232 fl km^{-2} year^{-1} (at the foothills of Mitumba Mountains), while the total lightning "hot spot" on Earth is observed over Lake Maracaibo with 250 fl km^{-2} year^{-1} (Albrecht et al. 2011). Lake Maracaibo thunderstorm activity is very localized, determined by nocturnal convergence of land-lake and mountain-valley breezes over a warm lake, building the perfect scenario for thunderstorm development of more than 300 days per year (Albrecht et al. 2011). Frequent lightning activity (30–50 fl km^{-2} year^{-1}) is also observed over Florida, Cuba, and Indonesia-Malaysia due to land-ocean sea breezes, and over the borders of Argentina, Paraguay, and Brazil where the greatest individual flash rates per mesoscale convective systems are observed (Cecil et al. 2005; Zipser et al. 2006).

In addition to mapping the lightning distribution, the instrument suite on the TRMM satellite allows more detailed characterization of the thunderstorms producing lightning. The TRMM radar and radiometer (see Microwave Radiometers and Radar, Meteorological) also show more intense storms over land (Cecil et al. 2005; Zipser et al. 2006). But for a given radar or radiometer signature, a storm over land is likely to produce more lightning than an otherwise similar storm over ocean (Liu et al. 2011). This suggests differences in the mixed phase microphysics and precipitation, hinted at by lightning but not resolved by the radar or radiometer uniquely by themselves.

More information on LIS and OTD can be found at http://thunder.msfc.nasa.gov/.

The future of lightning mapping from space

The next generation of NOAA Geostationary Operational Environmental Satellite (GOES-R) series and the EUMETSAT Meteosat Third Generation (MTG) (see Geostationary Earth Orbit (GEO)) will detect, locate, and measure continuous total lightning activity over their full disk with a nominal resolution of 10 km. GOES-R will carry the Geostationary Lightning Mapper (GLM) and it is scheduled to be launched in late 2015, while the MTG will carry the Lightning Imager (LI) and it is scheduled to be launched in 2018. Both GLM and LI are heritages of OTD and LIS, but GOES-R and MTG are equipped with improved communications systems and much greater telemetry bandwidth to ensure a continuous and reliable flow of the remote sensing products. The GOES-R series will maintain the 2-satellite system over the western hemisphere, with the operational GOES-R satellites at 75°W and 137°W. The GLM and LI together will provide continuous full-disk total lightning for storm warning and nowcasting (e.g., early warnings of tornadic activity, hail, and floods – see Severe Storms) for half of the globe. A geostationary lightning imager (GLI) having more limited coverage of mainland China and adjacent ocean is also planned for the Chinese FY-4 next-generation geostationary satellite series. More information on GOES-R GLM and MTG-LI can be found at http://www.goes-r.gov/ and http://www.eumetsat.int/, respectively.

Cross-references

Geostationary Earth Orbit (GEO)
Microwave Radiometers
Optical/Infrared, Radiation
Radar, Meteorological
Radiation, Electromagnetic
Severe Storms

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Lightning

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