FINNISH METEOROLOGICAL INSTITUTE
CONTRIBUTIONS

No. 91

THUNDERSTORM CLIMATOLOGY AND LIGHTNING LOCATION APPLICATIONS IN NORTHERN EUROPE

Antti Mäkelä

Department of Physics
Faculty of Science
University of Helsinki
Helsinki, Finland

ACADEMIC DISSERTATION in meteorology

To be presented, with the permission of the Faculty of Science of the University of Helsinki, for public criticism in Auditorium Brainstorm (Erik Palménin aukio 1) on November 12, 2011, at 12 o'clock noon.

Finnish Meteorological Institute
Helsinki, 2011

ISBN 978-951-697-753-2 (paperback) ISSN 0782-6617
Unigrafia
Helsinki, 2011

ISBN 978-951-697-754-9 (PDF)
http://ethesis.helsinki.fi
Helsinki, 2011

FINNISH METEOROLOGICAL INSTITUTE

Published by	Finnish Meteorological Institute P.O. Box 503 FIN-00101 Helsinki, Finland	Series title, number and report code of publication Finnish Meteorological Institute Contributions 91, FMI-CONT-91 Date November 2011

Author
Antti Mäkelä

Name of project

Commissioned by

Title
Thunderstorm climatology and lightning location applications in northern Europe

Abstract

Thunderstorm is a dangerous electrical phenomena in the atmosphere. Thundercloud is formed when thermal energy is transported rapidly upwards in convective updraughts. Electrification occurs in the collisions of cloud particles in the strong updraught. When the amount of charge in the cloud is large enough, electrical breakdown, better known as a flash, occurs.

Lightning location is nowadays an essential tool for the detection of severe weather. Located flashes indicate in real time the movement of hazardous areas and the intensity of lightning activity. Also, an estimate for the flash peak current can be determined. The observations can be used in damage surveys. The most simple way to represent lightning data is to plot the locations on a map, but the data can be processed in more complex end-products and exploited in data fusion. Lightning data serves as an important tool also in the research of lightning-related phenomena, such as Transient Luminous Events.

Most of the global thunderstorms occur in areas with plenty of heat, moisture and tropospheric instability, for example in the tropical land areas. In higher latitudes like in Finland, the thunderstorm season is practically restricted to the summer season. Particular feature of the high-latitude climatology is the large annual variation, which regards also thunderstorms.

Knowing the performance of any measuring device is important because it affects the accuracy of the end-products. In lightning location systems, the detection efficiency means the ratio between located and actually occurred flashes. Because in practice it is impossible to know the true number of actually occurred flashes, the detection efficiency has to be esimated with theoretical methods.

Publishing unit
Finnish Meteorological Institute, Earth Observation

Classification (UDC)	Keywords
551.515.4	convective systems, thunderstorms
551.594.221	lightning
551.508.94	lightning location
551.501.8	remote sensing

ISSN and series title
0782-6117 Finnish Meteorological Institute Contributions

ISBN
978-951-697-753-2 (paperback), 978-951-697-754-9 (pdf)

Language	Pages	Price
English		

Sold by	Note
Finnish Meteorological Institute / Library P.O. Box 503, FIN-00101 Helsinki, Finland	

Julkaisija Ilmatieteen laitos

PL 503, 00101 Helsinki

Julkaisun sarja, numero ja raporttikoodi
Finnish Meteorological Institute
Contributions 91, FMI-CONT-91

Julkaisuaika
Marraskuu 2011

Tekijä
Antti Mäkelä

Projektin nimi

Toimeksiantaja

Nimike
Ukkosklimatologiaa sekä salamanpaikannussovelluksia Pohjois-Euroopassa

Tiivistelmä

Ukkonen on ilmakehän vaarallinen sähköilmiö. Ukkospilvi on seurausta lämpöenergian voimakkaasta kulkeutumisesta (konvektio) ilmakehän alemmista kerroksista ylöspäin. Ukkospilvi sähköistyy, kun pilveä kasvattava voimakas nousuvirtaus aiheuttaa pilvihiukkasten yhteentörmäyksiä, joissa tapahtuu sähkövarausten erottumista. Kun pilven sähkövaraus on kasvanut riittävän suureksi, tapahtuu läpilyönti eli salama.

Salamoiden paikantaminen on nykypäivänä yksi tärkeimmistä vaarallisen sään havaintomenetelmistä. Salamahavainnoista nähdään lähes reaaliajassa, missä ukkosalueet etenevät ja kuinka kiivasta salamointi on. Lisäksi jokaiselle paikannetulle salamaniskuille saadaan mm. arvio huippuvirralle. Jälkikäteen havaintoja voidaan hyödyntää vahinkotapausten selvittämisessä. Yksinkertaisimmillaan salamanpaikannustietoa esitetään pisteinä kartalla. Tietoa voidaan jalostaa myös monimutkaisemmiksi tuotteiksi ja eri havaintoaineistojen yhdistelmiksi. Lisäksi salamanpaikannustietoa voidaan hyödyntää salamaan liittyvien seurannaisilmiöiden kuten esimerkiksi yläsalamoiden tutkimuksessa.

Runsaimmin maapallolla ukkostaa siellä missä on tarjolla runsaasti lämpöä, kosteutta ja troposfäärin epävakautta, esimerkiksi tropiikin maa-alueilla. Korkeilla leveysasteilla kuten Suomessa ukkoskausi rajoittuu käytännössä kesään, ja samoin kuin lähes kaikilla sääsuureilla Suomessa, myös ukkosten esiintymisellä on suurta vuosivaihtelua.

Kaikkien mittalaitteiden osalta on tärkeää tietää laitteen suorituskyky, esimerkiksi tarkkuus ja tehokkuus, koska nämä vaikuttavat suoraan lopputuotteiden täsmällisyyteen. Salamanpaikantamisessa tärkeä suure on havaintotehokkuus, joka tarkoittaa paikannettujen salamoiden lukumäärän suhdetta todellisuudessa esiintyneiden salamoiden lukumäärään. Koska todellisuudessa esiintyneiden salamoiden lukumäärää on käytännössä mahdotonta tietää varmuudella, joudutaan laitteiston tehokkuus usein arvioimaan teoreettisin menetelmin.

Julkaisijayksikkö
Uudet havaintomenetelmät

Luokitus (UDK)
551.515.4
551.594.221
551.508.94
551.501.8

Asiasanat
ukkonen
salama
salamanpaikannus
kaukokartoitus

ISSN ja avainnimike
0782-6117 Finnish Meteorological Institute Contributions

ISBN
978-951-697-753-2 (paperback), 978-951-697-754-9 (pdf)

Kieli
englanti

Sivumäärä

Hinta

Myynti
Ilmatieteen laitos / Kirjasto
PL 503, 00101 Helsinki

Lisätietoja

Preface

The scientific research behind this thesis has been made at the Finnish Meteorological Institute (FMI) in the Earth Observation Unit.

I started my career at FMI as a summer trainee in 2001. My task was to fill in Dr. Tapio J. Tuomi, whose was the only scientist at FMI whose expertise was thunderstorm research. Summer is a difficult period in Finland; it is the season when all the action occurs, but also the season when everybody in Finland should be on vacation. Therefore, when Tapio was in vacation, somebody had to be there to answer all the questions from the media, authorities, citizens, insurance companies etc, who needed detailed information of the phenomena. Every summer since 2001, I filled in Tapio's position, until I got my semi-permanent position in 2005 as a MSc graduate student.

The team work with Tapio was extremely fruitful most of all because of our different backgrounds; the team consisting of a physicist and a meteorologist proved to be extremely fruitful because thunderstorms consist both of these topics.

When Tapio retired, it was quite straightforward task to take responsibility of the thunderstorm research at FMI because, after all, we had been working together so many years. But I have to admit that only a few weeks after his retirement I noticed the importance of a ”team”, and I wondered how Tapio had been able to work single handed a couple of decades.

I thank all of my colleagues and supervisors, as well as all the authors and co-authors in my papers, especially Pekka Rossi, David Schultz, Jakke Mäkelä and Niko Porjo. Jussi Haapalainen helped me a lot regarding the technical aspects of lightning location. I thank my parents, Jorma and Hannele, for always being there for me, and also my sister Annika and my brother Atte, who have encouraged me and kicked my bottom to get things done. I thank Prof. Philip Krider from the University of Arizona and Dr. Jochen Grandell from EUMETSAT for reviewing this thesis and providing suggestions to make it better. Besides Tapio, many thanks go also to Hannu Savijärvi and Ari-Matti Harri for reading and commenting this paper. Finally, I want to thank Hanna for giving me the happiness, love and motivation for life.

A lady once sent me an email:”My little child is afraid of thunderstorms and she is wondering if it is really necessary for thunderstorms to occur? So, is it? And what would the world be without thunderstorms?”. At first hand, the question sounded silly, but when replying to the question, I noticed that the answer was difficult to formulate in a simple and understandable way. And actually, I am still looking for the right answer.

Kellokoski, September 2011

Antti Mäkelä

List of original publications

I Tuomi, T.J. and Mäkelä, A., 2008: Thunderstorm climate of Finland 1998-2007. *Geophysica*, **44**, 29–42.

II Mäkelä, A., Rossi, P. and Schultz, D.M., 2010: The daily cloud-to-ground lightning flash density in the contiguous United States and Finland. *Mon. Wea. Rev.*, **139**, 1323–1337. DOI: 10.1175/2010MWR3517.1.

III Mäkelä, A., Tuomi, T.J. and Haapalainen, J., 2010: A decade of high latitude lightning location: effects of the evolving location network in Finland. *J. Geophys. Res.*, **115**, D21124, doi:10.1029/2009JD012183.

IV Tuomi, T.J. and Mäkelä, A., 2008: Binomial model of lightning detection efficiency. *J. Lightning Res.*, **1**, 1–8.

V Tuomi, T.J. and Mäkelä, A., 2009: Flash cells in thunderstorms. In *Lightning: Principles, Instruments and Applications*, Springer, 509–520.

VI Mäkelä, A., Kantola, T., Yair, Y. and Raita, T., 2010: Observations of TLE's above the Baltic Sea on Oct 9 2009. *Geophysica*, **46**, 79–90.

VII Mäkelä, J., Karvinen, E., Porjo, E., Mäkelä, A., and Tuomi, T.J., 2009: Attachment of Natural Lightning flashes to Trees: Preliminary Statistical Characteristics. *J. Lightning Res.*, **1**, 9–21.

Summaries of the original publications

The contents of Papers I–VII and the author's contribution are briefly outlined below.

I Tuomi, T.J. and Mäkelä, A., 2008: Thunderstorm climate of Finland 1998-2007. *Geophysica*, **44**, 29–42.

Paper I shows the thunderstorm climatology of Finland in 1998-2007. The role of the author was to analyse lightning location data (e.g., calculate ground flash densities) and to browse the literature for studies made in other countries and regions.

II Mäkelä, A., Rossi, P. and Schultz, D.M., 2011: The daily cloud-to-ground lightning flash density in the contiguous United States and Finland. *Mon. Wea. Rev.*, **139**, 1323–1337. DOI: 10.1175/2010MWR3517.1.

Paper II discusses the regional differences of thunderstorm intensity measured with the daily ground flash density. The role of the author was to analyse the lightning data and to draw the main conclusions.

III Mäkelä, A., Tuomi, T.J. and Haapalainen, J., 2010: A decade of high latitude lightning location: effects of the evolving location network in Finland. *J. Geophys. Res.*, **115**, D21124, doi:10.1029/2009JD012183.

Paper III describes the importance of the monitoring of lightning location system performance. The paper shows a ten-year evolution of the Finnish lightning location system, and discusses how various configuration changes affect the performance of the system. The author was responsible for most of the scientific work and results.

IV Tuomi, T.J. and Mäkelä, A., 2008: Binomial model of lightning detection efficiency. *J. Lightning Res.*, **1**, 1–8.

Paper IV investigates how the detection performance of a lightning location system can be estimated with a binomial distribution. The author analysed ground truth data from a data set of known lightning induced failures into power transmission lines. This subject had only a minor role in the paper.

V Tuomi, T.J. and Mäkelä, A., 2009: Flash cells in thunderstorms. In *Lightning: Principles, Instruments and Applications*, Springer, 509–520.

Paper V shows how lightning location data can be organised as flash cells to provide easier monitoring of convective cells in operational forecasting. The author wrote parts of the manuscript and collected reference literature.

VI Mäkelä, A., Kantola, T., Yair, Y. and Raita, T., 2010: Observations of TLE's above the Baltic Sea on Oct 9 2009. *Geophysica*, **46**, 79–90.

PAPER VI is a case study about the first observation of Transient Luminous Events near Finland. The study is based on photographs by a semi-amateur photographer Timo Kantola, who captured these phenomena. The author collected all the necessary meteorological material together and analysed the lightning location data to find the parent flashes causing the TLE's.

VII Mäkelä, J., Karvinen, E., Porjo, E., Mäkelä, A., and Tuomi, T.J., 2009: Attachment of Natural Lightning flashes to Trees: Preliminary Statistical Characteristics. *J. Lightning Res.*, **1**, 9–21.

PAPER VII deals with the effects of lightning flashes to trees, which is not a widely studied subject. The author provided and analysed the lightning location data to find the corresponding tree strokes, and weather radar data to estimate whether there had been precipitation near the tree before and at the time of the stroke.

1 INTRODUCTION

This thesis gives a comprehensive overview about the use and possibilities of lightning location systems (LLS) in climatology and operational meteorology. LLS is a device capable to estimate the location of occurrence of a lightning discharge, usually a stroke or a flash (see Chapter 2.1). There are many different types of LLS: some are designed to locate *ground flashes*, *cloud flashes*, or *total lightning* (i.e., both ground and cloud flashes). Furthermore, there are large differences in the versatility and sensitivity of the systems, depending on how detailed information is measured and how weak discharges need to be detected.

All modern LLS's consist of a *sensor* (at least one but usually many) and a *central processor* (Fig. 1.1a-b). The purpose of the sensors is to detect the signal emitted by the lightning discharge and pass the information to the central processor (Fig. 1.1b), which calculates the estimated location of the discharge and outputs it to the end-user (Fig. 1.1c).

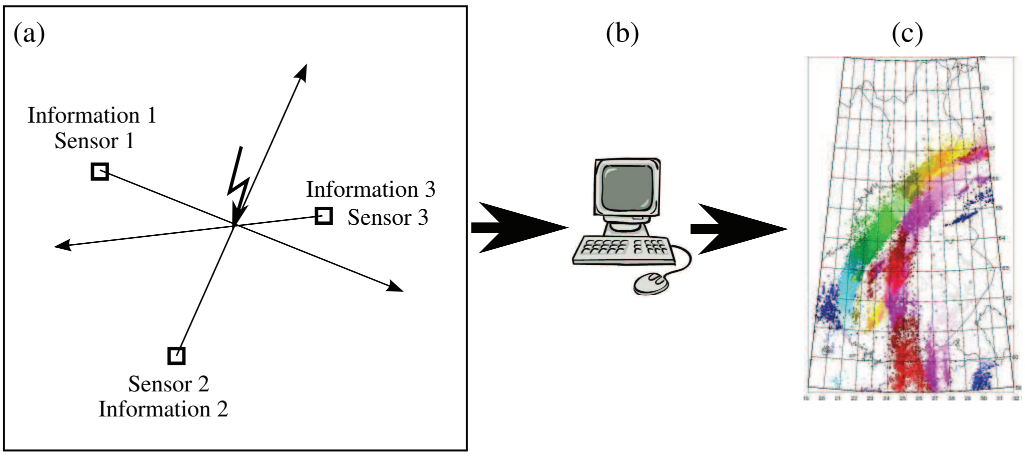

FIGURE 1.1. Illustration of the lightning location principle. (a) Sensors detect lightning discharge. (b) Central processor. (c) Lightning locations plotted on a map.

An important feature of an LLS with several sensors is the distance between the sensors, i.e., sensor *baseline*. This parameter determines the efficiency of the whole system: the radiation field of the lightning signal attenuates proportionally to the inverse distance when it propagates away from its originating point. Therefore, a weak-amplitude signal cannot be located unless the sensors are close to each other (the sensor density is high). Because it would not be practical to cover the whole Earth with lightning sensors with baselines of a few kilometres, different types of systems have been developed to fulfill different needs. A crude classification according to the baseline is the following (also in Table 1.1):

– Short baseline systems: baseline from a few metres up to a few kilometres. Usually very sensitive total lightning systems. They usually cover only small areas, such as airports, or are used in research and usually exploit Very High Frequencies (VHF) and/or Low Frequencies (LF) (Richard et al., 1986; Thomas et al., 2001; Betz et al., 2007).

- Medium baseline systems: baselines up to a few hundred kilometres. The most common type. They detect most efficiently ground flashes, but also cloud flashes. Usually LF or Very Low Frequencies (VLF) (Cummins et al., 1998; Cummins and Murphy, 2009).

- Long baseline systems: baselines up to thousands of kilometres. Mostly ground flashes only, especially high-amplitude ones. Benefits are low cost, wide coverage, while disadvantages are lower detection efficiency and poorer location accuracy than with shorter baselines. Usually LF and VLF (Lee, 1986; Rodger et al., 2006; Said et al., 2010).

- Optical instruments: satellite-based instruments, either on a low earth orbit (a few hundred kilometres) or on geostationary orbit (altitude approximately 36 000 km). Single instrument covers large areas and detects total lightning, but the detection efficiency and especially location accuracy are poorer than with ground-based systems (Christian et al., 1989, 2003; Stuhlmann et al., 2005; Finke, 2009).

Table 1.1 Different lightning location system types and methods, and some example systems. IC = intracloud lightning, CG = cloud-to-ground lightning, TOA = Time-Of-Arrival, DF = Direction Finding.

	Lightning Type	Method	Example Systems
Short	IC+CG	TOA	LDAR, LMA, Orfeo
Medium	CG / IC+CG	DF/TOA/Interferometry	Vaisala LF, Linet, SAFIR
Long	CG	TOA	ATDNET, Vaisala VLF, Zeus, WWLLN
Optical	IC+CG*	Digital image processing	LIS, GLM**, LI**

**Cannot discriminate between different lightning types.*
***Not yet in operation.*

Before the era of automatic lightning detection systems, regular thunderstorm observations were made by human observers at fixed sites and often in connection with other meteorological observations. This made possible the calculation of *thunderstorm days*, T_D, i.e., the local number of days with thunderstorm per year at a fixed site (also termed as keraunic level; see e.g., Hamberg 1917). The radius from which a flash can be observed aurally or visually is ideally about 20 km or even more, but in practice it is often as low as 10 km because of environmental attenuation and obstacles (Fleagle, 1949). Although the early estimations of T_D were based on only a sparse sample of the actual thunderstorm climatology, the results have remained valuable, and T_D is still a useful climatological parameter describing the occurrence of thunderstorms.

The secrets of electricity were starting to unravel in the 18th century, when Thomas Dalibard and Jacques de Romas in France, and Benjamin Franklin in America, pursued to prove with mast and kite experiments that also lightning was an electrical phenomenon (Krider, 2006; Berger and Amar, 2009). Later, with the increased knowledge of electromagnetism, it was possible to design devices for the automatic detection of lightning. The first *flash counters* were developed already in the 1890s (Popov, 1896). Flash counter is a device detecting the electromagnetic pulses emitted by lightning flashes and, so to speak, counting them. The flash counters provided more detailed statistics of thunderstorm climatology and they were widely used in the 20th century (Prentice, 1972).

The first LLS's were developed in the 1920s (Watson-Watt and Herd, 1926). They were based on *direction finding* sensors, which detected the lightning signal, measured its azimuth (i.e., bearing of arrival) with cross-looped antennas, and reported the azimuths from two or more sensors to the central processor, which calculated the lightning location by triangulation (Fig. 1.1; e.g. Norinder, 1953; Krider et al., 1976, 1980). (Before the era of computers, the first central processors were the scientists themselves, manually intersecting the azimuths). Later, systems based on the measurement of exact *time-of-arrival* of the lightning signal were developed (Lewis et al., 1960; Lee, 1986). In these systems, the sensor recorded the arrival time of the lightning signal, and reported it to the central processor. Using the differences in the arrival times of the signal to different sensors, the location of lightning could be calculated. The first versions were complicated and expensive because a high-accuracy clock based, for example, on a rubidium oscillator was needed to obtain the exact time stamp; precise time is needed because the lightning signal propagates with the speed of light (300 meters during one microsecond). With the present cheap and reliable GPS (Global Positioning System) devices, the temporal information can be obtained easily and accurately. The combination of direction finding and time-of-arrival is also possible and used widely nowadays.

The systems described above are ground-based. Besides these, satellite-based instruments have become important tools, especially for the global mapping of lightning. The instrument is basically a sensitive digital camera, situated on a satellite, looking towards the Earth for lightning flashes. With suitable filters it is possible to detect an emission of light from a lightning flash even in daylight conditions. The wavelength used is 777.4 nm (oxygen), which is clearly distinguishable from other electromagnetic radiation. Up to now, the instruments have been onboard low earth orbit satellites orbiting around the Earth. This means that a certain region is under the instrument for only some minutes per cycle. However, instruments situated on geostationary satellites have been planned to be launched before year 2020 (Christian et al., 1989; Stuhlmann et al., 2005; Finke, 2009); these instruments will provide continuous observations of lightning over a constant area.

All lightning location systems trigger to a certain electromagnetic impulse emitted by lightning. Maybe the most common triggering impulse is the high-current return stroke of a cloud-to-ground flash. Typically, the sensors accept only the wave shapes common to ground strokes, and filter out everything else including the background noise. The optical instruments in space trigger to the optical signals of lightning, but similar rejection criteria are in these sensors as well.

The instruments mentioned above are remote sensing tools for finding out various characteristics of thunderstorms. For T_D statistics, the human and flash counter observations were reasonably adequate, and the global T_D distribution published for example by WMO (World Meteorological Organisation) in 1956 is surprisingly accurate (Fig. 1.2).

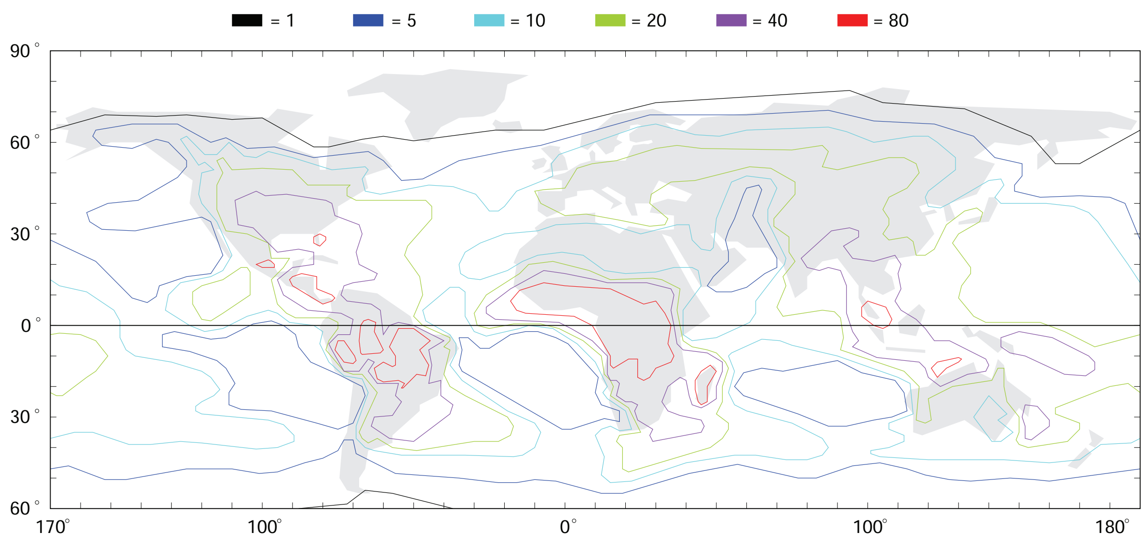

FIGURE 1.2. World map showing the average annual number of thunderstorm days. The isolines are 1 (black), 5 (blue), 10 (cyan), 20 (green), 40 (purple), and 80 (red) thunderstorm days yr^{-1}. Based on WMO Publication 21, and is reproduced e.g. in Rakov and Uman (2003).

Figure 1.2 shows how the thunderstorm activity is spread over the Earth: tropical continental regions experience a high number of thunderstorm days per year (T_D about 80 or more), and the activity decreases towards higher latitudes, mainly because of smaller amount of solar radiation. Outside tropics, T_D value of 80 is achieved only in Florida. In Finland, between 60-70°N and 20-30°E, the values are 10...5, i.e., about one tenth of the values in the tropics. Between latitudes 60-70°N, Finland seems to represent the region of the highest activity, similar to that in northern Russia, while in the North America the values lie between 1 and 5. In the southern hemisphere, there are practically no thunderstorms poleward of latitude 60°S.

T_D does not give information about the *frequency of lightning* because a day with one flash and a day with 1000 flashes both make one thunderstorm day at an observation site. Therefore, it is convenient to calculate the occurrence frequency of lightning per certain *unit area* per certain *time interval*; this leads to a quantity called *flash density*. The unit area used for the calculation is arbitrary, but its size affects, of course, the density value. A widely used area is a 10 km x 10 km square, because it brings out possible smaller features in the climatology, yet not smoothing the picture too much. Also, the time step is arbitrary, depending on the purpose. In climatological studies, the time step is usually from one month to several years, while in operational meteorology the step varies from one minute to one day.

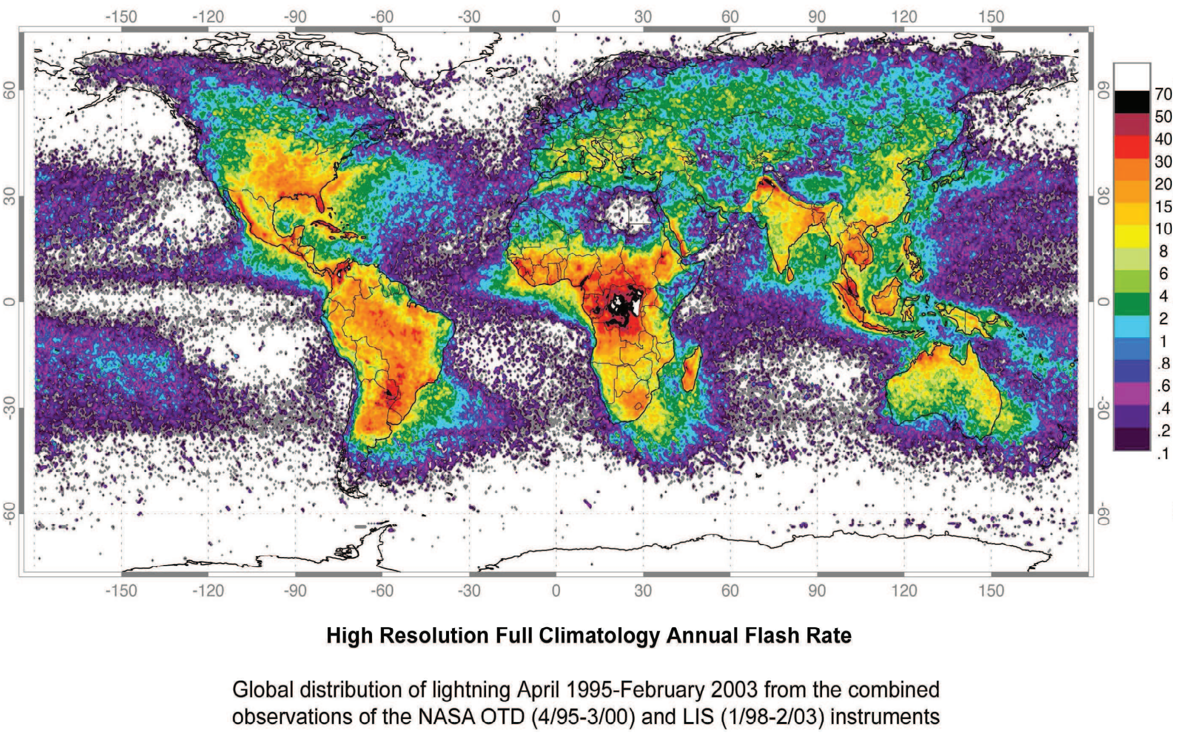

FIGURE 1.3. World map showing the average annual total lightning flash density (flashes km^{-2} yr^{-1}) based on optical instruments. Courtesy: NASA.

The average annual global total lightning flash density is shown in Fig. 1.3. The regions with largest values are very similar to those in Fig. 1.2: tropical continental areas, Florida, Caribbean islands, and Indonesia. A large concentration of flashes is also in the Himalayas, although this area does not stand out so clearly in the map of thunderstorm days (Fig. 1.2). This indicates that the annual number of flashes may be the result of either nearly constant and longer accumulation of flashes, or due to short and intense accumulation (i.e., less thunderstorm days but still large amount of flashes), which means that there are differences in the intensity and properties of *individual* *thunderstorms* in different regions. So far, we have used the term thunderstorm rather loosely. What is actually observed is lightning (flashes), the thunder heard, or the associated winds etc. We will eventually focus on lightning. At a fixed observation site (small area), or its computational equivalent in lightning location data, thunderstorms may be defined as lightning episodes separated by long enough non-lightning periods. Durations are typically one or more hours, and usually no more than one episode occurs during one day. In this sense, thunderstorm is a *statistical counting unit*. This is an important point in this thesis.

On the other hand, thunderstorms develop as cells, which usually move past the observation site during their lifetime and cannot be physically associated with a fixed observation site. A thunderstorm episode usually consists of a group of several cells associated with a larger weather system. The cell aspect will be discussed in Chapter 4.

The three basic ingredients for the development of a thunderstorm are *moisture*, *instability* of the troposphere, and a *lift* mechanism (Doswell, 2001). The relations between these three determine the intensity of the thunderstorm, and more precisely, the greater the values are in the lower atmosphere, the more intense are the storms. If the thunderstorm intensity is defined, for example, by the total number of flashes during its lifetime, its statistical distribution starts from one flash and ends up to several thousands of flashes per storm. In some parts of the world the climatological conditions are favourable for storms that lie in the extreme end of the distribution. Such storms are the ones that cause devastating damages, floods, strong winds, large hail, and even deaths.

In operational meteorology the forecasting of especially intense thunderstorms is a difficult task. Although the *possibility* for an intense thunderstorm to occur can be forecast even several days ahead, the *actual* location of occurrence and movement of the storm are visible only after the storm has already developed. Therefore, remote sensing devices, such as LLS's, for the real time monitoring of thunderstorms have become essential tools in the present-day operational meteorology. A forecaster sees in real time the approach and development of the storm and gets an idea of its threat level as well as the route of the storm.

To get the most accurate knowledge about the properties of the storm, it is important to know the *performance* of the LLS. Key parameters regarding the performance are *detection efficiency* (the ratio of located to occurred flashes) and *location accuracy*. The higher the detection efficiency, the more complete picture one gets of the storm intensity; the better the location accuracy, the more accurately the strike point of a flash can be determined. Both of these parameters are difficult to determine reliably, because the true number of the actually occurred flashes cannot be known, and because the calculation of strike point is subject to various errors. Therefore, the values of these parameters are estimated either purely theoretically, or statistically with small subsets of flashes. The operator of the system should continuously monitor the performance parameters especially when technical changes are made to the system.

The location accuracy in lightning location is not an absolute quantity but a probabilistic one: with mathematical probability calculations, the strike point can be estimated with certain uncertainty. When the sensor number in the network is large, the uncertainty is usually small.

This thesis focuses on many of the issues mentioned in this chapter and especially regarding Finland. We will start from an overview of thunderstorms in general and thunderstorms in Finland (Chapter 2). Then, Chapter 3 discusses lightning location performance and primarily detection efficiency. Chapter 4 presents the benefits and importance of lightning location applications and describes how the lightning data can be used in climatological studies and in operational meteorology. Concluding remarks and discussion are given in Chapter 5.

2 Thunderstorm climatology

The tropospheric atmosphere is always in motion. The main reason for this is the unequal distribution of solar radiation to the Earth which eventually causes perturbations in the temperature and pressure fields of the atmosphere. Other major forcing factors are the rotation of the Earth around its axis and the Earth's gravity. The atmosphere, like any other fluid, is driven towards equilibrium between the changing forces by horizontal and vertical motions. This leads to a chaotic circulation system consisting of motions starting from microscopic scale and extending into synoptic scale (thousands of kilometres). The formation of a thunderstorm is also related to the balancing effect and conservation of energy via a very effective energy transport method called *convection*.

2.1 Thunderstorms - an overview

The basic unit of all thunderstorms is a convective *cell*. The term "convective cell" was established in the early 20th century by Henri Bénard (1901), and the occurrence of convection in the atmosphere was first shown in the study of Byers and Braham (1949). A cell consists of a (convective) core of upward moving air, driven by a buoyant force and surrounded by a region of subsiding air. The ascending or descending motions of an air volume or parcel are often illustrated by those of a hot-air balloon; the balloon ascends or descends because the air inside has different properties compared to the surrounding air (Fig. 2.1), and the greater the difference, the larger the buoyant force, B, which is defined as (see e.g. Holton, 1992):

$$B = g\frac{T_{parcel} - T_{environment}}{T_{environment}}, \qquad (2.1)$$

where g is gravity, and T_{parcel} and $T_{environment}$ are the temperatures of the air parcel and the surrounding air, respectively. The force is positive upward. Actually, the "force" is defined per unit mass and has the dimension of acceleration (ms^{-2}). For an unstable atmosphere, the buoyant force is large and positive; then there are better conditions for intense vertical motions.

In a convective cell the rising part, *updraught*, lifts moist and warm low-level air up with speeds of 10 metres per second or more. It is strongest in a limited horizontal area which deserves the name *core*. When the moisture in the ascending air condenses, a convective cloud is formed which rapidly extends to higher altitudes if the ascending motion is strong enough and persistent (Fig. 2.1a-c). Eventually, when the growing cloud particles are so large that they start to fall, the *downdraught* and the associated heavy precipitation area are formed (Fig. 2.1d). This precipitation core is well visible in a weather-radar display. As the downdraught reaches ground, vertical motion turns and spreads into horizontal and blocks the updraught from lifting more energy (i.e., moisture) into the cloud (Fig. 2.1e); finally the cloud dissipates (Fig. 2.1f). The downdraught can be very sudden and intense, and this *downburst* can cause severe damages. Also, large *hail* and *tornadoes* are thunderstorm-related phenomena.

The life cycle of a thunderstorm cell contains three stages: *cumulus* stage (Fig. 2.1a-c), *mature* stage (Fig. 2.1d) and *dissipation* stage (Fig. 2.1e-f), respectively. The lifetime of a cell is about or less than one hour.

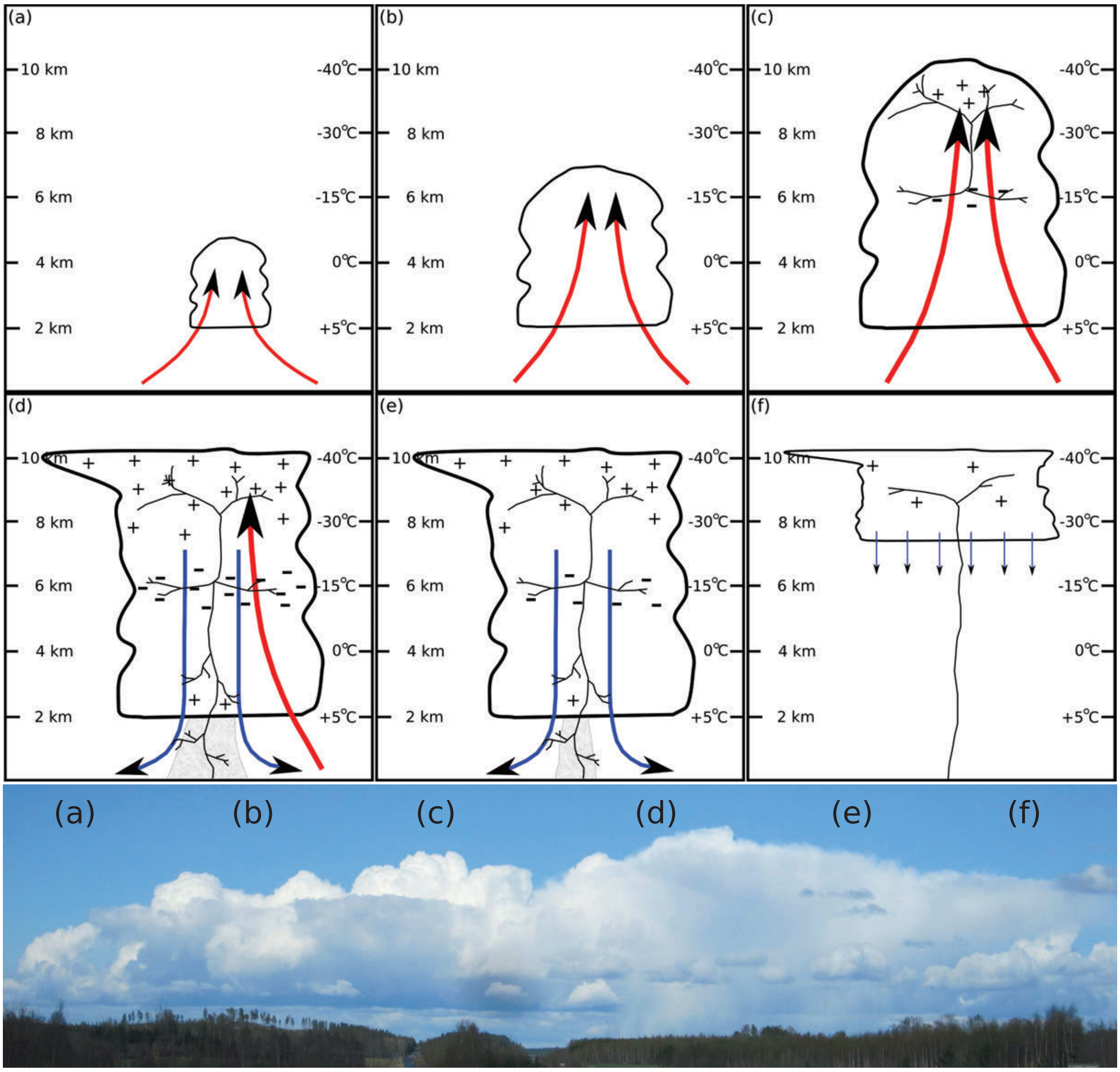

FIGURE 2.1. The life cycle of a convective cell and a thundercloud (photograph below) producing lightning. The updraught produces the cloud [(a)] which grows rapidly [(b)]. The cloud is electrified by cloud particle collisions and the first discharge occurs [(c)]. The precipitation starts and the downdraught forms [(d)]. Downdraught blocks the feeding of energy [(e)] and the cell dissipates, i.e., subsides and evaporates [(f)]. Photo: Hanna Tietäväinen.

The electrification of the cloud is mainly due to the so-called *graupel-ice mechanism* (Reynolds et al., 1957; Williams, 1989; Williams et al., 1991; Baker and Dash, 1994; MacGorman and Rust, 1998; Saunders, 2008; Stolzenburg and Marshall, 2008); the intense updraught makes cloud particles of different nature to collide which causes separation of charges. The responsible particles in the collisions are *graupels* (size about a millimetre) and *ice crystals* (about 10 micrometres). Also, supercooled water is an important ingredient (Takahashi, 1978; Black and Hallet, 1998). Charging is most effective at the altitude of the -15°C isotherm, and at this level graupels gain a net negative polarity (excess of electrons) and ice crystals a net positive polarity (deficit of electrons). Because of the size differences of the particles, updraught carries the ice crystals rapidly into the upper parts of the cloud while the heavier graupels float at the central and lower parts of the cloud. The graupels usually start to gain positive charge when they descend to altitudes of higher temperature. This leads to a tripolar charge structure illustrated in Fig. 2.1. However, several other charging mechanisms have been suggested (e.g., Moore et al., 1989), which can also contribute to the electrification process, especially after the graupel-ice mechanism has already electrified the cloud to some degree. For example, after the electric field of the cloud has intensified, electrostatic *induction* causes polarization in the colliding particles and further amplifies the electrification process (e.g., Black and Hallet, 1998).

When enough, or actually too much, charge has been accumulated, an electrical breakdown, a *lightning discharge* occurs. A lightning discharge is a series of various electrical discharges, the total event being called a *flash*. A ground flash has one or more temporally and often spatially separated ground contacts (strike points); these partial discharges are called *strokes*.

Usually, the activity starts with a cloud flash between the opposite charge centres inside the cloud (Williams et al., 1999; MacGorman et al., 2006), and a few minutes later a ground flash occurs. Cloud flashes are the majority of all flashes, and their share is typically greater at lower latitudes (Mackerras and Darveniza, 1994; Mackerras et al., 1998). Ground flashes are termed *negative* or *positive* depending on from which charge center they neutralize charge. When the cloud dissipates, also lightning activity starts to cease, but positive ground flashes may still occur from the remnant cloud top. A typical thunderstorm consists of several adjacent cells of different stages; new cells are forming in the front of the storm and dissipating cells remain in the rear section.

To better understand the concepts discussed in this thesis, the list below gives a short description of some of the most used thunderstorm terminology:

- Cell (convective or thunderstorm): convection-driven circulation of upward and downward moving air. Thunderstorm cell refers to a cell which eventually produces lightning.

- Thundercloud: developed convection cloud (*cumulonimbus*), consisting of at least one thunderstorm cell. Often clearly distinguishable from other clouds, but sometimes may be embedded in frontal cloud systems.

- Thunderstorm: refers to the phenomenon itself. Includes the thundercloud, thunderstorm cells and lightning. Phenomenologically, for example, a large thundercloud, lasting 10 hours but consisting of many shorter-lived cells, may be called a thunderstorm. May also be defined as a statistical counting unit, so the exact meaning depends on the context.

- Discharge: a neutralizing breakdown between a negative and a positive concentration of charge. Also a collective term for a series of partial discharges.

- Ground stroke: the discharge between cloud and ground, i.e., one where the discharge channel has a point of contact with the ground (or a grounded object).

- Flash: consists of one or several strokes. Also a generic name for a temporally limited series of lightning discharges.

- Event: defined in this paper as any single electrical process in a thundercloud. Does not indicate the type of the event, i.e., it can be a discharge, stroke or a flash.

2.2 Finnish thunderstorm climate

As mentioned in Chapter 1, the majority of global thunderstorms occur in the areas with plenty of solar warming to the surface of the Earth. Therefore, the diurnal activity of thunderstorms follows the daily cycle so that the peak occurs on the local afternoon, especially when the local afternoon is on the large continental tropical areas (Asia, Africa, South-America). Also, annual variation is clearly visible because of the larger fraction of land masses on the northern hemisphere; this means that a peak is reached during the northern summer. At every instant there are approximately 1000 ongoing thunderstorms, which together produce a flash rate of about 100 s^{-1} (Orville and Spencer, 1979). The literature gives various values, and the estimation depends on, of course, how a ”thunderstorm” is defined. In any case, if we assume the cloud flash-ground flash ratio to be 5, this means a ground flash rate 1 min^{-1} per thunderstorm. Although a typical flash rate of 1 min^{-1} for one thunderstorm is actually a good estimation, the variation is large. For example, Zipser et al. (2006), who studied the question ”where are the most intense thunderstorms on Earth?”, noted that in a North-Argentinian thunderstorm on 30 December 1997, the flash rate was 225 min^{-1}! The result was based on optical observations from space. We will return to this issue later in this chapter.

Much has been written about the thunderstorm climatology of the United States (Orville and Huffines, 1999; 2001), Middle and Southern Europe (Schulz et al., 2005; Soriano et al., 2005), and also other parts of the world (Pinto and Pinto, 2003). However, thunderstorm climatology at high latitudes is not a widely described topic. Paper I gives a description about the Finnish thunderstorm climate for years 1998-2007. It is an extension to the study of Tuomi and Mäkelä (2003), regarding the synoptic classification of thunderstorms in Finland in 1998-2002. PAPER I shows that the position of Finland between two largely different climatological zones, the Atlantic maritime climate in the west and the Eurasian continental climate in the east, introduces several intriguing aspects to the thunderstorms in Finland. For example, although the majority of both frontal and airmass thunderstorms are related to the western sector, the majority of flashes are related to thunderstorms from the eastern sector. This observation gives in principle a possibility to be better prepared to storms which approach from a direction which statistically favours intense storms.

Although the results of PAPER I regard mostly the period of modern lightning location in Finland (1998-2007), it also presents a time series of the annual amount of ground flashes in 1960-2007, based on flash counter and former lightning location networks (Fig. 2.2a). The annual averages of basically all weather parameters in Finland fluctuates from year to year (see e.g. Heino, 1994), and this is clear also for thunderstorms; the annual average ground flash density varies from approximately 0.1 to 1 ground flashes (km^{-2}) and the thunderstorm-day number between 5 and 25 days yr^{-1}).

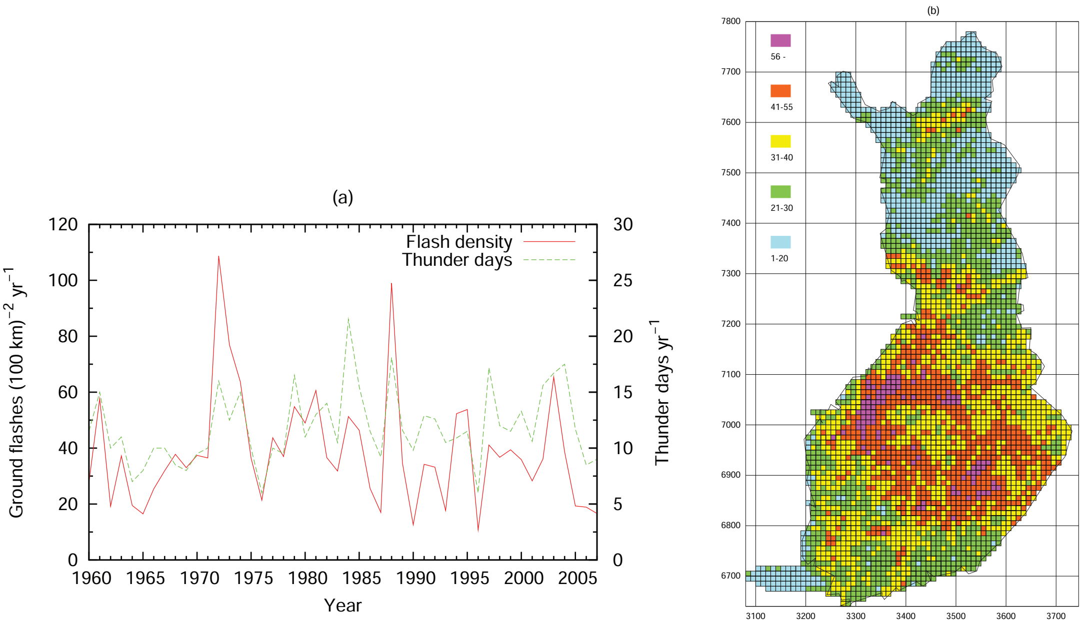

FIGURE 2.2. (a) The annual average ground flash density and thunder-day number in Finland in 1960-2007, and (b) the regional distribution of the annual average ground flash density in Finland in 1998-2007. The area includes continental Finland and the south-western archipelago, i.e., excludes open sea areas. Adapted from PAPER I.

There is some regional variation in the annual average ground flash density in Finland (Fig. 2.2b), but the values are substantially smaller compared to the extreme thunderstorm climates in the world. During the operation of the present LLS (since 1998), the largest values are found in the southern half of Finland, from the south-eastern corner to Ostrobothnia near the western coast. It seems that there is no clear single pattern for the most intense thunderstorm episodes except that these storms are related to air masses originating from the Balkan-Black Sea region, i.e., associated with the eastern sector (Tuomi and Mäkelä, 2003; PAPER I). It should also be noted, that in Finland a large portion of all annual flashes are the result of a few intense thunderstorm episodes (more than 10 000 flashes per day), while during a typical thunderstorm day the amount of flashes is much less.

One of the most important findings in PAPER I is that statistics from a ten-year or shorter period at high latitudes is not sufficient for an accurate climatological investigation. For example, the slight concentration of flashes in northern Finland in Fig. 2.2b is largely the result of only one intense thunderstorm day in 2005; in a climatologically short period in a highly variable climate, a single event may give to the distribution an excessive weight.

2.3 REGIONAL VARIATION OF THUNDERSTORMS

The *intensity* of a thunderstorm, or any other weather phenomenon, is far from trivial because it can be determined in many different ways. For instance, the intensity classification of tropical cyclones is based on the wind speed on the Beaufort scale, but the intensity classes are not the same globally. Tornado intensity is expressed with the so-called Fujita-scale (Doswell et al., 2009) based on wind speed and the caused damages.

Although the incurred damages are one way to classify a storm, it is not purely objective, because it always needs a *visual* observation of the damages; for example, a devastating storm causing massive damages over a highly populated area could be termed "violent", but a similar storm over some distant territory is not classified in the same way. Furthermore, the human inspection of damages is always prone to subjective interpretations.

One objective way to classify various quantities is *statistical analysis*; an extensive distribution gives information about the *occurrence frequency* or the *occurrence probability* of a certain quantity value. Let's use as an example the flash rate mentioned above regarding the results of Zipser et al. (2006). The value 225 flashes min^{-1} seems indeed a high number but if we place it on a distribution containing all other possible flash-rate values, we really see the rare occurrence of such a value.

In Chapter 1 we already mentioned that an annual distribution of flashes does not indicate well the intensity of individual storms, because for example a large accumulation of annual flashes may be the result of constant but moderate thunderstorm activity throughout the year, or a shorter but more intense period; these both may give the same annual picture.

To overcome the problem mentioned above, Fig. 2.3 shows an example of the distribution of the *daily* ground flash rates in different regions. The data in the figure

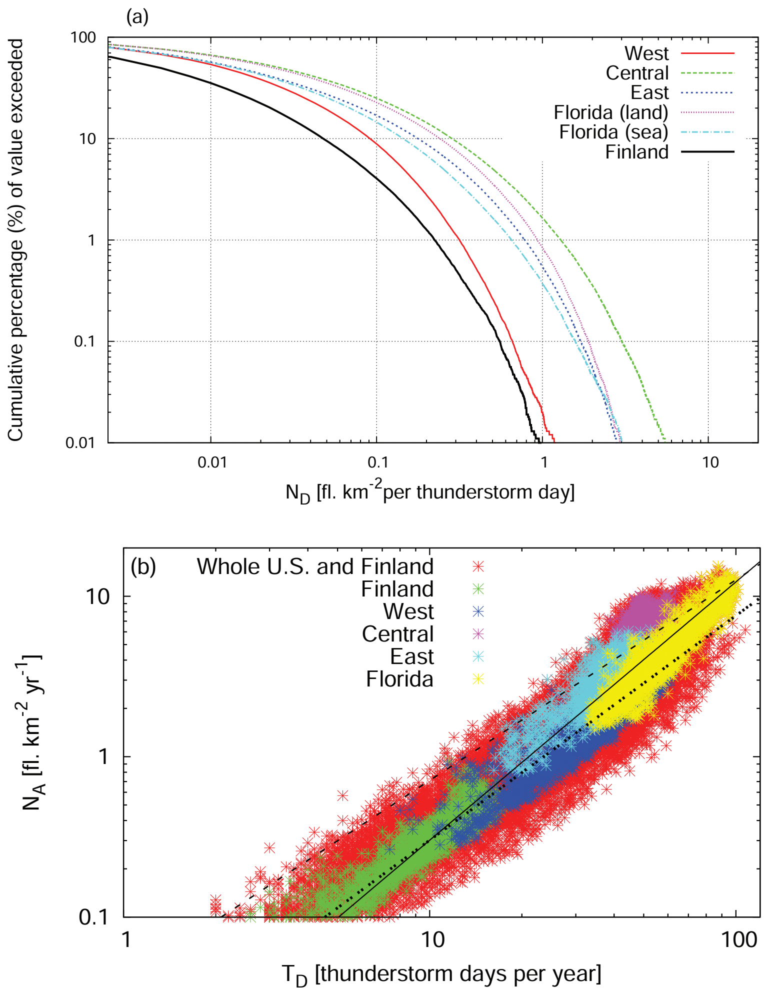

FIGURE 2.3. (a) The cumulative distribution of the daily ground flash density, and (b) the relationship between the annual average ground flash density and the number of thunderstorm days T_D in different areas in the United States and Finland, calculated on 20 km × 20 km squares. The solid line is the best fit of the data set; the two other lines are fits from Anderson et al. (1984, dashed) and Kuleshov and Jayaratne (2004, dotted). Adapted from PAPER II.

has been calculated on 20 km × 20 km squares using 24 hour time steps; i.e., the distributions indicate how the daily ground flash density varies in different regions. The data set covers years 2003-2007 for the United States and 2002-2009 for Finland. This square size has been chosen because it corresponds well to the human-observable surface area, 400 km^2, equivalent to a circle of radius 11.2 km. In Fig. 2.3a, the x-axis indicates a flash density value which is exceeded on y-percentage of thunderstorm days. For instance in Florida, a flash rate of 1 km^{-2} $T_D{}^{-1}$ is exceeded on average in 1 % of thunderstorm days while in Finland the 1-percent value is only 0.2 km^{-2}

$T_D{}^{-1}$. Therefore we can safely say that according to ground flash rates, thunderstorms in Florida are more intense than in Finland. An important finding in the figure is that although the curves disperse at higher x-axis values, they are very similar for the lower values; this means that a ”typical” thunderstorm day in any region can be considered as modest.

Figure 2.3b complements 2.3a by showing the relationship between the annual average ground flash density and the annual average number of thunderstorm days. The data has been calculated for the same 20 km $\times$ 20 km squares and 24-hour time steps as in Fig. 2.3a. The figure indicates how many thunderstorm days are needed in a square to produce a certain annual ground flash density. The results are interesting. The populations of points of different regions are clearly distinguishable in the plot, and for example, the Finnish points (green) represent the mildest thunderstorm climatology; a small number of thunderstorm days corresponds to a small number of annual flashes, while in Florida a large number of thunderstorm days result in a large number of flashes. However, the United States-central region (purple) pops up in the plot as the most flash-efficient area of all, because a high annual average flash density is achieved with relatively few thunderstorm days.

2.4 Discussion

If the state of the atmosphere requires rapid vertical motions to keep the energy balance of the lower atmosphere, deep, moist convection will occur that eventually leads to the formation of a thunderstorm. Thunderstorm can be viewed as a *dynamical* and *electrical* entity; the dynamical part includes the formation and dissipation of the thundercloud, while the electrical processes are responsible for the accumulation of charge inside the cloud and finally the electric breakdown. The dynamical part of the cloud is, however, the primary element because it serves as the executive factor for all other processes in the cloud.

The global distribution of thunderstorms has large variation. At high latitudes, the thunderstorm season is usually short which leads to fewer thunderstorm days and smaller flash density. In areas where the ingredients for thunderstorms are present all the year round, more thunderstorm days and flashes occur. The differences between land and water surfaces are also clearly distinguishable, i.e., much less flashes occur over water areas.

A thunderstorm is capable of causing devastating damages due to straight line and rotational winds, precipitation, hail and lightning. Extensive measurements of these quantities provide a statistical distribution, which indicates their observed mean, median and extremes as well as other statistical quantities. For lightning, a valuable quantity is ground flash density, indicating the amount of ground flashes per unit area during a certain time step. As we have shown, the distribution of ground flash density suggests that in any climate a typical and most common thunderstorm is relatively weak;

however, the extreme values vary dramatically from climate to another.

The Finnish thunderstorm climate contains large year-to-year variation in the number of flashes and thunderstorm days, and severe thunderstorm episodes do not even occur every year. However, when they do occur, they may reach intensities comparable with storms occurring for example in the southern Europe.

Proper understanding of the distribution of thunderstorms on the Earth has many potential benefits in the fields of meteorology, hydrology, engineering, civil protection and many other fields. The modern planning and construction of urban areas needs information about the magnitudes of lightning and precipitation rates to ensure that the infrastructure copes with the most intense storms. Furthermore, the impact of climate change on the convective weather phenomena can be monitored with the present state-of-the-art LLS.

3 The performance of lightning location systems

The basic concept and typical methods of lightning location were described in Chapter 1. In this chapter we discuss the interpretation of lightning location data, i.e., the output of a lightning location system (LLS), and what important issues there are to know about the performance of an LLS before interpreting the data.

3.1 Performance - an overview

Lightning location performance indicates how well an LLS measures lightning compared to the real occurred lightning. The performance may be described in several different ways and it can also be determined for a certain lightning parameter. For example, an optical instrument on a satellite usually has a good detection efficiency but poorer location accuracy (e.g., Rakov and Uman, 2003); this means that the performance regarding detection efficiency can be said to be good while it is less good for the accuracy. Also, the difference between the measured and the actual peak current and polarity of a lightning discharge is related to the performance of the LLS.

In this chapter the performance is discussed in a more general way; we discuss here the effects of a non-perfect LLS to the measured lightning parameters. We concentrate especially to the performance of the Nordic Lightning Information System (NORDLIS), where the Finnish Meteorological Institute (FMI) is a member (Fig. 3.1).

The main and most widely used output parameters of an LLS are the spatial and temporal information of a lightning discharge; these parameters inform *where* and *when* the discharge has occurred. Nowadays, the temporal information (based on GPS) is extremely accurate while the spatial accuracy has a large variation depending both on the discharge itself and on the performance of the LLS, including the fact that the position of the discharge relative to the network geometry affects also the performance. Lightning data includes also other parameters such as peak current and multiplicity, i.e., the number of strokes in a ground flash.

A lightning location system detects electromagnetic radiation emitted by lightning discharges. A natural lightning discharge is not a simple spark, rather it is a complex collection of partial discharges, which restricts how well it can be detected and located. On the other hand, if the LLS would be infinitely sensitive with infinite accuracy, theoretically it would be possible to detect all possible partial discharges. Today some high-performance small-area systems can trace whole discharge channels (representative samples of small discharges along the channels), but the amount of data is overwhelming and difficult to present and interpret compared, for example, to the simple set of ground-strike points. In practice, the sensor density and sensitivity is such that all discharges over appreciable areas cannot be ever detected. Also, the fact that lightning sensors are usually tuned for a certain archetypal discharge makes some less-ordinary

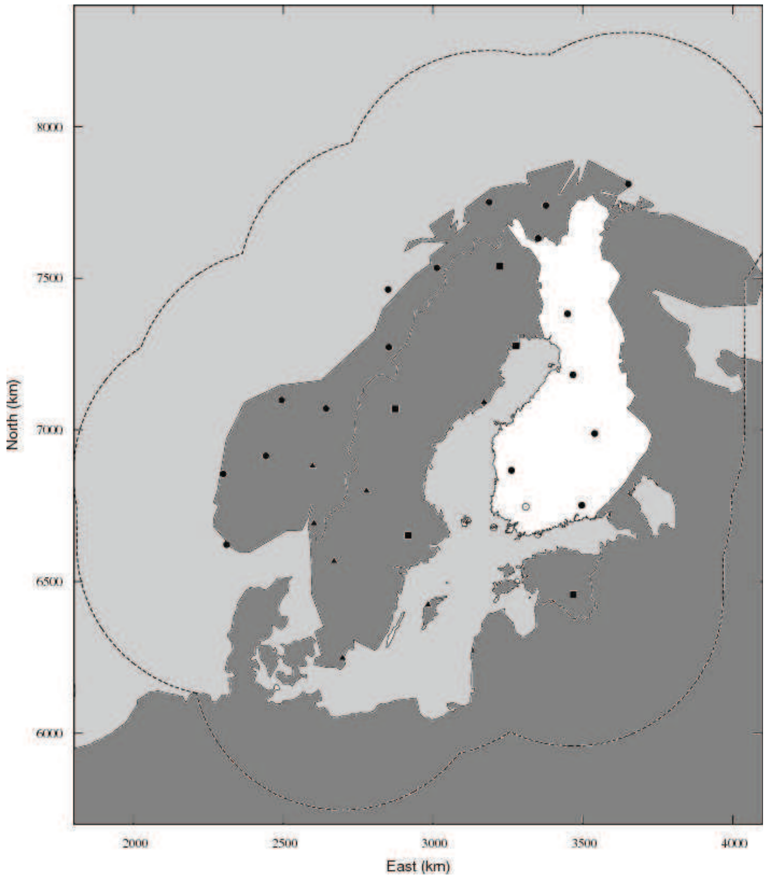

FIGURE 3.1. The NORDLIS lightning location network; Finland is highlighted white. Triangles, circles and squares represent different types of sensors. The dotted line shows the approximate efficient coverage area. Adapted from PAPER III.

discharges to be unrecognized and hence undetected.

An example of the performance of an LLS is presented in PAPER III. The Paper shows the evolution of several lightning location parameters during ten years, from 1998-2007. The key point in PAPER III is to discuss how the changes in the LLS, for example, adding more sensors to the network, affects the measured lightning parameters. Figure 3.2 illustrates this by showing the ten-year variation of the median peak current of the first ground strokes [(a)] and the mean multiplicity [(b)] of located flashes in Finland in 1998-2007.

There is year-to-year variation in Fig. 3.2, which can be interpreted in two ways; either the population of flashes used to calculate the statistics in Fig. 3.2 varies from year to year, or the LLS has measured the data differently from year to year. Clearly, the population of flashes changes every year, but it is thought that the statistics of the indicated quantitites should not vary greatly in a constant climate. Therefore, a large effect is due to the LLS.

All changes in the LLS are made to improve the performance of the system. How-

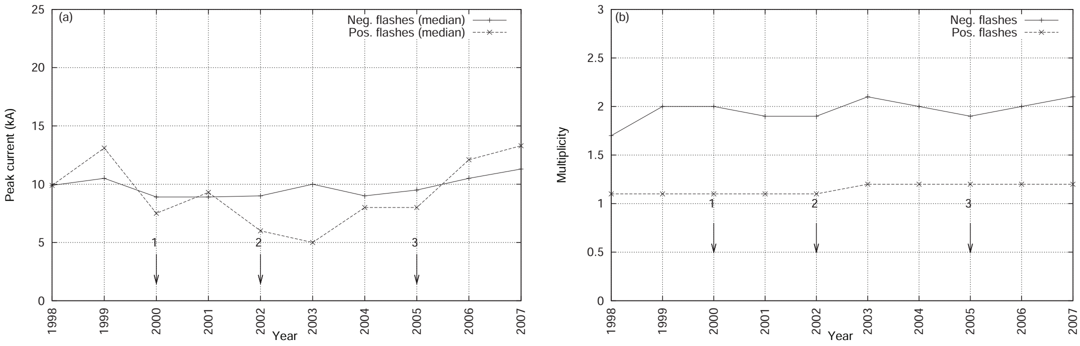

FIGURE 3.2. The median peak current [(a)] of the first ground strokes, and the mean multiplicity [(b)] in Finland in 1998-2007 according to the FMI-NORDLIS lightning location system. The numbered arrows indicate the following: 1) the sensitivity (gain) of the sensors was increased, 2) NORDLIS-cooperation began, greatly increasing the number of available sensors, and 3) the new central processor was installed at FMI. Adapted from PAPER III.

ever, sometimes a planned change may introduce another, unplanned change, which may affect only a certain lightning parameter. In Fig. 3.2 the numbered arrows indicate three major changes in the LLS used by the Finnish Meteorological Institute (FMI): 1) the sensitivity (gain) of the sensors was increased, 2) NORDLIS cooperation began, and 3) the new central processor was installed at FMI. The sensitivity increase (1) caused the LLS to detect even weaker discharges, which decreased also the median peak current, especially for positive ground flashes (Fig. 3.2a). However, for the mean annual multiplicity (Fig. 3.2b) this apparently had no effect. This is likely because the more sensitive sensors detect a greater number of weak single-stroke flashes but also a higher number of weak subsequent strokes in multi-stroke flashes, the effects perhaps cancelling each other.

For the peak current, the curve of positive flashes varies much more than for negative flashes, and even when there have not been any changes in the network. The most probable explanation for this is the well-known misclassification problem: a lightning location system sometimes misclassifies a cloud flash as a ground flash, typically a weak positive (Cummins et al., 1998; Schulz et al., 2005). In Finland, unusual abundance of weak positive flashes has been observed during individual intense storm situations (especially in 2003); no clear meteorological explanations have been found so far, but a partial explanation may be as follows. In intense storms, the cloud flash – ground flash ratio is usually large. Now, if the ratio of misclassifications is assumed constant, an increase in the cloud flash-ground flash ratio causes increase in the number of misclassified events. Furthermore, if a large number of annual flashes are due to a couple of intense storms, they give a large weight into the statistics of lightning parameters.

3.2 Detection efficiency

Detection efficiency (DE), the ratio between the located and actually occurred events, is an important yet difficult parameter to estimate reliably. It is often based on theoretical models or on comparisons with actual known strike points. A good theoretical model may predict not only the overall level of the network efficiency, but also describe its spatial variation; the latter method is based on case studies and gives precise information for the subset of events in question, but this information has limited spatial validity.

PAPER IV presents a binomial model to estimate the lightning detection efficiency in Finland. The model examines the *number of sensors reporting* (NSR) a flash (actually its first stroke) in Finland, and the average value of NSR (ANSR); NSR indicates how many sensors have succesfully participated in the lightning location of a single event, and ANSR is the average value for a population of events. Therefore, ANSR represents the *expectation value* of a binomial probability distribution. For the NORDLIS network, the minimum is NSR = 2, because at least two sensors are needed to determine the location. NSR is a known parameter for each located event, and it is related to the performance of the system, as PAPER IV shows.

The basis of the model is the observation that for the NORDLIS network over Finland, NSR for the first ground strokes has a dependence on the peak current I (Fig. 3.3): a flash with peak current 5 kA has practically never NSR greater than 5, a flash with peak current 10 kA has NSR never greater than 10, and so forth. A closer examination of our data shows that a relationship max(NSR) = $I + 1$ is the best. It is important to note that this relation is characteristic for the NORDLIS network over Finland, i.e., it may not be valid as such for other networks.

The binomial distribution is a well-known mathematical expression; it determines the success probability of a certain phenomenon when there are two possible outcomes, success and failure. The binomial formula is expressed as:

$$P = \sum_{k=0}^{n} \binom{n}{k} p^k (1-p)^{(n-k)}, \tag{3.1}$$

where P is the probability of getting exactly k successes out of n trials when the probability of a single success is p. Equation 3.1 can also be used in lightning detection efficiency calculations because, after all, detection efficiency stems from the relative numbers of successes (to detect the event) and failures (to miss the event). In lightning location, the parameters in Eq. 3.1 are: n = number of sensors *available* for detection = N, k = sensors that *actually* detect the event = NSR, p the probability that a single sensor detects the event, and P = the probability that the event *will* be located = DE:

$$DE = \sum_{NSR=2}^{N} \binom{N}{NSR} p^{NSR} (1-p)^{(N-NSR)}. \tag{3.2}$$

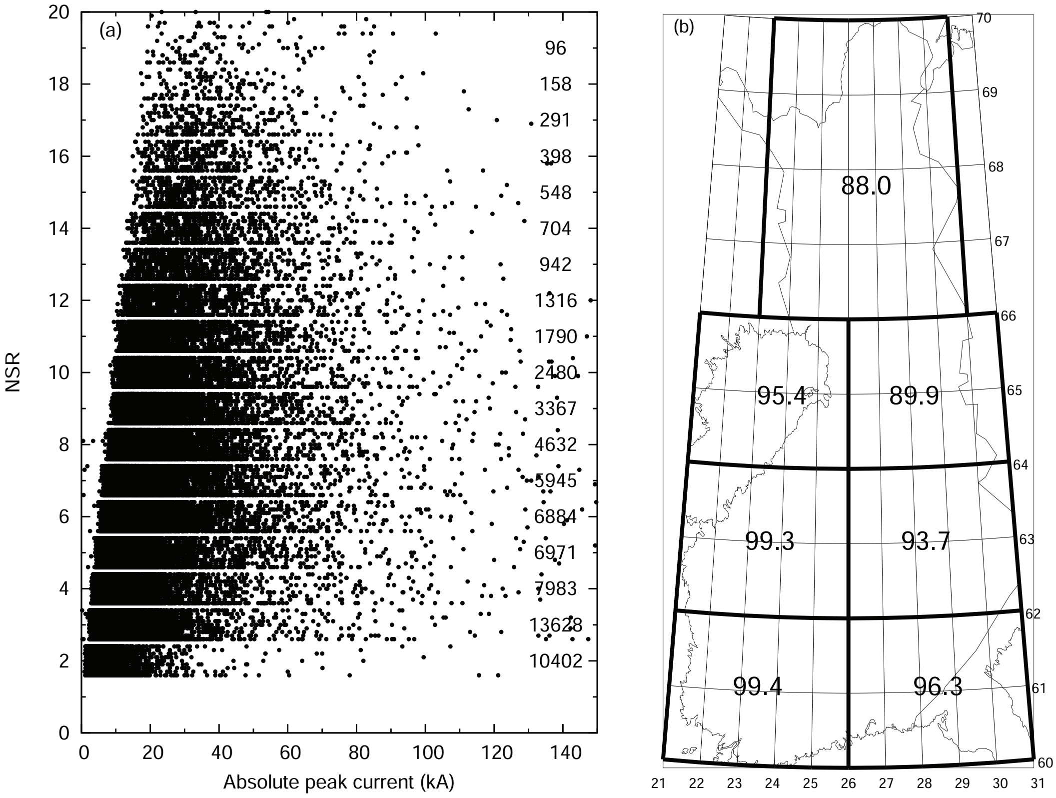

FIGURE 3.3. (a) Peak current (kA) versus the number of sensors reporting (NSR) first strokes in Finland in 2006. Each integer value of NSR has been displaced by a random factor up to $\pm$ 0.5 to illustrate the accumulation of points towards the left; the number of points is indicated on the right. (b) The estimated regional detection efficiency in 2005-2006 according to the binomial model. Reproduced from PAPER IV.

Eq. 3.2 expresses how different sensor combinations eventually produce the network DE. The basic idea is that for a given peak current I, a number of available sensors N = max(NSR) = $I + 1$ is suggested by the sharp left boundary in Fig. 3.3a. Now, by calculating the *expectation value* of NSR for the distribution by weighting Eq. 3.2 with NSR and dividing by DE, we get the modelled ANSR:

$$ANSR = \frac{\sum_{NSR=2}^{N} NSR \binom{N}{NSR} p^{NSR} (1-p)^{(N-NSR)}}{DE}. \qquad (3.3)$$

Because ANSR is readily available from the lightning data, we can use it to estimate the network DE in the following way:

1. For a given peak current, we choose a value of p, and calculate DE and ANSR from Eqs. 3.2 and 3.3.

2. We vary the value of p until the calculated ANSR matches the measured ANSR.

3. We record the value used in the matched case.

4. The model is tested for each integer value of the peak current I with the relation $N = I + 1$. In practice, peak current values in the range $I \pm 0.5$ kA are used for each integer N.

5. The overall DE is calculated as the mean of the DE values for each peak current, weighted by the numbers of strokes.

The single probability, p, is defined as an average probability of the sensors to detect the event, and its value turns out to be about 0.3. In the equations, p is actually a dummy variable; we vary its value in Eq. 3.2 until the modelled ANSR matches the measured one. Although the binomial DE model contains many assumptions, it gives reasonable estimates about the NORDLIS DE over Finland. However, there are some limitations and notions:

1. The model is not applicable for small networks (N less than about 5), or for too sparse networks where p is low due to long baselines rather than probabilistic reasons.

2. The model described in PAPER IV may not be usable for other networks as such. The exact left boundary in Fig. 3.3a may be different.

3. The lower peak current boundary, say strokes weaker than 3 kA, is problematic because the nature of the low amplitude strokes is questionable, i.e., many of them may not actually be ground strokes and the boundary remains vague. Also, the number of strokes in this boundary is significant, which brings a strong weight in calculating the overall DE.

4. The use of a single probability p for all sensors must be understood as an ”average” probability that a sensor detects an event. A test calculation suggests that this assumption is not critical in the model accuracy.

According to PAPER IV, the average DE over Finland varies between about 88.0% ... 99% (Fig. 3.3). The values may seem optimistic but actually they are in accordance with other studies (e.g. Idone et al., 1998; Jerauld et al., 2005); especially the fact that the DE for a highly sensitive network approaches 100% for flashes with peak currents above 10 kA. However, we agree that errors may arise due to the low-amplitude events.

3.3 DISCUSSION

The performance of a lightning location system involves a wealth of interesting topics to be investigated, because there are a lot of issues that are not well documented and known. We have shown here examples how the network performance may affect the lightning statistics; if the statistics are not correct, the thunderstorm climatology calculated from the statistics are also incorrect.

In several studies it has been noted that a lightning location system works extremely well for the majority of flashes. Problems occur for flashes which reside on the extreme ends of the lightning distribution. Besides errors rising from single peculiar flashes, problems may occur also because of abnormal thunderstorm episodes. For example, a thunderstorm may produce flashes with so high a flash rate that some of the sensors are saturated with signals, which may cause a temporary drop in the detection efficiency.

The efficiency of an LLS may be highly improved in the course of years. An example of this is shown in PAPER III. Lightning data over Finland in 2007 is reprocessed with two different central processor settings; those used in the 5-sensor network in 2000, and those used in 2007 during the NORDLIS cooperation (about 30 sensors). So, we "simulate" the year 2000 conditions by including only the five FMI sensors in the processing, and we compare regionally the flash counts to the "perfect" network. The result is shown in Fig. 3.4.

The following features are visible in Fig. 3.4:

1. The ratio is everywhere below 1.0,

2. The ratio is larger in the eastern parts, because the FMI sensors are the easternmost sensors in the NORDLIS network as well.

Fig. 3.4 is an example of *relative* detection efficiency; on average, the relative detection efficiency between a 5-sensor and the whole NORDLIS network was in this case about 73 %, with large regional variation. Now, if the *absolute* detection efficiency in 2007 would be known, we could estimate also the DE of the 5-sensor network.

We conclude, that although the performance of an LLS can be highly improved during the years, this may not actually be true, because the improvement in certain area may introduce a set of problems or unknown issues in other areas. A good example is the ground flash detection efficiency dilemma: the detection efficiency improves if the sensors are more sensitive, but sensitive sensors detect events whose true nature is not clear (i.e., they may be cloud discharges). This means in practice that the ground flash detection efficiency may be larger than 100%! It is clear that the correct classification is a key issue regarding the detection efficiency estimations. A satellite-based optical instrument, especially on geostationary orbit, provides very useful climatological information because the coverage area is large and the data quality is practically constant from year to year.

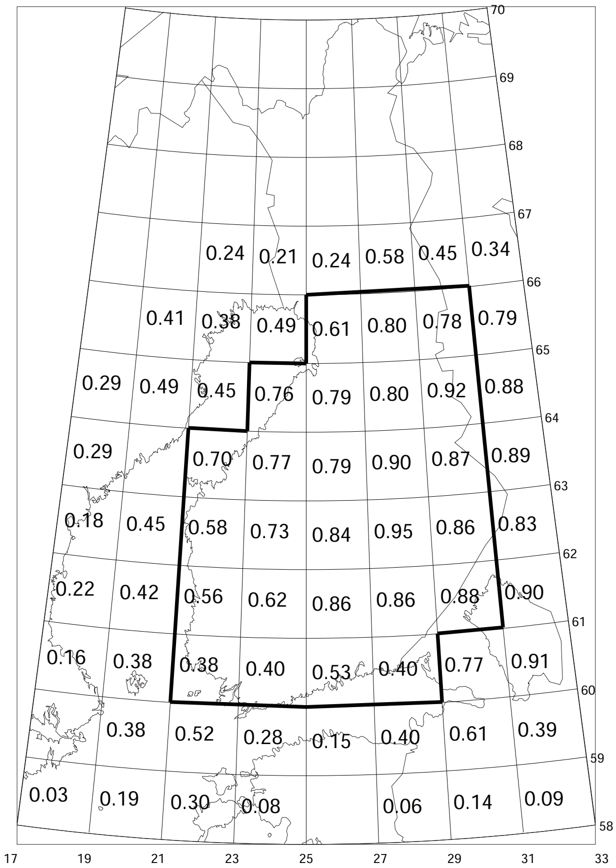

FIGURE 3.4. The ratio of located flashes, processed with two central processor configurations between a 5-sensor network and the NORDLIS network in 2007. The average ratio inside the thick line is 0.73. The ratio is calculated only for squares containg at least 100 flashes in the 5-sensor data. Adapted from PAPER III.

4 Lightning location in atmospheric science

The most common way to use lightning location data is to plot the located events on a map (see Fig. 1.1c). This kind of information can be used in many real time operations (operational meteorology, aviation, warning services, etc), while the stored historical data can be used in damage surveys and climatological studies.

Although plotting located events on a map is actually a very powerful tool for visualizing the motion of the thunderstorm areas, lightning data can also be transformed into several other products. The flash density product has already been mentioned in Chapter 1 (Fig. 1.3), which indicates how many events have been accumulated into a certain surface area during a certain time step and serves as an objective measure of thunderstorm intensity. Nowadays, a concept called *cell tracking* has made possible new approaches into the analysis of convective phenomena (Dixon and Weiner, 1993; Johnson et al., 1998; Morel et al., 2002).

4.1 Flash cells

One interesting method for the monitoring of thunderstorms is to study the occurrence of consecutive events in a specific thunderstorm, because the event rate is strongly linked to the electrical evolution of the storm, which on the other hand is linked to the dynamics and intensity of the convective system (see for example Finke, 1999). Figure 4.1a shows a conceptual model of how the consecutive ground flashes in a thunderstorm cell occur; the greatest ground flash density is typically connected with the heavy precipitation core. The same feature is apparent also in a real-case example in Fig. 4.1b, which shows the occurrence of ground flashes during the whole lifetime of a thunderstorm cell in Finland on July 24 2006; consecutive ground flashes (dots) are connected with line segments in temporal order. The storm movement has been approximately from northwest to southeast, and during its lifetime of almost three hours, the cell produced a total of 430 ground flashes. In the early and late stages of the evolution of the cell, the flash density and rate have been less intense than during the middle stage. In the flash rate histogram of Fig. 4.1c, there are two peaks visible, which indicates the most intense stages of the storm evolution.

The visualization of cells with flashes is not straightforward. Unlike weather radar images, where precipitation cores more clearly represent the convection cells, flash maps do not that clearly show distinguishable cores because flashes tend to occur erratically over the whole area of the cell, i.e., also outside its core. Hence, the sequence of flashes in Fig. 4.1b has been extracted from a larger flash-data set with a *flash-cell method* described in Paper V; its purpose is to *identify* individual flash cells in the data and follow their motion, flash rate etc.

The main point in Fig. 4.1 is that the visualization of individual flashes is not necessary, and sometimes not even helpful, to give information about the cell movement.

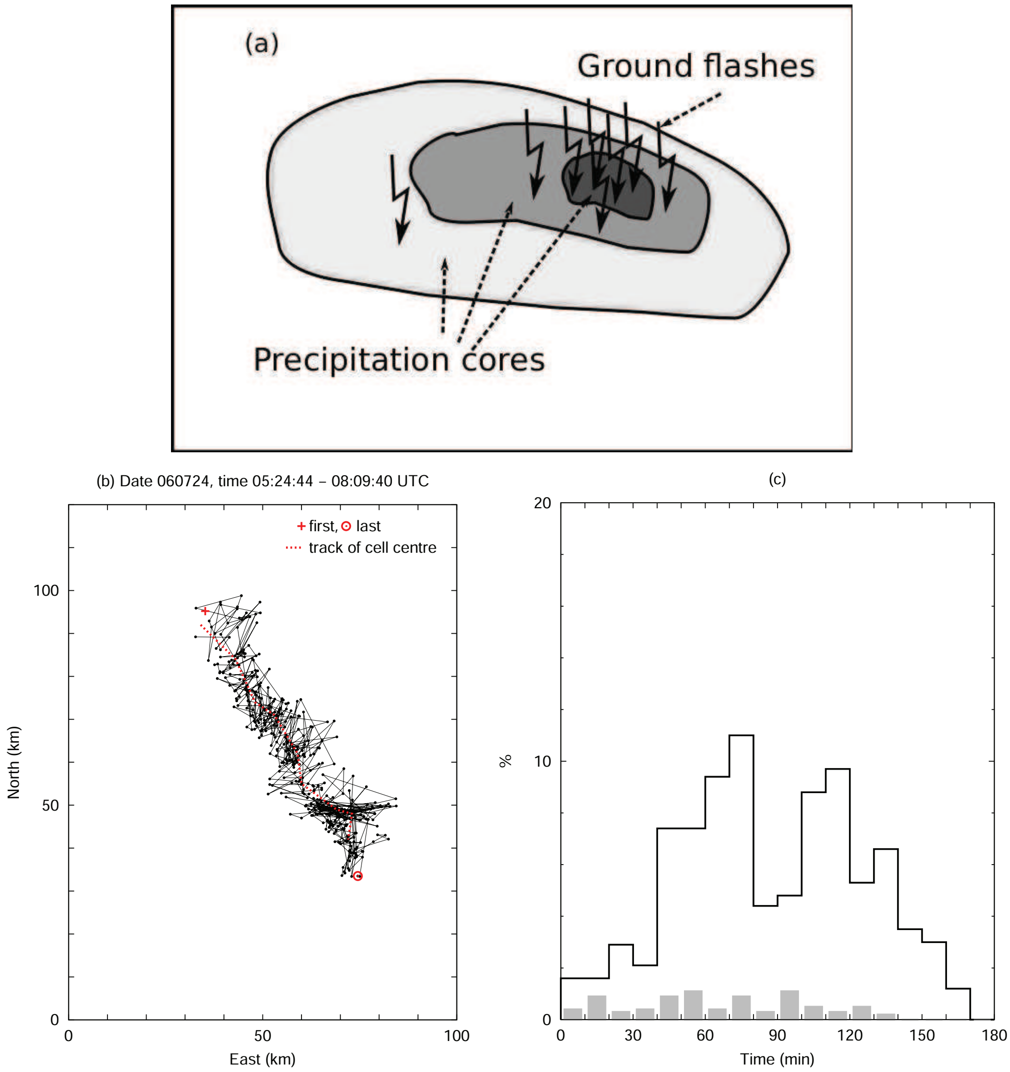

FIGURE 4.1. (a) Conceptual model of a thunderstorm cell; most of the ground flashes occur near the heavy precipitation core. (b) Located 430 ground flashes (black filled circles) during the life cycle of a thunderstorm on July 24 2006. Temporally successive flashes are connected with lines; the first and last flash in the cell are marked with red plus-sign and circle, respectively. The location of the cell centre (dashed line) is calculated as the running mean position of the 20 most recent flashes. (c) The distribution of negative (white) and positive (gray) ground flashes per 10 minutes in the thunderstorm cell shown in (b). Figures (b) and (c) are based on PAPER V.

The flash-cell method calculates the instantaneous cell-centre position as the average of the 20 most recent flashes in the cell. The path of the cell centre is the dashed line in Fig. 4.1b.

The principle of the flash-cell method is the following.

(1) All flashes of the episode in question are associated with flash cells. The cells are

formed with repeated application of these rules.

(2) The time and position of a new located flash is compared to all existing (open) cells: if the new flash is close enough in time ($< T$, e.g. 15 min) and space ($< R$, e.g. 15 km) to an existing cell, it is attached to it; if not, the flash opens a new cell. If more than one cell meets the conditions, the flash is attached to the spatially closest one.

(3) The present position (centre) of each cell is calculated as the average position of the 20 most recent flashes of the cell (or all flashes if there are less than 20 flashes in the cell),

(4) The present lifetime of each cell is the time difference between the first and the latest flash of the cell; if there are no flashes attached to a cell within a time limit (T) from the latest flash, the cell will be closed and the latest flash remains the last one.

(5) Steps (2)-(4) are repeated every time a flash is located.

The calculated moving cell-centre points may be plotted on a map, either alone or over the background of the actual flashes.

The flash-cell method is one example how lightning location data can be arranged into weather objects which, instead of including the whole set of individual flash data, have statistical or ”macroscopic” features such as lifetime, flash rate and density, speed and direction of motion. This has been found to be helpful in operational applications. Figure 4.2 is an example. Instead of seeing a random-looking growing cluster of flashes, an operational forecaster sees in real time the flash cells represented by their centres and recognizes their motion; in other words, lightning data has been filtered in a way that the end user gets only the most relevant information. Also, in the near future it will be possible to attach to the object all kinds of data which have accurate temporal and spatial information. For example, Rossi et al. (2010) have included real time emergency response center data regarding weather related emergency calls (flash floods, large hail, fallen trees etc).

4.2 Thunderstorm intensity

The intensity of thunderstorm is an intriguing term. In the media, terms such as ”devastating”, ”violent”, ”severe”, ”exceptional” etc. are often used. In these cases, the intensity classification is based on eyewitness reports or solely on the dramaturgy of the reporter. In the spoken language the intensity of a thunderstorm can be expressed in many ways, because it is actually a subjective matter; a person not fond of severe weather likely classifies a storm as ”severe” easier than, for example, a storm chaser does.

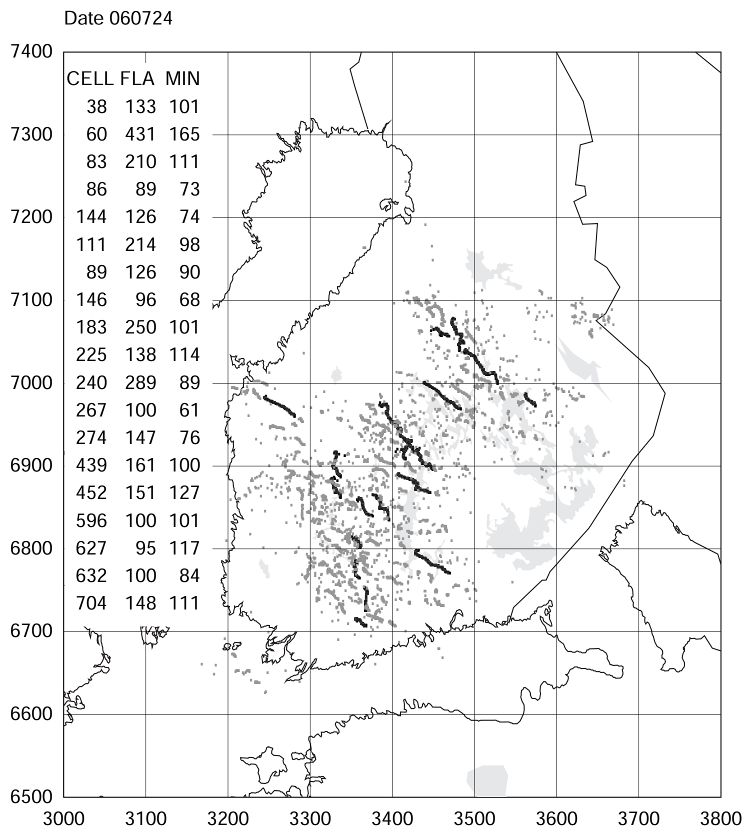

FIGURE 4.2. Lightning location data arranged as flash cells on July 24 2006. Black lines are the cell centres of the largest cells listed at the left; gray colours show the centres of the rest of the cells. Based on PAPER V.

In meteorology, many phenomena can be classifed into certain intensity classes according to their objective properties. For instance, wind speed can be classified with the Beaufort scale, which is based on the effects of the wind to the environment. Tornadoes are classified according to their caused damages and wind speeds with the Fujita scale (or Enhanced Fujita Scale) or TORRO scale (e.g., Doswell et al., 2009).

All the above mentioned scales are based on damages or measured physical properties (say, wind speed). Another possibility to classify weather phenomena is to study the *frequency of occurrence* or the *rarity* of a certain parameter. The basis is statistical rather than physical although the parameters themselves (e.g., flashes) may be measured physically. For this, a *distribution* is an objective concept for this purpose. Fig. 4.3 shows an example of a normally distributed random parameter. The mean value is zero, and the minimum and maximum values are -3 and 3, respectively. Fig. 4.3 shows that there is at most a 5 % probability that the parameter values are less than -2 or greater than 2, and the cumulative distribution (right) in Fig. 4.3 indicates that 15 % of the values are less than -1, and 85 % of the values are less than 1. By choosing

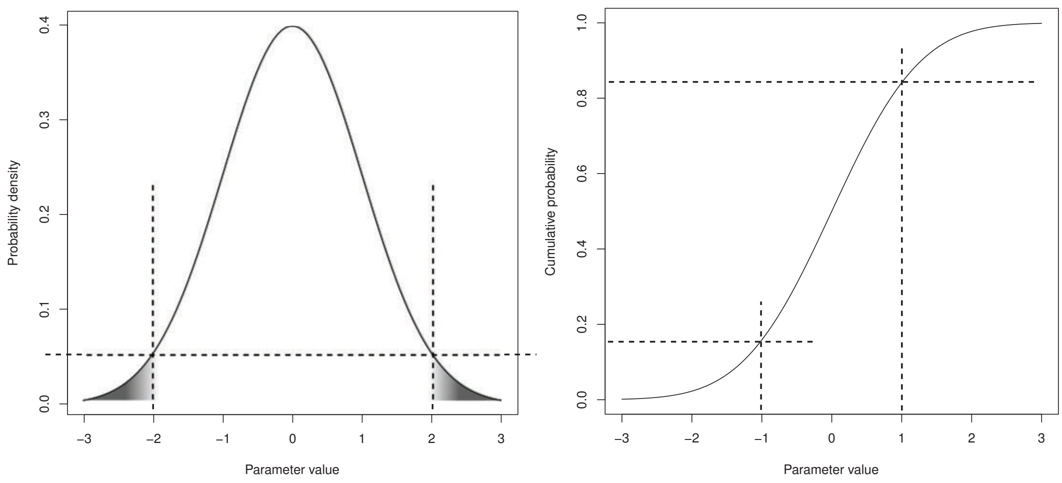

FIGURE 4.3. Example of a probability density distribution (left) and cumulative probability distribution (right) for a normally distributed random parameter.

certain percentiles from the distribution, we can justifiably say that a certain parameter value is statistically more exceptional than some other value. We can use this approach also to thunderstorms and especially to flash density.

The distribution of daily ground flash density values in the United States and Finland are shown already in Fig. 2.3a, which illustrates how the daily accumulation of ground flashes varies in different regions. The main conclusions from Fig. 2.3a are:

(1) The median (50 percentile) value is very similar in all regions; 0.01 ... 0.03 ground flashes per square kilometre per thunderstorm day (i.e., a typical thunderstorm day in all regions is ”moderate”),

(2) Variation is large for the smaller percentiles (i.e., for the more intense and rare thunderstorm days); the first percentile values are 0.23 ... 1.27 ground flashes per square kilometre per thunderstorm day.

Point (1) means that the most common type of thunderstorm day in all studied regions is ”moderate” in terms of ground flash density, and point (2) indicates that a very large variation is present in the most extreme values. Point (2) also means that a rare daily ground flash density value in Finland (say, the first percentile in Fig. 2.3a) is not as rare, for example, in the Central parts of the United States because this value is exceeded in about 20% of thunderstorm days. An interesting notion is that the daily ground flash density in Florida is smaller than in the Central United States, although the annual accumulation of ground flashes is larger in Florida. This suggests that the most violent thunderstorms, measured with the number of located ground flashes, in the United States occur specifically in the central parts of United States. The values in Finland are similar to those in the western part of the United States. The regional first percentile values in the United States and Finland are shown in Fig. 4.4.

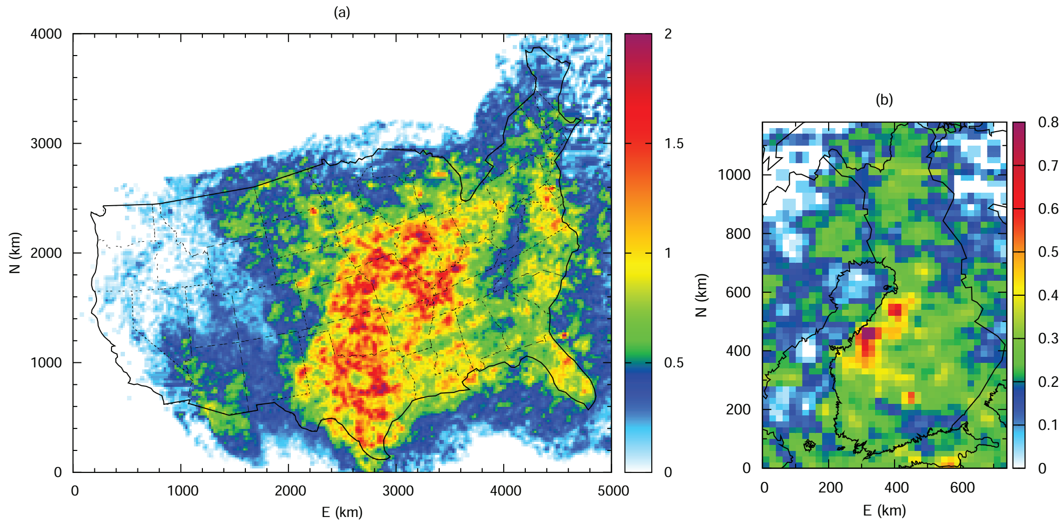

FIGURE 4.4. The first percentile daily ground flash density values from Fig. 2.3a for the United States and Finland. Note the different color scales. The unit is ground flashes per square kilometre per thunderstorm day. Based on PAPER II.

4.3 OTHER APPLICATIONS

4.3.1 Transient Luminous Events

Besides operational and climatological purposes, lightning location data can be used for many case-specific purposes such as insurance and authority investigations. There are more exotic, scientifically interesting phenomena that are the consequence of lightning. For example, it has been found that some lightning flashes produce high-energy radiation (gamma and X-rays) and even bursts of antimatter. Although a lightning location system does not detect these phenomena, it does detect the parent flash causing them. Therefore, lightning location data can be used, for example, for analyzing what are the properties of flashes causing these phenomena. A well-known class is called Transient Luminous Events (TLE).

Transient Luminous Events are induced by thunderstorms. TLE's occur in different shapes and colours; *sprites* are red, carrot-like phenomena, extending downwards from mesosphere; *elves* are circle-like, occurring in the lower ionosphere; *blue jets* and *gigantic blue jets* are flash-like plumes, extending from the top of the thundercloud up to an altitude of about 50-80 km. For more detailed information about TLE's, see for example Boccippio et al., 1995; Fukunishi et al., 1996; Chern et al., 2003; Pasko, 2007; Chen et al., 2008.

TLE's are quite recent phenomena in the thunderstorm research; the first observations were made in 1989 (Franz et al., 1990). Since then, TLE's have been routinely observed all over the world where thunderstorms occur. TLE's are not electric break-

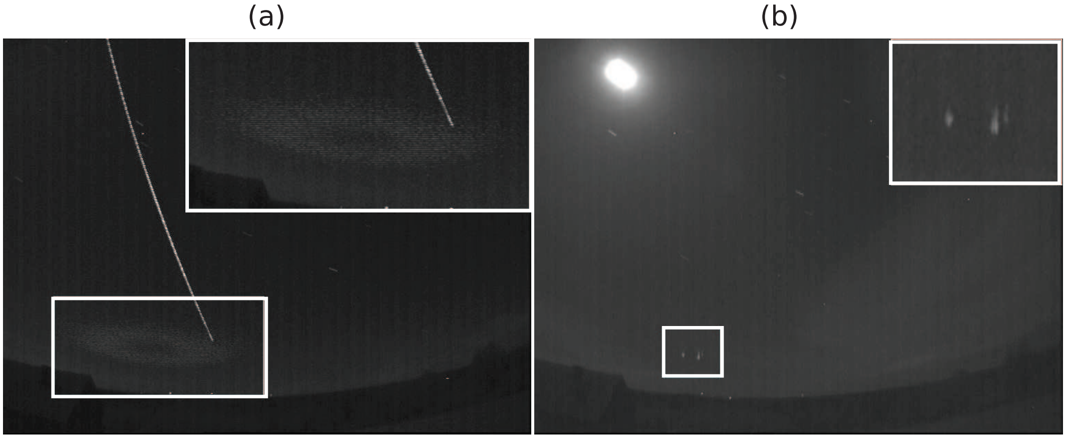

FIGURE 4.5. (a) Elves, and (b) sprite observed by Timo Kantola near Finland on October 9 2009. The rectangles are zoomed in the upper right corner. Based on PAPER VI.

downs such as ground and cloud flashes, rather they are the consequence of a sudden and intense electric field change in the thunderstorm caused by a ground flash. The field change accelerates the free electrons of the upper atmosphere, making them collide with atmospheric molecules. The collision causes changes in the excitation states of the molecules, which in favourable conditions leads to observable emissions of radiation in the wavelengths of visible light. The colour-producing mechanisms are similar to those of aurora.

Because TLEs are faint phenomena, their observation usually requires sensitive camera and dark background. Therefore, at high latitudes, such as Finland, their detection is more difficult than at lower latitudes, because during the high thunderstorm season (summer) even the night is relatively bright (e.g., the stars are not visible). The best conditions for observations are in late summer or in autumn, when the evening and night become dark enough and extensive thunderstorms may still occur.

The conditions were suitable on October 9th, 2009, when an amateur Finnish photographer, Timo Kantola, captured the first TLE's near Finland (Fig. 4.5). Interestingly, the observations were the highest-latitude observations of this kind in the world. (In 2010 there were new observations in Finland at even higher latitudes). The observations were the first proof that TLE's indeed occur also at high latitudes and their observation is possible on routine basis.

4.3.2 Lightning strikes to trees

It is suspected that a very common strike target for a ground flash is a tree, especially in regions with plenty of lightning and trees. Hence for example in Finland, which is an extremely forested country, there should be enormous numbers of lightning-struck trees. However, very little is known about the effects and role of lightning to trees.

Anecdotal evidence suggests that actually finding a lightning-struck tree is a rare case. Only when the strike hits a tree situated near populated area and causes perceptible damage, it may be discovered; however, it is suspected in PAPER VII that most often the flash causes no visible damage at all.

PAPER VII is based on a data set of a total of 37 lightning-struck trees. The motivation of the paper is to show the variety of damage types for different tree species, and the dependence of the damages on the properties of soil, environment and lightning. PAPER VII is one of the most detailed studies made in this field. Also in this study, the lightning location system has an important role because it reveals the properties of the strokes in question.

The data set is collected in two ways; browsing forested areas according to lightning location data, and browsing lightning location data according to reported lightning struck trees (Fig. 4.6). Some cases could be checked with extremely high detail (as that in Fig. 4.6), but for most of the cases only a rough information was available. Although neither of the collection methods are perfect, the following conclusions can be made from the study:

(1) If the surface of the tree and the soil is wet, the tree is less likely to be severely damaged,

(2) The degree of the damage does not seem to depend on the tree species,

(3) Explosive damage is more likely for a not-healthy tree,

(4) the struck tree is not always the highest in the neighbourhood,

(5) High peak current strokes cause more severe damage,

(6) High multiplicity does not indicate more severe damage.

Due to the scarce data set, the results are, of course, only suggestive. The tree study raised also some questions which could be important regarding lightning protection. For example, if a tree is located near a protected target, should the risk calculations be changed because the tree may affect the lightning attachment process? Tree data has been collected routinely at FMI since 2009, so the study results may be updated with a larger data set in the near future.

4.4 DISCUSSION

We can conclude that a lightning location system (LLS) may give important background information in many fields. The primary purpose of an LLS is to pinpoint, preferably in real time, where thunderstorms are occurring at the moment and how intense the storms are. Historical data can be analyzed to produce lightning climatologies, but provides useful information for other fields as well. The study of upper-atmospheric phenomena,

FIGURE 4.6. A lightning flash to a tree (European aspen, *Populus tremula*) in Finland (in the city of Porvoo). The distance from the camera was 50 m. According to lightning location data, the flash was single-stroke with peak current -6 kA (i.e., weak or moderate). No visible damage was observed to the tree, not even later that summer. Heavy precipitation was observed before and after the flash, indicating the tree and soil to be wet. Note how the flash is attracted by the tree only just very close to the ground. Based on PAPER VII. Photograph: Niklas Montonen.

such as TLEs, and the inspection of lightning-struck trees are some interesting topics which have not yet been extensively studied and deserve further attention in the future, especially at high latitudes.

5 Summary and concluding remarks

Convective clouds are formed when energy is transported upwards by convection in an unstable troposphere. If enough energy is available and the state of the atmosphere allows rapid vertical motions, the evolving cumulonimbus cloud reaches the dimension of a thundercloud. The electrification of the cloud is due to the collision of cloud particles (graupel and ice crystals) in the cloud air filled with super-cooled water. When enough charge has accumulated into the cloud, it is neutralized in the form of lightning, as cloud and ground flashes.

Although the formation mechanisms of thunderstorms are basically similar all over the world, the intensity and frequency of occurrence are highly variable globally. In certain climates, thunderstorms occur almost daily, while for example in Finland the season for thunderstorms is practically limited to summer (May–September; Paper I). Therefore, globally there are large climatological differences in the number of thunderstorm days and number of occurred flashes per year. However, the total number of flashes per year in a certain climate does not clearly indicate the intensity of individual thunderstorms because the same annual accumulation of flashes can be the result of ”modest” and longer thunderstorm season, or of ”intense” and shorter season.

The amount of lightning in a single thunderstorm may vary from one flash to thousands of flashes per storm. A distribution of the daily number of flashes is one way to characterize the variation of individual thunderstorm days between different regions. The comparison of the cumulative distributions of the daily ground flash density in the United States and in Finland suggests that the typical thunderstorm day in all regions is modest; however, the largest daily ground flash density value in Finland is not at all uncommon in Florida or the central parts of the United States (Paper II).

The thunderstorm climatology of a region can be measured with a lightning location system (LLS). The working principle of an LLS is to detect individual lightning events (e.g., a ground flash) and determine its strike point. The LLS is usually composed of several sensors which detect the lightning signal, and a central processing unit, which calculates the lightning location according to the time and bearing information received from the sensors. The LLS may also be based on a single sensor, for example in an optic imager on a satellite.

As a physical instrument, an LLS is always imperfect due to both technical reasons and the randomness of the discharge process. The statistics of the measured lightning parameters, such as number of located events, peak current and multiplicity, vary from year to year, but it is difficult to know which variations are caused by technical and which by natural reasons (Paper III). The detection efficiency is an important parameter regarding lightning location, because it indicates how large portion of the actually occurred events the system detects. The parameter is difficult to estimate, but fortunately some methods do exist. Because to locate and not to locate an event can actually be viewed as a binomial probability, DE can be estimated, for example, with a so called binomial model (Paper IV).

The most common way to visualize lightning location data is to show the located events on a map, but the data may also be filtered to highlight certain features. For example, a flash-cell algorithm (Paper V) organizes lightning location data into flash cells, whose counterparts are the high-reflectivity precipitation cores in weather radar data. Each flash cell has its own individual properties, such as age, flash rate, direction of motion etc. The motion of flash-cell centres can be monitored in real time, and their visualization gives a more representative picture of the convective situation than a typical raw lightning map does.

Besides lightning flashes to ground and air, thunderstorms also induce other phenomena. Transient Luminous Events (TLE) are thunderstorm-related phenomena occurring from the top of the thundercloud (an altitude of about 10 km) up to the ionosphere (about 100 km). A typical lightning location system does not detect the TLE, but it does detect the parent flash causing the TLE. Therefore, lightning location data can be used to pinpoint the probable location of TLE and provide information of the parent flash causing it (e.g., peak current; Paper VI).

When lightning hits the ground, it may cause damages. Because there are plenty of trees on the surface of the Earth, especially where most of the global thunderstorms occur (e.g., in the rainforests in Africa and South America), and trees are tall objects, a tree is a very common strike target. However, how different tree species react to lightning and how the lightning parameters affect the type of the damage is not a well-studied subject. In the studies made in Finland (Paper VII) it has been found, for example, that precipitation before and during the hit causes a protective effect to the tree; the wet tree surface conducts the lightning current efficiently to ground and it is possible that the tree does not experience any damage. Also, the higher is the peak current, the more likely is a severe damage to the tree. Besides the biological examination, the tree data can be used to estimate the location accuracy of the LLS, because the exact strike point is known.

This thesis has summarized the use of lightning location data in climatology, operational meteorology and in some other fields, as well as the question of the quality of the data itself. It is suspected that in the future the methods presented in this paper are further processed to provide even more sophisticated algorithms and methods. As the stream of meteorological data is growing all the time, it is clear that various automatic expert systems are needed to filter and analyze the data to produce simple self-explanatory end-products especially for the nowcasting of severe weather events. Despite the fact that thunderstorm research has been continuously active for several hundreds of years, the phenomenon still contains many unsolved questions. A lightning location system, whether on ground or in space, is one of the most important tools for finding the answers.

References

Anderson, R. B., Kroninger, H., Niekerk, H.R., and Meal, D.W., 1984: Development and field evaluation of a lightning earth-flash counter. *IEE Proc.*, **131 A**, 118–124.

Baker, M.B., and J.G. Dash, 1994: Mechanism of charge transfer between colliding ice particles in thunderstorms. *J. Geophys. Res.*, **99**, 10621–10626.

Bénard, H., 1901: Les Tourbillons Cellulaires dans une Nappe Liquide Transportant de la Chaleur par Convection en Régime Permanent. *Annales a Chimie et de Physique*, Paris 7 Série, Tome XXIII, 62–144.

Berger, G., and Amar, S.A, 2009: The noteworthy involvement of Jacques de Romas in the experiments on the electric nature of lightning. *J. Electrostatics*, **67**, 531-535.

Betz, H.-D., Schmidt, K., Fuchs, B., Oettinger, W.P., Höller, H., 2007: Cloud lightning: detection and utilization for total lightning measured in the VLF/LF regime. *J. Lightning Res.*, **2**, 1–17.

Black, R.A., and J.Hallet, 1998: The mystery of cloud electrification. *American Scientist*, **86**, 526–534.

Boccippio, D.J., Williams, E.R., Lyons, W.A., Baker, I., and Boldi, R., 1995: Sprites, ELF transients and positive ground strokes. *Science*, **269**, 1088–1091.

Byers, H.R., Braham, R.R., 1949: The Thunderstorm. US Government Printing Office, Washington 25, DC, USA, 287 p.

Chen, A.B., Kuo, C.L., Lee, Y.J., Su, H.T., Hsu, R.R., Chern, J.L., Frey, H.U., Mende, S.B., Takahashi, Y., Fukunishi, H., Chang, Y.S., Liu, T.Y., and Lee, L.C., 2008: Global distributions and occurrence rates of transient luminous events. *J. Geophys. Res.*, **113**, A08306, doi:10.1029/2008JA013101.

Chern, J.L., Hsu, R.R., Su, H.T., Mende, S.B., Fukunishi, H., Takahashi, Y., and Lee, L.C., 2003: Global survey of upper atmospheric transient luminous events on the ROCSAT-2 satellite. *J. Atmos. Sol. Terr. Phys.*, **65**, 647–659, doi:10.1016/S1364-6826(02)00317-6.

Christian, H. J., R. J. Blakeslee, and S. J. Goodman, 1989: The detection of lightning from geostationary orbit. *J. Geophys. Res.*, **94**, 13 329–13 337.

–, Blakeslee, R.J., Boccippio, D.J., Boeck, W.L., Buechler, D.E., Driscoll, K.T., Goodman, S.J., Hall, J.M., Koshak, W.J., Mach, D.M., and Stewart, M.F., 2003: Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *J. Geophys. Res.*, **108**, doi:10.1029/2002JD002347.

Cummins, K.L., Murphy, M.J., Bardo, E.A., Hiscox, W.L., Pyle, R.B., Pifer, A.E., 1998: A combined TOA/MDF technology upgrade of the US National Lightning Detection Network. *J. Geophys. Res.*, **103**, 9035–9044.

Cummins, K.L., and Murphy, M.J., 2009: An overview of lightning locating systems: history, techniques, and data uses, with an in-depth look at the U.S. NLDN. *IEEE Trans. Atmos. Elec.*, **51**, 499-518.

Dixon, M.J., and Weiner, G., 1993: TITAN: Thunderstorm Identification, Tracking, Analysis, and Nowcasting – A radar-based methodology. *J. Atmos. Oceanic Technol.*, **10**, 785–797.

Doswell, C.A. III, 2001: *Severe Convective Storms*. Meteor. Monogr., **28**, Am. Met. Soc., 561 p.

Doswell, C.A. III, Brooks, H.E., and Dotzek, N., 2009: On the implementation of the enhanced Fujita scale in the USA. *Atmos. Res.*, **93**, 554-563. 4th European Conference on Severe Storms.

Finke, U., 1999: Space-time correlations of lightning distributions. *Mon. Wea. Rev.*, **127**, 1850–1861.

–, 2009: Optical detection of lightning from space. In *Lightning: Principles, Instruments and Applications*, Springer, 271–286.

Fleagle, R. G., 1949: The audibility of thunder. J. Acoust. Soc. Amer., 21, 411–412.

Franz, R.C., Nemzek, R.J., and Winckler, J.R., 1990: Television Image of a Large Upward Electrical Discharge Above a Thunderstorm System. *Science*, **249**, 48-51, doi:10.1126/science.249.4964.48.

Fukunishi, H., Takahashi, Y., Kubota, M., Sakanoi, K., Inan, U.S., and Lyons, W.A., 1996: Elves: Lightning-induced transient luminous events in the lower ionosphere. *Geophys. Res. Lett.*, **23**, 2157–2160.

Halmevaara, K., Rossi, P., Mäkelä, A., Koistinen, J., and Hasu, V., 2010: Supplementing convective objects with national emergency report data. *The Sixth European Conference on Radar in Meteorology and Hydrology*, Sibiu, Romania, 6 p.

Hamberg, H.E., 1915: Askdagarnes frekvens i Sverige 1730-1915 / Fréquence des Jours d'Orage en Suéde 1730-1915. *Appendice I aux Observations Météorologiques Suédoises*, **57**, 174 p.

Heino, R., 1994: Climate in Finland during the period of meteorological observations. *Finnish Meteorological Institute Contributions*, **12**, 209 p.

Holton, J.R., 1992: *An introduction to dynamical meteorology.* Academic Press, California, USA, 511 p.

Idone, V. P., Davis, D.A., Moore, P.K., Wang, Y., Henderson, R.W., Ries, M., and Jamason, P.F., 1998: Performance evaluation of the U.S. National Lightning Detection Network in eastern New York. Part II: Location accuracy. *J. Geophys. Res.*, **103**, 9045–9056, doi:10.1029/98JD00155.

Jerauld, J., Rakov, V.A., Uman, M.A., Rambo, K.J., Jordan, D.M., Cummins, K.L., and Cramer, J.A., 2005: An evaluation of the performance characteristics of the U.S. National Lightning Detection Network in Florida using rocket-triggered lightning. *J. Geophys. Res.*, **110**, D19106, doi:10.1029/2005JD005924.

Johnson, J.T., MacKeen, P.L., Witt, A., Mitchell, E.D., Stumpf, G.J., Eilts, M.D., and Thomas, K.W., 1998: The Storm Cell Identification and Tracking Algorithm: An enhanced WSR-88D algorithm. *Wea. Forecasting*, **13**, 263–276.

Krider, E. P., 2006: Benjamin Franklin and lightning rods. *Physics Today*, **59**, 42–48.

Krider, E. P., Noggle, R.C., and Uman, M.A., 1976: A Gated, Wideband Magnetic Direction Finder for Lightning Return Strokes. *J. Appl. Meteor.*, **15**, 301–306.

–, Noggle, R. C., Pifer, A. E., and Vance, D. L., 1980: Lightning Direction-Finding Systems for Forest Fire Detection. *Bull. Amer. Meteor. Soc.*, **61**, 980–986.

Kuleshov, Y., and E. R. Jayaratne, 2004: Estimates of lightning ground flash density in Australia and its relationship to thunderdays. *Aust. Meteor. Mag.*, **53**, 189–196.

Lee, A.C.L., 1986: An experimental study of the remote location of lightning flashes using a VLF arrival time difference technique. *QJRMS*, **112**, 203-229.

Lewis, E.A., Harvey, R.B., and Rasmussen, J.E., 1960: Hyperbolic direction finding with sferics of transatlantic origin. *J. Geophys. Res.*, **65**, 1879-1905.

MacGorman, D.R. and W.D. Rust, 1998: *The Electrical Nature of Storms*. Oxford University Press, 422 p.

MacGorman, D., Apostolakopoulos, I., Nierow, A., Murphy, M.J., Demetriades, N., Cramer, J., and Krehbiel, P., 2006: Improved timeliness of thunderstorm detection from mapping larger fraction of lightning flashes. *2nd Conf. on Meteorological Appl. of Lightning Data*, Atlanta, USA, 7 p.

Mackerras, D., and Darveniza, M., 1994: Latitudinal variation of lightning occurrence characteristics. *J. Geophys. Res.*, **99**, 10813–10821.

Mackerras, D., Darveniza, M., Orville, R.E., Williams, E.R., and Goodman, S.J., 1998: Global lightning: total, cloud and ground flash estimates. *J. Geophys. Res.*, **103**, 19791–19810.

Moore, C.B., Vonnegut, B., and Holden, D.N., 1989: Anomalous electric fields associated with clouds growing over a source of negative space charge. *J. Geophys. Res.*, **94**, 13127–13134.

Morel, C., Sénési, S., Autones, F., and Labatut, L., 2000: The Rapid Developing Thunderstorms (RDT) product of the nowcasting SAF. Prototyping activities and quality assessment using GOES images. *Proceedings of the 2000 Meteorological Satellite Data Users' Conference*, Eumetsat and CNR, Bologna, Italy, 698–705.

Norinder, H., 1953: Long distance location of thunderstorms. In *Thunderstorm Electricity*, ed. by H.R. Byers, Univ. of Chicago Press.

Orville, R.E., and Spencer, D.W., 1979: Global lightning flash frequency. *Mon. Wea. Rev.*, **107**, 934–943.

Orville, R.E., and Huffines, G.R., 1999: Lightning ground flash measurements over the contiguous United States: 1995–1997. *Mon. Wea. Rev.*, **127**, 2693–2703.

Orville, R.E., and Huffines, G.R., 2001: Cloud-to-ground lightning in the United States: NLDN results in the first decade. *Mon. Wea. Rev.*, **129**, 1179–1193.

Pasko, V.P., 2007: Red sprite discharges in the atmosphere at high altitude: the molecular physics and the similarity with laboratory discharges. *Plasma Sources Sci. Technol.*, **16**, S13–S29.

Pinto, I.R.C.A., and Pinto, O. Jr., 2003: Cloud-to-ground lightning distribution in Brazil. *J. Atmos. Solar-Terrestrial Phys.*, **65**, 733-737.

Popov, A.S., 1896: Instrument for detection and registration of electrical fluctuations. *Journal of Russian Physics and Chemistry Society XXVIII*, **1**, 1-14.

Prentice, S.A., 1972: CIGRE lightning flash counter. *Electra*, **22**, 149–171.

Rakov, V.A., and Uman, M.A., 2003: *Lightning Physics and Effects*. Cambridge University Press, 850 p.

Reynolds, S.E., Brook, M., and Gourley, M.F., 1957: Thunderstorm charge separation. *J. Meteorol.*, **12**, 426–436.

Richard, P., Delannoy, A., and Laroche, P., 1986: Results of spatial and temporal characterization of the VHF-UHF radiation of lightning. *J. Geophys. Res.*, **91**, 1248-1260.

Rodger, C. J., S. Werner, J. B. Brundell, E. H. Lay, N. R. Thomson, R. H. Holzworth, and R. L. Dowden, 2006: Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): Initial case study. *Ann. Geophys.*, **24**, 3197–3214.

Said, R.K., Inan, U.S, and Cummins, K.L., 2010: Long-range lightning geolocation using a VLF radio atmospheric waveform bank. *J. Geophys. Res.*, **115**, D23108, doi:10.1029/2010JD013863.

Saunders, C.P.R., 2008: Charge separation mechanisms in clouds. *Sp. Sci. Rev.*, **137**, 335–353.

Schulz, W., Cummins, K., Diendorfer, G., and Dorninger, M., 2005: Cloud-to-ground lightning in Austria: A 10-year study using data from a lightning location system. *J. Geophys. Res.*, **110**, D09101, doi:10.1029/2004JD005332.

Soriano, L. R., de Pablo, F., and Tomas, C., 2005: Ten-year study of cloud-to-ground lightning activity in the Iberian Peninsula. *J. Atmos. Solar-Terrestrial Phys.*, **67**, 1632–1639.

Stolzenburg, M., and Marshall, T.C., 2008: Charge structure and dynamics in thunderstorms. *Sp. Sci. Rev.*, **137**, 355–372.

Stuhlmann, R., A. Rodriguez, S. Tjemkes, J. Grandell, A. Arriaga, J. Bezý, D. Aminou, and P. Bensi, 2005: Plans for EUMETSAT's Third Generation Meteosat geostationary satellite programme. Adv. Space Res., **36**, 975–981.

Takahashi, T., 1978: Riming electrification as a charge generation mechanism in thunderstorms. *J. Atmos. Sci.*, **35**, 1536–1548.

Thomas, R.J., Krehbiel, P.R., Rison, W., Hamlin, T., Harlin, J., and Shown, D., 2001: Observations of VHF source powers radiated by lightning. *Geophys. Res. Lett.*, **28**, 143-146.

Tuomi, T. J., and Mäkelä, A., 2003: Synoptic classification of thunderstorms in Finland. *Geophysica*, **39**, 3–30.

Watson-Watt, R.A., and Herd, J.F., 1926: An instantaneous direct-reading goniometer. *Journal of the Institution of Electrical Engineers*, **64**, 611-622.

Williams, E.R., 1989: The tripole structure of thunderstorms. *J. Geophys. Res.*, **94**, 13151–13167.

Williams, E.R., R. Zhang ja J. Rydock, 1999: Mixed phase microphysics and cloud electrification. *J. Atmos. Sci.*, **48**, 2195–2203.

Williams, E. R., Boldi, B., Matlin, A., Weber, M., Hodanish, S., Sharp, D., Goodman, S., Raghavan, R., and Buechler D., 1999: The behavior of total lightning activity in severe Florida thunderstorms. *Atmospheric Research*, **51**, 245–265.

WMO Publication 21, 1956.

Zipser, E. J., D. J. Cecil, C. Liu, S. W. Nesbitt, and D. P. Yorty, 2006: Where are the most intense thunderstorms on Earth? *Bull. Amer. Meteor. Soc.*, **87**, 1057–1071.