

## Synoptic Classification of Thunderstorms in Finland

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### *Abstract*

*Thunderstorm systems in Finland in 1998-2002 are classified into different types according to the synoptic-scale weather analysed on surface weather maps. A thunderstorm system is defined to include all individual thunderstorms within the country associated with the same surface synoptic factor, e.g. a front proceeding across the country. The factors are the cold front, warm front, occluded front and stationary front (with thunderstorm development nearly along the frontal line); and warm air mass, cold or polar air mass, and the pre-cold-frontal squall line. In addition, a distinction is made between air masses from the western sector, directly influenced by the Atlantic Ocean, and those from the eastern sector, having a more continental nature. Heavy- or moderate-thunderstorm systems occur mostly in the warm air mass and the cold front, and are also relatively frequent in the stationary front and the pre-cold-frontal squall line. Air-mass thunderstorms are more frequent than frontal storms, especially in the latter half of the warmest season, July-August. Thunderstorms, both frontal and air-mass, are most often associated with the western, Atlantic air mass, but a higher percentage of flashes is associated with the eastern, continental air mass. The thunderstorm-climatic variability between years can be characterized not only by the thunder days and flash density, but also by the nature of the air mass and the frontal activity.*

*Key words: synoptic weather, thunderstorm, Finland, lightning location, climate, air mass*

### *1. Introduction*

Finland is one of the most northern European countries, situated between 60 and 70 degrees latitude. During the summer season, typically May-September, there are roughly 100 days with lightning occurring within the country, and a few days exceeding 10 000 ground flashes. The mean thunder day number, i.e. the annual number of days with thunder or lightning reported by a local human observer, is about 12. The mean annual number of flashes is well over 100 000 and the mean flash density is about 0.4 per km<sup>2</sup>. A series of yearbooks, *Lightning Observations in Finland*, is published since 1984 (e.g. *Tuomi*, 2002). The lightning observations since 1998 are based on a so-called Impact lightning location system (*Cummins et al.*, 1998), which locates ground strokes

and groups them into ground flashes. In Finland, the mean number of strokes per flash (the multiplicity of a flash) is slightly below 2. Although the multiplicity varies with the violence of a thunderstorm, only the flash is used here as the counting unit of lightning.

The geographical position of Finland is peculiar not only by its far-northern situation but also by the differences in its neighbouring regions. In the west, and particularly in the south-west, the influence of the Atlantic Ocean is evident, supported by the Baltic sea and its two arms around Finland (the Gulf of Bothnia to the north and the Gulf of Finland to the east; see Fig. 1a). In the south, south-east and east, there is a direct connection to the eastern European and western Asian continental climate, where the Balkan - Black Sea region is an important cradle of thundery weather.

Generally, the weather in Finland is strongly influenced by the location of the polar jet and the associated polar frontal zone, which usually traverses from west to east, or from south-west to north-east. *Rumney* (1968) presents maps of the mean global distribution of air masses, and the summer case (Fig. 5.3, not reproduced here) shows the American-Atlantic polar front reaching Central Europe from the west, and the shorter SW-NE directed East-European polar front from Balkan to central Russia. Accordingly, the air mass in Finland in summer is maritime polar on the average. Sometimes the frontal zone takes a more northern route, and continental air mass dominates in southern or even in northern Finland. The front may also take a long turn through southern and south-eastern Europe and approach Finland from the south or south-east, bringing an air mass with continental tropical properties. The typical summer afternoon temperature in Finland is 15-25 degrees Celsius, and a temperature exceeding 25 degrees is termed "hot". The temperature rarely rises above 30 degrees. Hot periods, often with increased moisture, are normally associated with the warm air mass coming from the south or south-east.

Although the air masses in Finland – polar or mid-latitude – lie behind the climate records, e.g. the spatial distribution of temperature, published statistics of the occurrences of different air masses are extremely scarce. A quotation from *Kolkk* (1969) states: "Finland belongs to the frontier between polar cold and southern warm air masses, associated with frequent cyclonic activity. The path of the cyclones is most usually directed from the south-west to the north-east... In summer, airflows from the (Eurasian) continent give rise to the hottest periods." We will demonstrate that such a change in the nature of air mass is reflected in the occurrence and intensity of thunderstorms in Finland. Before the modern age of automatic weather and lightning observation methods, there were a few attempts to classify and characterize thunderstorms in Finland. Over a century ago, *Sundell* (1887) stated: "We distinguish two kinds of thunderstorms, cyclonic storms (i.e. frontal) and warm-mass storms ... Most of those observed in Finland in 1887 seem to be of the warm-mass type." *Oksanen* (1921a) studied the thunderstorms of the first years of the 1900's and found that the surface wind before an approaching thunderstorm was most often southerly or south-westerly. *Oksanen* (1921b, 1940) studied also the arrival directions of thunderstorms and obtained the same dominating directions. We quote the latter results in Section 7 and make a comparison with the present data in Table 4. For Helsinki alone, *Oksanen*

(1948) summarized wind and thunderstorm-arrival directions for 1887-1947. The most frequent arrival direction was W (20 %), followed by SW (17 %). Due to its situation on the south coast, Helsinki does not represent well the whole country. *Harjama* (1955) examined thunderstorms in southern Finland in 1949-1953 and concluded that 62 % of the thunder days were associated with air-mass storms and 38 % with frontal storms. He also distinguished four different types of air-mass storms according to how the instability of the troposphere is involved.

The early studies cited above are examples of the ways how thunderstorms may be classified: with a network of fixed observation sites, the direction of arrival may be recorded; an observed thunderstorm may also be related with the prevailing air mass or a passing front. The existence of such studies reflects the interest in the relation between the geographical position of Finland, mentioned above, and the occurrence of thunderstorms. We will continue the classification, using more modern instruments and methods, focusing on the overall situation over the country and also considering the intensity of thunderstorms (as measured by the amount of lightning). In addition to the lightning location data, we will utilize ready-analyzed weather information in its most widely used form: the synoptic surface weather maps. The surface synoptic factors important for thunderstorms are fronts, air masses and surface troughs. For this reason, we use the term "synoptic classification" in the title to distinguish from other possible methods of classification. Although tropospheric instability is an important factor for the occurrence of thunderstorms, for example in forecasting, we do not consider it in this study. The occurrence of a thunderstorm is itself a token that an instability threshold has been exceeded. This study should give a statistical basis for questions about where thunderstorms come from, are there more frontal than air-mass storms, what kind of thunderstorms are most violent, etc. And, how things vary from year to year. Each country has its own thunderstorm climate, and this study is an attempt to characterize the Finnish thunderstorms with a small number of synoptic-scale parameters.

Surface synoptic classification was already used to some extent by *Byers and Braham* (1949), who conducted a set of detailed case studies of thunderstorms including e.g. weather and electric-field soundings and weather radar data. Their thunderstorm classification was based on air masses, fronts and squall lines, but was limited to case studies during one year. A recent book, *MacGorman and Rust* (1998), continues similar studies with more modern methods, but is clearly concentrated on the electrical properties with less emphasis on the synoptic condition. *Kane et al.* (1987) characterized precipitation in mesoscale convective systems (MCS) by dividing the weather in four categories related to frontal activity; no sounding data was used. *Houze et al.* (1990) classified mesoscale convective complexes (MCC, a large elliptical form of MCS) according to their organisation of heavy rain, revealed by radar, as well as to weather sounding data. *Geerts* (1998) classified MCS cases solely on the basis of radar data, identifying the times of initiation and dissipation of rain, the organization (linear or nonlinear) and motion of high-reflectivity cells. Paths of travel were identified but not related to frontal activity. A similar study was made in Finland by *Punkka* (2002) for years 2000 and 2001. In both years, June was unusually quiet, but in July, strong

convective systems approached mainly from the south-east or south. In August, more systems came from the south-west or west over the relatively warm Gulf of Bothnia. These features should also be seen in the thunderstorms. The occurrence of ground lightning in MCC has been studied e.g. by *Goodman and MacGorman* (1986). In their 10 cases, the average duration is about 14 hours and the maximum flash rate is about 3 000 flashes/hour.

The present study is a kind of complement to the more traditional form of thunderstorm climatology, that based on flash density. A typical example is provided by *Huffines and Orville* (1999), who have calculated flash densities in a grid of about 18 km x 22 km over the USA. Thunderstorm duration is described in terms of so-called flash hours (analogous to thunder days) for each grid element. That kind of climatology emphasizes the geographical distribution of thunderstorms within the country, as well as their durations experienced by local observers.

In the present study, cloud-electrical data are not available. The basic data set consists of the located ground flashes, with daily maps used for the preliminary selection of cases. The synoptic weather is deduced from regular daily 12 UTC North-European maps as well as from UKMO (United Kingdom Meteorological Office) 00 UTC European maps. Local time in Finland in summer is UTC + 3 h. Weather radar data are not analysed but used only indirectly to help relating thunderstorm systems with fronts etc. Satellite images (NOAA visible) are used in a similar way. The terminology used here is explained first (Section 2), then the problem is illustrated by a few examples (Section 3). The statistics will be presented in several ways: thunderstorms related to (synoptic) surface-weather conditions (Section 4); thunderstorms related to the nature of the surface air mass (Section 5); and monthly occurrences of the thunderstorm types (Section 6). In Section 7, local arrival directions of thunderstorms are compared with the early data. Finally, the beginning and end times of thunderstorm systems are described (Section 8). The period includes five years 1998-2002, because Impact, radar and satellite data, as well as UKMO maps, are regularly available since 1998.

## 2. Terminology

As noted in the Introduction, the location of the polar front is the most important synoptic factor in the Finnish weather. The mean direction of approach of the surface frontal zone is from the west or south-west, but other directions also occur. The left side (usually the northern side) of the zone contains polar air mass, and the right side contains mid-latitude air mass. When a point in the front starts to bend into a cusp, the heading section of the front becomes a warm front and the trailing section a cold front. The movement of the fronts near a well-developed cusp is relatively fast and transverse, "front-like", with a clear warm-air sector between. With the development of the cyclonic low, the cold front merges with the warm front into an occluded front, which lies in the polar-mass side. Each of these three types of fronts gives rise to thunderstorms, the most effective being the cold front.

A section of the polar front far from, or long before, a developing low is relatively straight, meandering only slightly without a sharp cusp. It may have alternating cold-front and warm-front sections that move nearly longitudinally (along the direction of the frontal zone) with very slow transverse motion. It is called a stationary (or quasi-stationary) front, without distinguishing between the cold-front and warm-front sections even though the former may be more efficient in producing thunderstorms. Storm development is almost parallel with, rather than perpendicular to, the frontal line. Physically, the stationary-front cases might be included in the cold-front cases, and sometimes it may be difficult to tell the difference. Anyway, the distinction is made here, but the cases may be merged if desired.

Air-mass thunderstorms may have a number of causes. Here the classification is limited to situations which can be normally identified on a surface weather map. Warm-mass storms occur often in the warm sector between the fronts, but may also be more independent of the frontal zone. Cold-mass storms or polar thunderstorms occur in the polar air mass and are usually less active. A special class of air-mass thunderstorms is what will be called here squall-line storms. Generally, squall lines may occur in fronts or in non-frontal areas, but we restrict the term here to a special type of non-frontal cases. The point is that intense air-mass thunderstorms may show front-like behaviour while being clearly separated from frontal zones. Often they turn out to be associated with surface trough lines shown on the 00 UTC UKMO maps (unfortunately, not shown on the North-European 12 UTC maps). All trough lines do not produce thunderstorms. The trough lines lie often in the warm air mass and are nearly parallel to the cold front, and the associated thunderstorms are evidently what *Byers and Braham* (1948) call pre-cold-frontal squall lines. For short, we use just the term squall line.

As mentioned in the Introduction, early studies often presented the relative frequencies of thunderstorm arrival directions; the eight main and intermediate points of compass were used (cf. Section 7). However, the local direction of passage of a thunderstorm does not necessarily represent well the synoptic situation. In many cases, the motion of individual thunderstorm cells deviates about  $45^\circ$  to the left from the storm system development; sometimes the system development may dominate the apparent arrival direction. There is also a particular type of situation which we consider important for relating thunderstorms with air masses and their directions of approach. A good example occurred on July 15-19, 2001 (part of this situation is shown in Fig. 8). There was a nearly south-north-directed stationary front over the Baltic Sea, and 200-400 km east of it in the warm air mass, a parallel surface trough line in the Baltic countries, slowly moving to the north towards Finland. In satellite images, a stratified cloud zone showed the position of the front while separate large convective clouds formed along the trough line. The warm air mass extended at least to the Balkan – Black Sea region. Associated with the trough line, violent squall-line thunderstorms occurred in southern and eastern Finland. The direction of approach of the clouds was the south and the air mass was mid-latitude continental, prevailing in the south and south-east relative to Finland. However, after entering Finland, the systems developed towards the north-east, i.e. their local arrival direction was SW rather than S.

This suggests that instead of the local direction of arrival, thunderstorms may be associated with the air mass by looking at the whole synoptic situation. Then however, it is not useful to divide the directions into the eight points of compass but a broader classification may serve the purpose. Based on practical experience, with no published statistics available, the direction of the Baltic Sea seen from Finland, i.e. a direction between SW and S, appears to be a dividing line between the continental mid-latitude air mass and the western polar air mass, at least in thunderstorm situations in summer. In the north, the division is more diffuse due to the rarity of the cases, but it may be set symmetrically between N and NE. Accordingly, whenever a thunderstorm occurs in Finland, the history of the air mass or front is traced back, typically less than 24 hours, using surface synoptic maps and satellite and radar images. If a thunderstorm occurs within, or comes with, an air mass or front from the 180° sector SW-N, we call it a western-type (W) thunderstorm. Polar air mass in summer comes often from the western sector, and hence many of the polar thunderstorms are of this type. Correspondingly, the thunderstorms associated with the eastern, more continental sector NE-S are called eastern (E).

To distinguish between a single thunderstorm (single-cell or multicell) and a case studied here, the latter is also called a "thunderstorm system", analogous to a convective system. All thunderstorm cells, either separate or in a multicell formation, caused by the same synoptic factor within the country, are included in the same thunderstorm system.

### 3. *Examples*

One illustrative example of each surface-synoptic category is given in this section. The dates are denoted in the form year-month-day. On the first title row of each lightning location map, the date is YYMMDD and the time is UTC; the second title row gives the number of located strokes (as shown on the map) and the corresponding number of flashes (the location system has an algorithm for grouping the observed strokes into flashes). The fronts and trough lines shown on the lightning location maps are adapted from the available weather maps and reproduced approximately as combinations of straight line segments. It is understood that the surface-frontal line is not necessarily the accurate location of most active convection. The satellite images are from NOAA visible-light data received at the Finnish Meteorological Institute.

Cold front: 2002-07-12

A typical approach of a cold front from the south-west. The convective clouds (Fig. 1b) at 11:20 UTC formed an arc along the front, except for a small cloud ahead in the north. The cloudiness in the farthest north is associated with a warm front. In Fig. 1a, the fronts are depicted at 12 UTC, and most of the lightning on the map (12 622 strokes, representing 6 867 flashes) occurred between 9 and 20 UTC. The individual thunderstorm cells moved almost perpendicularly to the cold front, i.e. followed its motion, but existed simultaneously along the frontal zone, as did the precipitation cells

seen by the radar (not shown). In the southern part of Finland, the temperature was 29 degrees Celsius before the cold front and 22 degrees after it.

TIME 020712 00:00 - 020713 00:00 UTC  
ON THE MAP 12622 STROKES ( 6867 FLASHES)

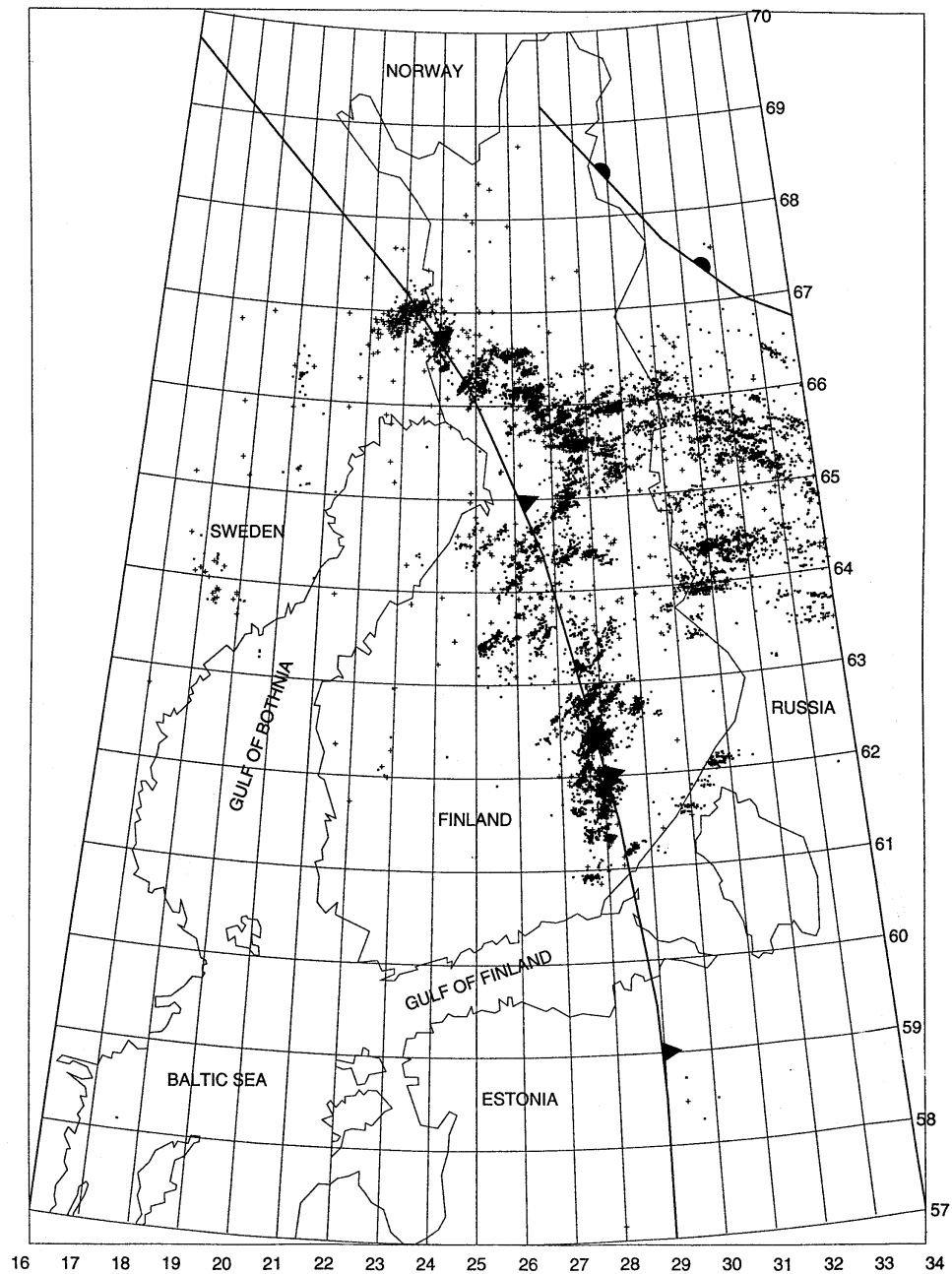


Fig. 1a. Located strokes on 2002-07-12, including some geographic names. The fronts at 12 UTC.

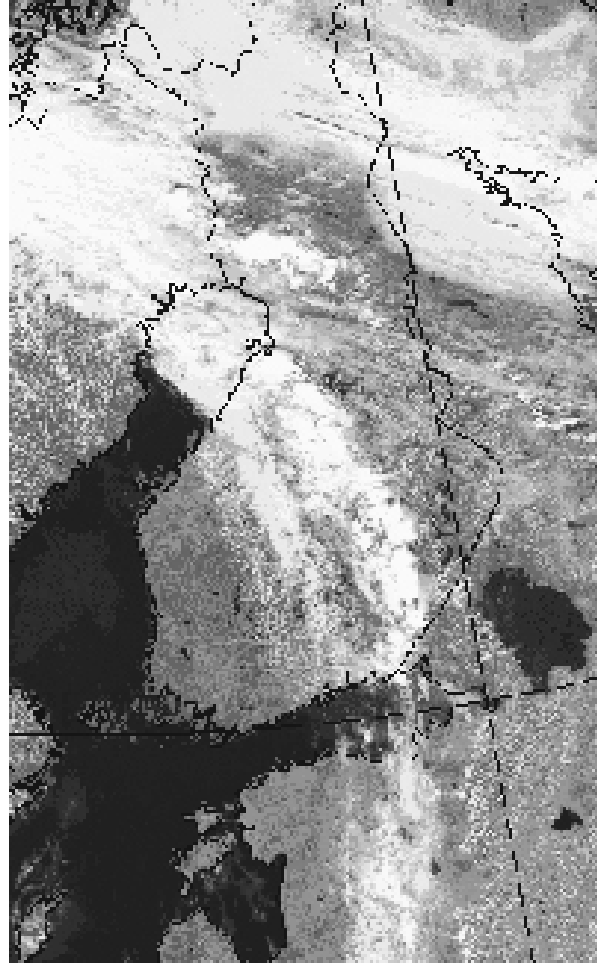


Fig. 1b. NOAA satellite visible image on 2002-07-12 at 11:20 UTC.

#### Warm front: 1999-07-06

Warm-front thunderstorms are relatively rare. For this case, no good satellite images were available, but the frontal system development is clear. In Fig. 2, there are several narrow trails of lightning over the southern half of Finland (and some in Estonia and Russia, ignored in the analysis). The 12 UTC frontal system formed a right angle between the warm and cold fronts and proceeded to the north-east. Even allowing possible inaccuracy in the location of the fronts, temporal analysis suggests that the northernmost trail (9-15 UTC) matches with the warm front and two trails in the central group (12-20 UTC) match with the cold front. The rest of the central group as well as the southernmost trails (2-12 UTC) belong to the warm sector. There were 7 700 flashes within Finland with 1 300 in the warm front, 2 500 in the cold front and 3 900 in the warm sector (the numbers given in the map are lower; in 1998 and 1999, the detection efficiency was lower, and corrected numbers are used in the statistics). This is an unusual example where a uniform-looking situation consists of three synoptically different thunderstorm systems. The temperature was 26-27 degrees in the warm sector and 16-18 degrees outside.



TIME 990706 00:00 - 990707 00:00 UTC  
ON THE MAP 33100 STROKES ( 18217 FLASHES)

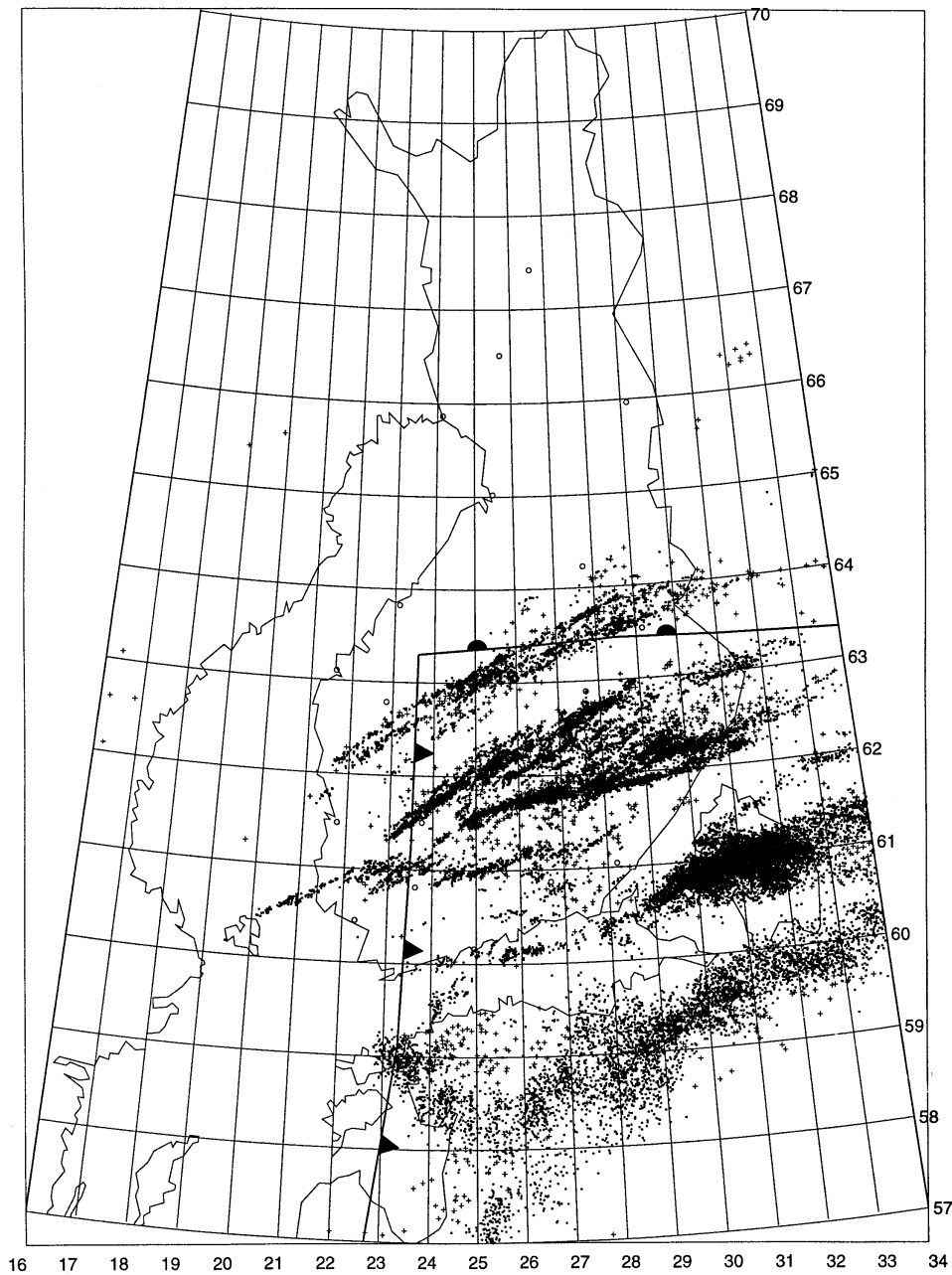


Fig. 2. Located strokes on 1999-07-06. The fronts at 12 UTC.

#### Occluded front: 2002-07-23

Like the warm front, the occluded front rarely gives rise to violent thunderstorms. Fig. 3 shows a relatively high-activity exception where lightning trails were proceeding to the north along with the frontal movement. The occluded front at 12 UTC was associated with a curved cloud pattern (not shown) where the thunderclouds and located

lightning matched well with the position of the front. The temperature was about 19 degrees at both sides of the front.

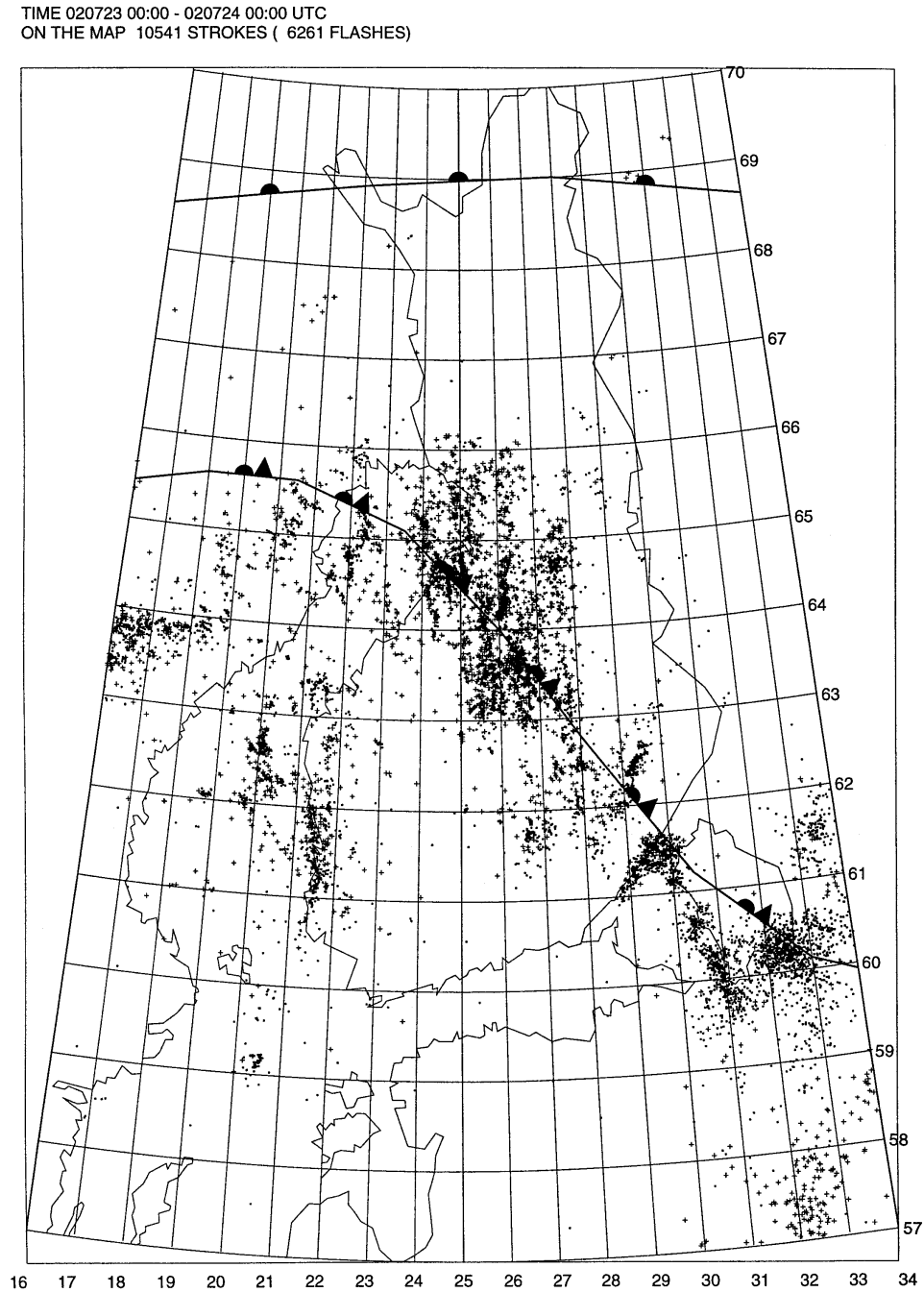


Fig. 3. Located strokes on 2002-07-23. The fronts at 12 UTC.

## Stationary front: 2000-06-28..29

This thunderstorm system was caused by an MCS, seen as a massive cloud of 300 km diameter. The last satellite image of that day (Fig. 4a) shows it just entering the south-eastern border of Finland at 17:01 UTC. A closer comparison shows that both lightning and heavy rain formed a front-like pattern of cells at the leading edge of the cloud. As seen in Fig. 4b, during the evening, night and morning the system proceeded to the north-west with a speed of 60 km/h. At 24 UTC, the flash front had bent into an L shape, with one arm to the south and the other to the east. The former arm perfectly matched with the front, which had a warm section at that point. The activity declined soon after the UTC midnight. The afternoon temperature was 20 degrees. The number of flashes within Finland was 12 000.

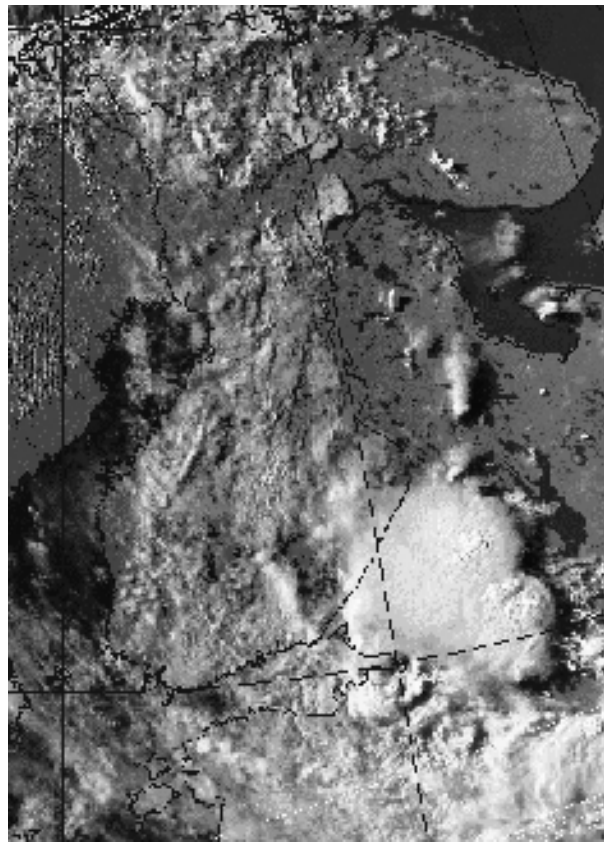


Fig. 4a. NOAA satellite visible image on 2000-06-28 at 17:01 UTC.

TIME 000628 00:00 - 000629 08:00 UTC  
ON THE MAP 40580 STROKES ( 17468 FLASHES)

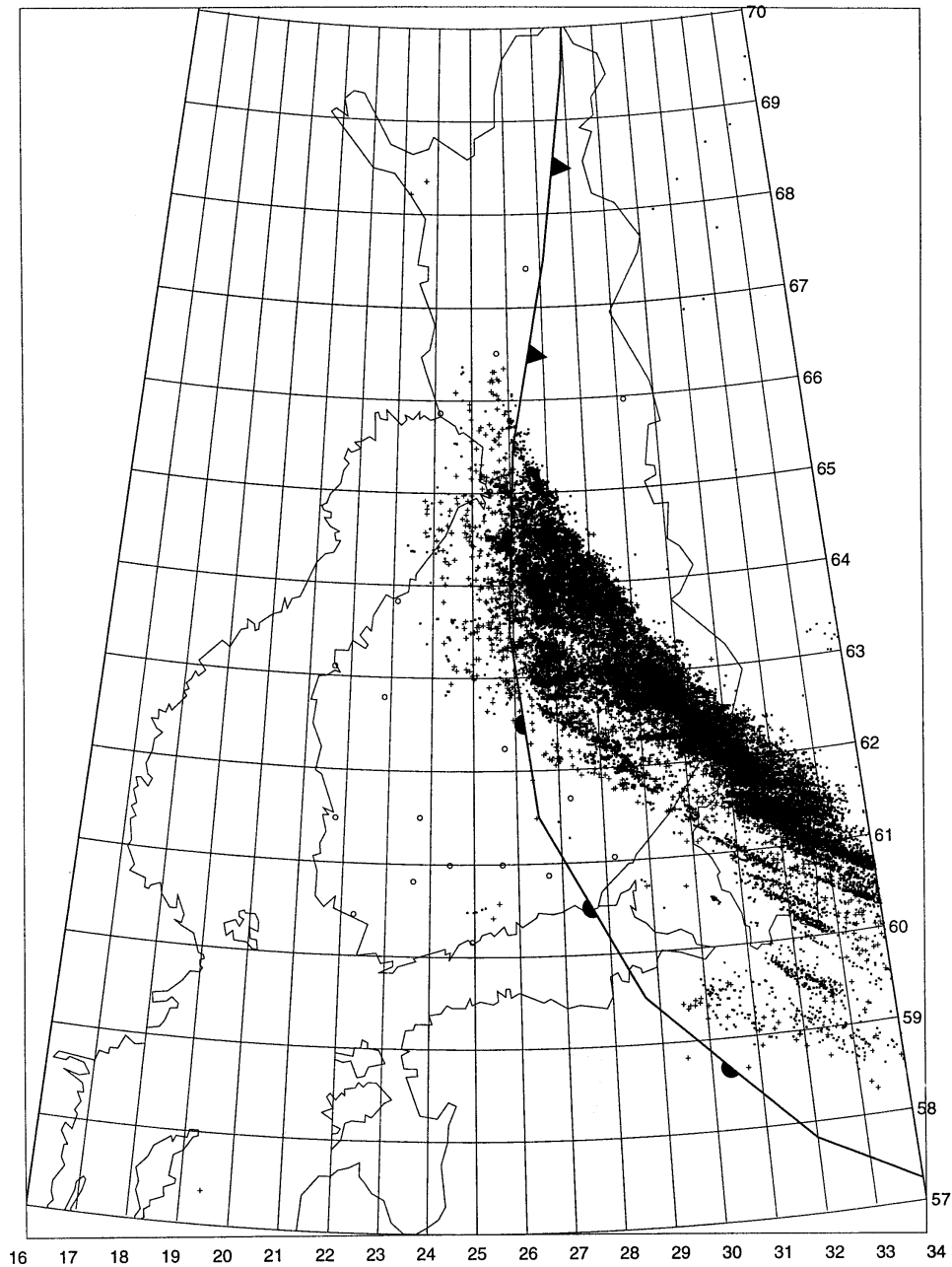


Fig. 4b. Located strokes on 2000-06-28, continuing to the next day 08 UTC. The front at 24 UTC (2000-06-29 00 UTC).

Polar: 2002-06-29

In Fig. 5a, at 12:03 UTC, there is a collection of thunderclouds over most of Finland with stratified cloud over Sweden. The latter was associated with an occluded front, well separated from the thunderstorm region in Finland. The front at 12 UTC and

the located lightning (6-18 UTC in Finland) are shown in Fig. 5b. This was a western-type polar-thunderstorm case, and the surface temperature was 12-17 degrees.

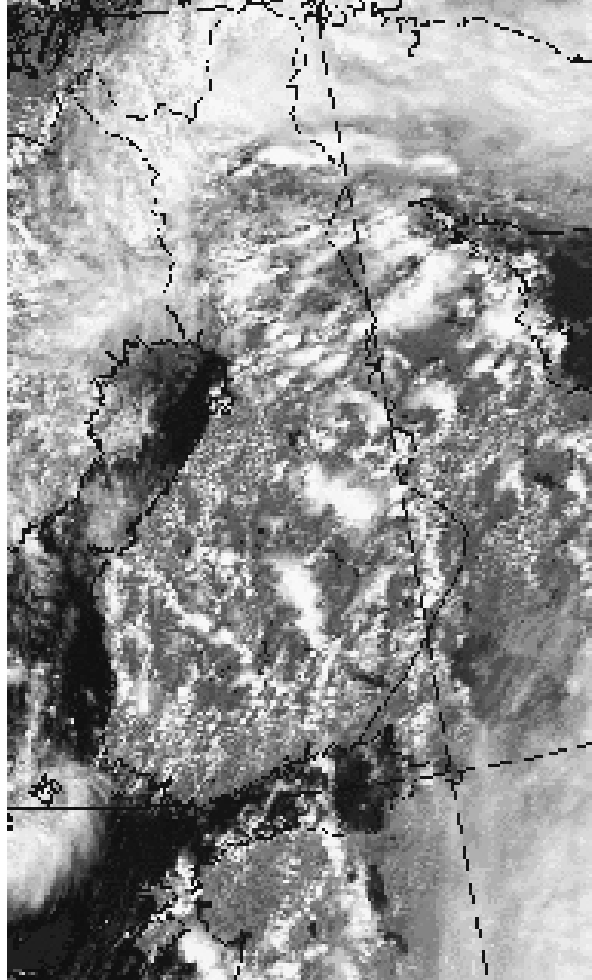


Fig. 5a. NOAA satellite visible image on 2002-06-29 at 12:03 UTC.

TIME 020629 00:00 - 020630 00:00 UTC  
 ON THE MAP 5138 STROKES ( 3761 FLASHES)

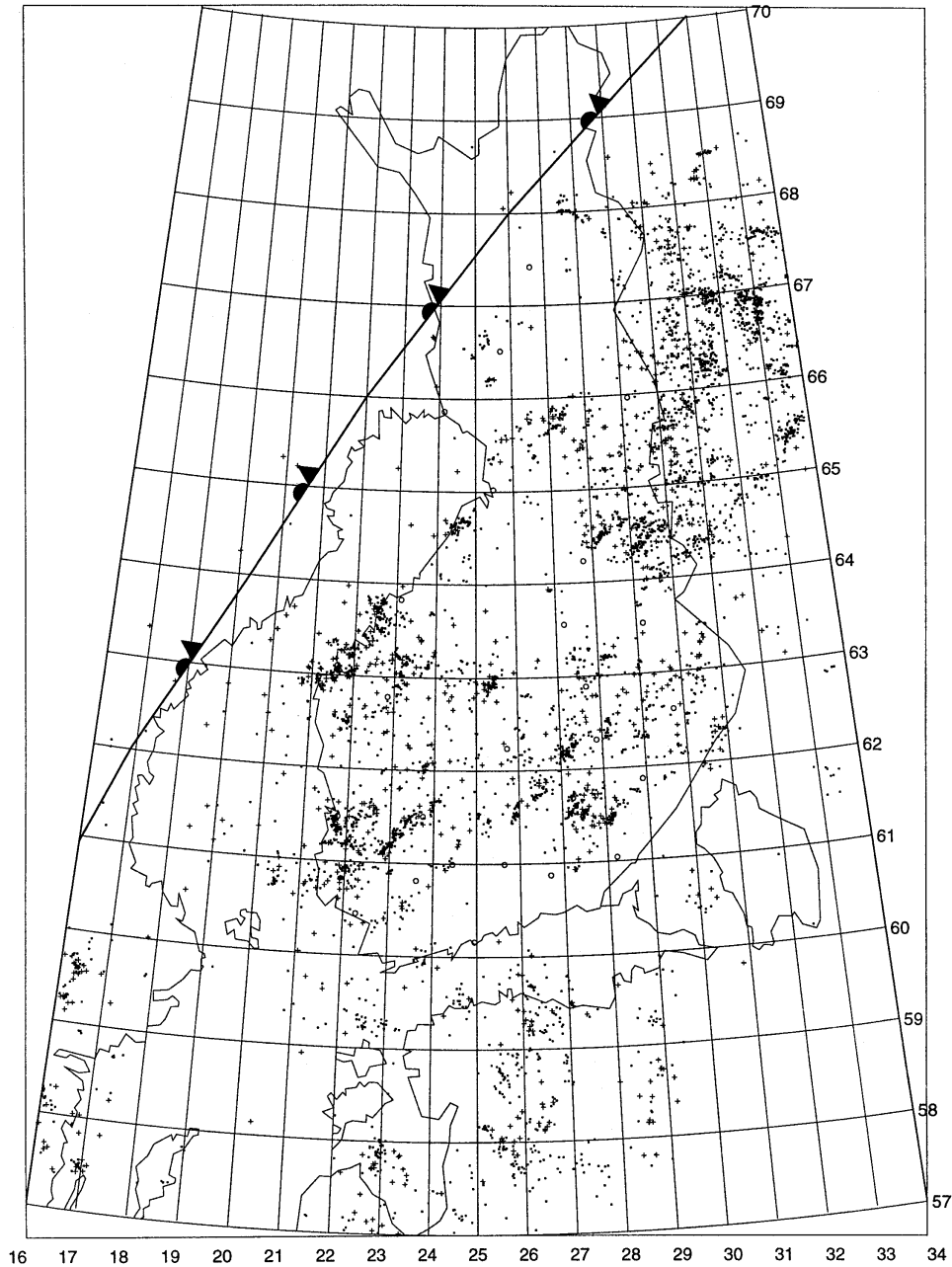


Fig. 5b. Located strokes on 2002-06-29. The front at 12 UTC.

#### Warm mass: 1998-07-09

The ten-day period 1 to 10 July 1998 had an unusually persistent type of weather. For seven of the ten days, small local afternoon (8-20 UTC in Fig. 6a) thunderstorms developed over western Finland, producing 1 400-4 600 daily flashes. Also the sea-breeze effect, a 20-km wide cloud-free zone on the coast, was very clear. The afternoon

temperature was 21-23 degrees. In spite of the daily appearance and disappearance of the local clouds and the absence of cell movement (or a slight movement to the north-east), the cloud anvils showed a tendency to be stretched to the north-west. For this particular day (Fig. 6b, at 12:09 UTC), thin upper cloudiness suggests an eastern nature of the air mass, although the slow motion of the surface air makes the notion rather vague in this case. The cloud anvil pattern is not apparent in the lightning location map.

TIME 980709 00:00 - 980710 00:00 UTC  
ON THE MAP 4059 STROKES ( 2739 FLASHES)

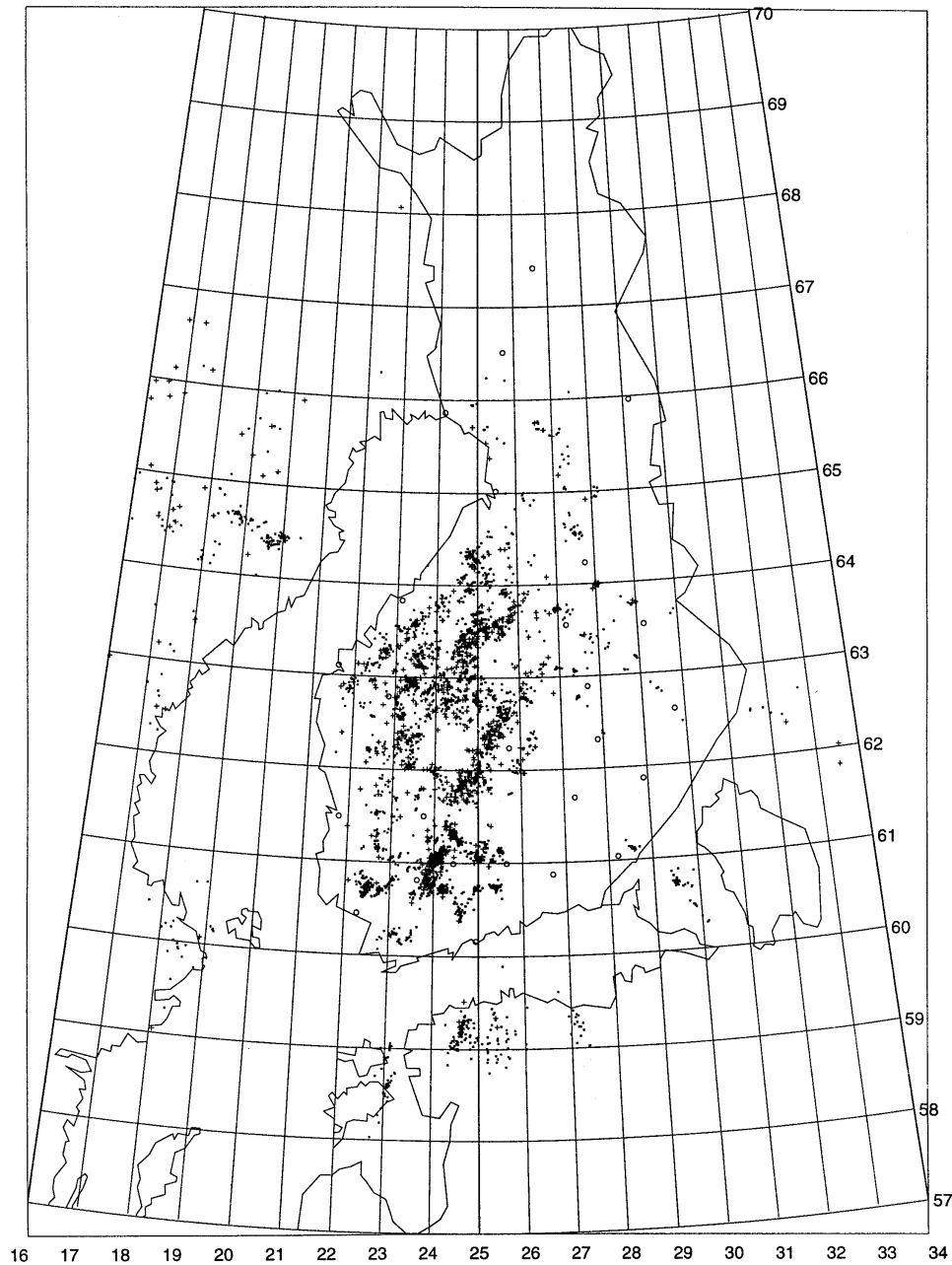


Fig. 6a. Located strokes on 1998-07-09. No fronts in Finland.

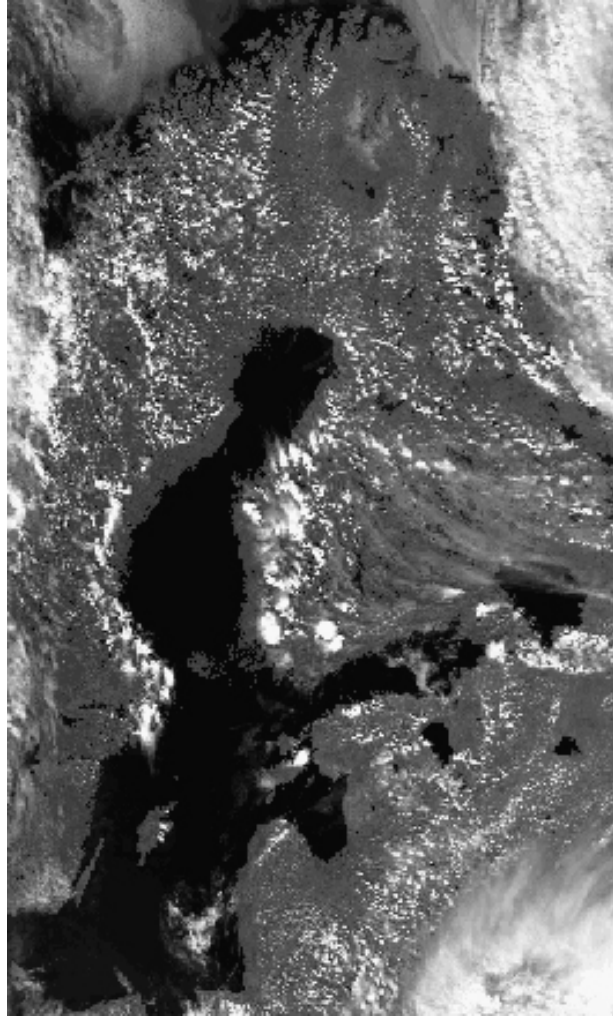


Fig. 6b. NOAA satellite visible image on 1998-07-09 at 12:09 UTC.

#### Squall line: 2001-07-14

Like the preceding case, this system also exhibited cloud anvils blown to the north-west (Fig. 7a, at 13:46 UTC). Now, however, the cells moved relatively rapidly to the north-east (Fig. 7b), mostly 5-21 UTC. The first impression is that of an occluded-front thunderstorm, but time-resolved analysis, as well as the satellite image, shows that the instantaneous thunderstorm area was wide along the direction of movement, rather than front-like, and that the thunderstorms came behind the front. The 00 UTC weather map (not shown here) has a bow-like trough line in southern Sweden. Its form, as well as the velocity of the overall system, suggests that in the afternoon the trough line matched with the leading edge of the thundercloud system in Fig. 7a, the occluded front being the cloud arc farther in the east. Hence, this case is judged to be a squall line, one of the few not preceding a cold front (but treated together with the pre-cold-frontal cases). The term squall "line" is misleading in this case because of the longitudinal



extent of the thundercloud region, perhaps associated with the strong curvature of the line. The temperature was 17 degrees.

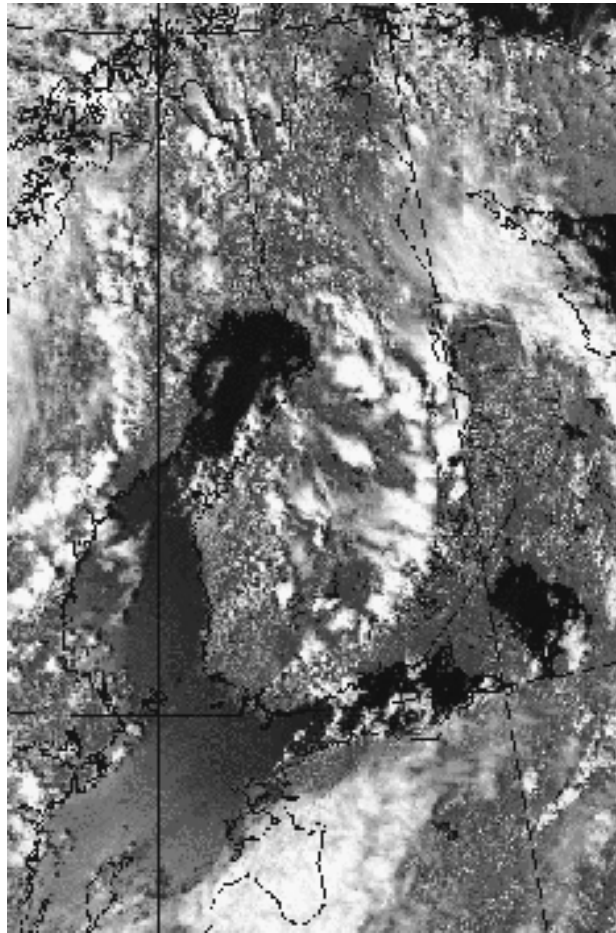


Fig. 7a. NOAA satellite visible image on 2001-07-14 at 13:46 UTC.

#### Squall line, pre-cold-frontal: 2001-07-18

Soon after the preceding case, western-type thunderstorms changed into eastern. A continuing chain of a stationary-frontal zone proceeded from the south to Finland during several days as already described above. Fig. 8 shows the located lightning, which occurred first at 17-19 UTC in the south-west, then developed front-like to the north-east at 20-22 UTC over the region where the trough line was at 24 UTC. That is, the flash front was parallel to but some 150 km ahead of the trough line. It is not clear how accurately the location of the analysed trough line represents the location of multicell clouds of 150-200 km diameter. After the UTC midnight (i.e. on the next morning), the cloud associated with the trough dissipated while continuing to the north-east, and another large cloud approached Finland in a little more eastern route; it was interpreted as a warm-mass case, and the cold front seen in Fig. 8 caused still another case. In the satellite images of the preceding afternoon (18th, not shown), the clouds developed into separate multicell clouds from which the existence or form of the trough

line is hard to see. Typically, a squall/trough line reveals itself by a front-like development of lightning and heavy precipitation in a region where a front does not exist. But, as seen in the preceding example, horizontally deeper zones may also develop. The highest afternoon temperature before the present thunderstorm system was 30 degrees.

TIME 010714 00:00 - 010714 22:57 UTC  
ON THE MAP 16805 STROKES ( 9658 FLASHES)

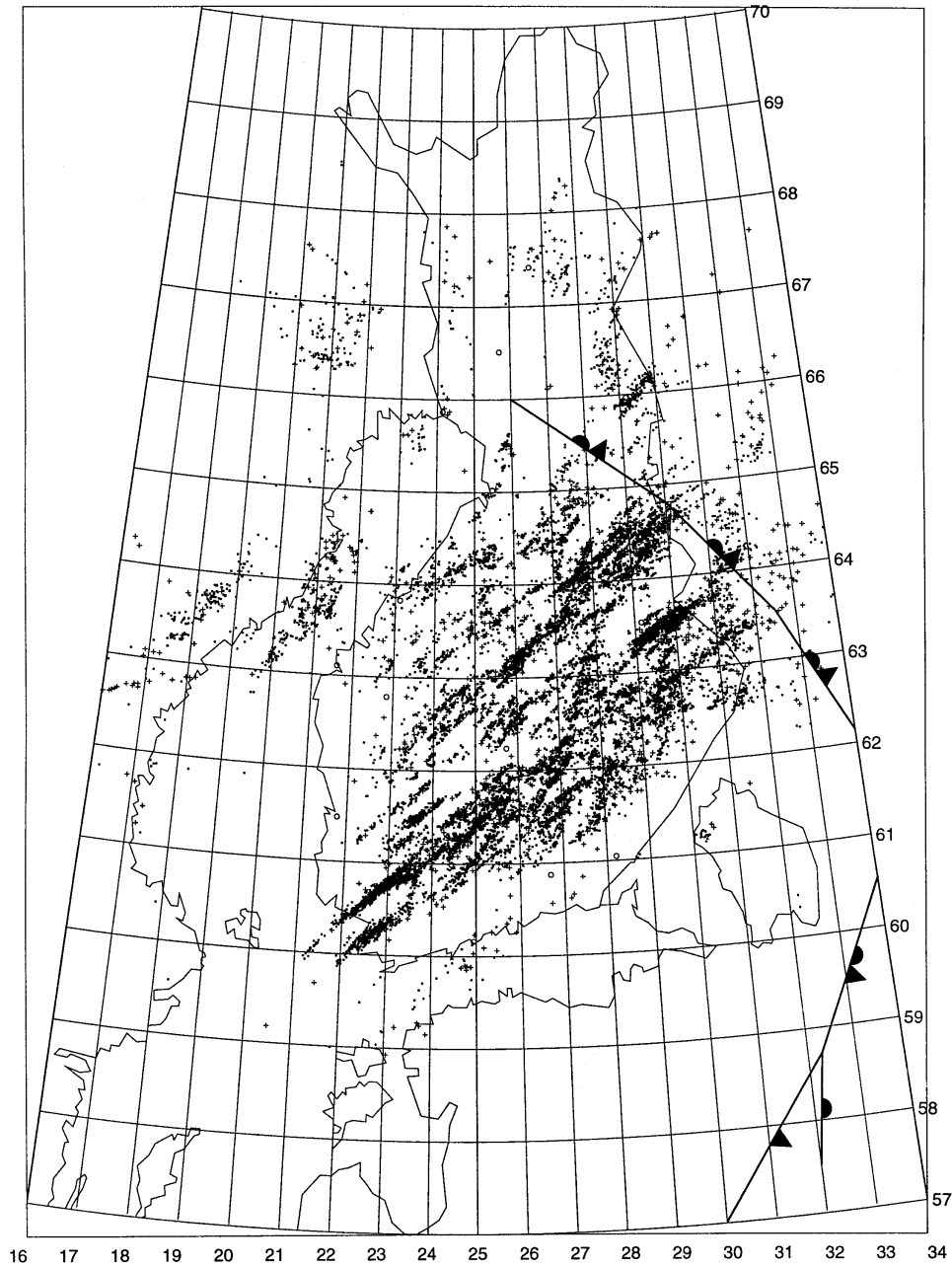


Fig. 7b. Located strokes on 2001-07-14. The fronts at 12 UTC.

TIME 010718 00:00 - 010718 23:59 UTC  
ON THE MAP 26512 STROKES ( 15114 FLASHES)

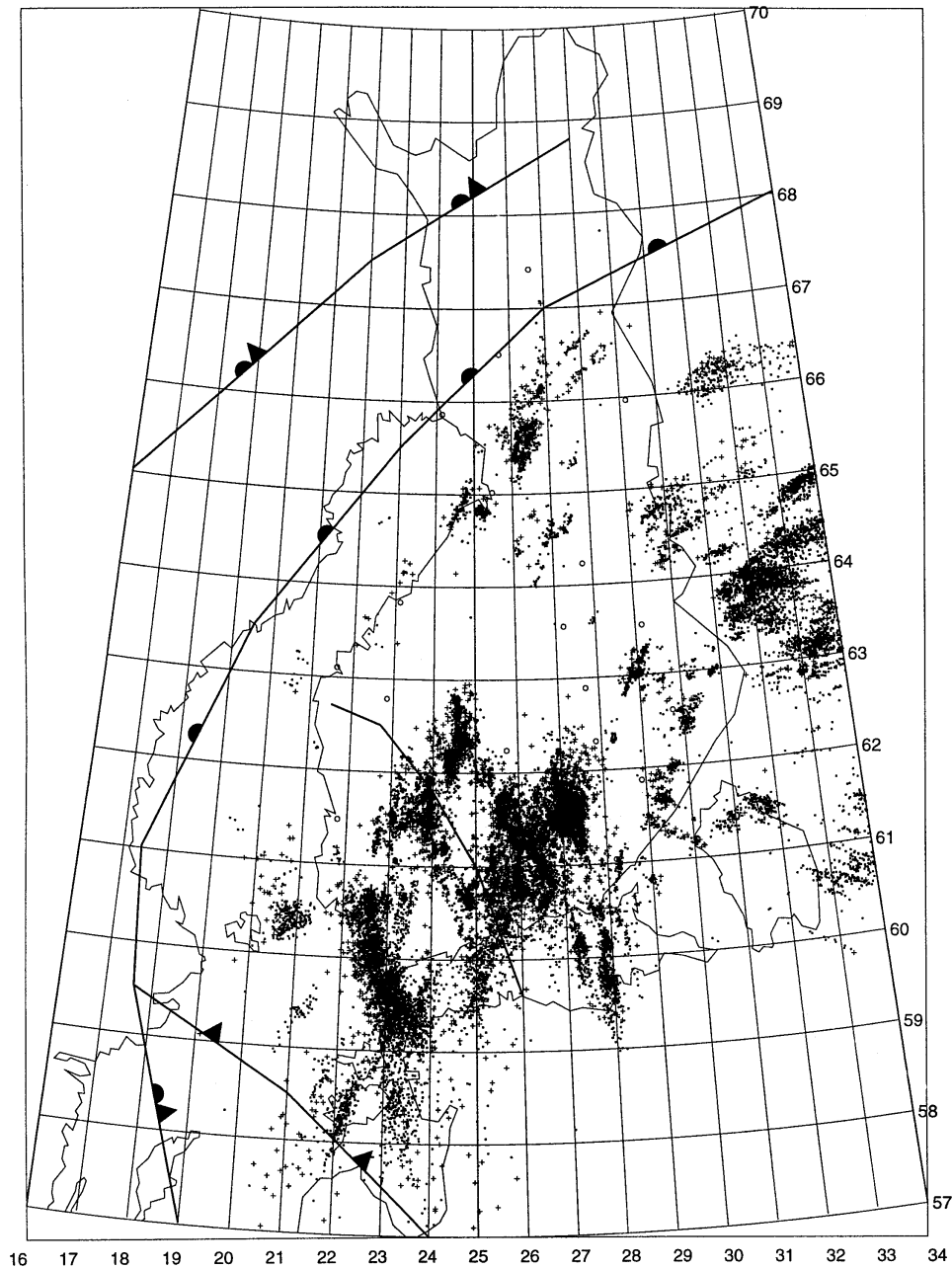


Fig. 8. Located strokes on 2001-07-18. The fronts at 24 UTC (2001-07-19 00 UTC). The thick line segment without frontal symbols denotes a surface trough.

#### 4. *Thunderstorms and weather conditions*

The cases for this study were chosen on the basis of daily maps of located flashes in Finland and its surroundings. While thunderstorms occur in Finland on about 100 days per season, the data were limited to days with at least 700 flashes within the

borders of Finland, excluding the open seas but including the south-western archipelago. If more than one case (thunderstorm system) occurred during a day, systems with at least 500 flashes were included. On the average, 28 days per year, i.e. about one fourth or third of all days of occurrence, met this criterion. This choice ignores modest and scattered thunderstorms, which are generally included in flash-density and thunder-day statistics. Needless to say, the public interest raised by a thunderstorm is proportional to its intensity, and the emphasis is here put on the nature of the more important ones. Because of the geographical limitations, the observed flashes for a system do not always represent the full period of the actual thunderstorm activity, but it is impossible to follow the whole life cycle of systems which are already developed when entering Finland, or continue high activity when exiting Finland. Yet many interesting systems do develop and decay mostly within the country, partly because the surrounding seas provide natural borders. This point is further discussed in Section 8 in terms of the duration of the thunderstorm systems.

Table 1 summarizes the data in terms of yearly numbers of different types of cases. Sometimes more than one system occur during a day, and in fact, the selected 142 days during the five years contain 170 cases. The first four classes are the different types of fronts, and the three last ones are air-mass storm types. The frontal and air-mass cases are also summarized separately.

Each category starts with the number of cases, followed by the total number of flashes (within Finland, rounded to 100) of the cases, and the number of flashes per case. The last number, flash percentage (fl %), is the fraction of the flashes in that thunderstorm-system type from the total number of flashes of that year, given in the "total" group at the bottom. For each year, the flash percentage indicates, for example, how one type of system may have a dominating role. Hence we may say that for year 1998, the two most important single types were warm-mass storms and squall-line storms; for 1999, the stationary front was the most important type; in 2000, the warm-mass type dominated; in 2001, the main periods were of the squall-line type; and finally, year 2002 had mostly cold-front thunderstorms.

Although there are wide year-to-year variations, some persistent features can be seen. Warm-front and occluded-front thunderstorms are rare and the number of flashes per case is low, with some exceptions. Polar thunderstorms also remain modest while their number is higher. Intense thunderstorms occur most notably with cold fronts, warm air mass, squall lines and stationary fronts. In the five-year mean, the squall-line storms have the highest number of flashes per case.

The "total" category at the bottom shows that all of the five years, measured by the total number of flashes, happened to be relatively close to the average. In long-term statistics, the most intense years have flashes 2.5 times the average, and the most meager years, 0.25 times the average. The yearly mean of flashes represented in the cases studied, given in the bottom right corner, is close to 100 000. The actual mean of these five years is about 109 000, i.e. some 10 000 yearly flashes in the modest and scattered thunderstorms are ignored in this study. They correspond to about 75 days or

cases per year, i.e. an average of 130 flashes per case. Their inclusion would give some more weight to the weaker categories, e.g. the polar thunderstorms.

Table 1. Classification of the annual thunderstorm systems into the four frontal and three air-mass types.

year		1998	1999	2000	2001	2002	total	mean
cold fr	cases	3	8	8	4	10	33	6.6
	flashes	15000	21500	12200	4600	41900	95200	19040
	fl/case	5000	2688	1525	1150	4190		2885
	fl %	15.9	19.6	12.3	6.1	35.2		19.2
warm fr	cases	4	1	0	0	1	6	1.2
	flashes	13700	1800	0	0	800	16300	3260
	fl/case	3425	1800	0	0	800		2717
	fl %	14.5	1.6	0	0	0.7		3.3
occl. fr	cases	1	4	1	2	3	11	2.2
	flashes	1500	7100	1500	4600	5000	19700	3940
	fl/case	1500	1775	1500	2300	1667		1791
	fl %	1.6	6.5	1.5	6.1	4.2		4.0
stat. fr	cases	2	7	4	5	5	23	4.6
	flashes	5500	36300	21400	7300	6800	77300	15460
	fl/case	2750	5186	5350	1460	1360		3361
	fl %	5.8	33.1	21.6	9.7	5.7		15.6
front	cases	10	20	13	11	19	73	14.6
	flashes	35700	66700	35100	16500	54500	208500	41700
	fl/case	3570	3335	2700	1500	2868	2856	2856
	fl %	37.8	60.9	35.5	22.0	45.8	42.0	42.0
w-mass	cases	6	8	10	4	7	35	7.0
	flashes	21500	23700	35900	6000	28900	116000	23200
	fl/case	3583	2963	3590	1500	4129		3314
	fl %	22.8	21.6	36.3	8	24.3		23.3
polar	cases	7	6	6	2	12	33	6.6
	flashes	16600	11700	8000	3200	18600	58100	11620
	fl/case	2371	1950	1333	1600	1550		1761
	fl %	17.6	10.7	8.1	4.3	15.6		11.7
squall	cases	4	3	4	10	8	29	5.8
	flashes	20700	7500	20000	49200	16900	114300	22860
	fl/case	5175	2500	5000	4920	2200		3941
	fl %	21.9	6.8	20.2	65.7	14.2		23.0
air-mass	cases	17	17	20	16	27	97	19.4
	flashes	58800	42900	63900	58400	64400	288400	57680
	fl/case	3459	2524	3195	3650	2385	2973	2973
	fl %	62.2	39.1	64.5	78.0	54.2	58.0	58.0
total	days	20	29	29	25	39	142	28.4
	cases	27	37	33	27	46	170	34.0
	flashes	94500	109600	99000	74900	118900	496900	99380
	fl/case	3500	2962	3000	2774	2585		2923

The "front" and "air-mass" rows show that the 34 yearly cases divide into 14.6 frontal ones with 42 % of the flashes (2 856 flashes/case), and 19.4 air-mass ones with 58 % of the flashes (2 973 flashes/case). Thus, the air-mass storm systems are more frequent and their mean intensity is slightly higher.

### 5. *Western-type and eastern-type thunderstorms*

The W and E types of thunderstorms associated with the two compass sectors were defined in Section 2. This division emphasizes the different thunderstorm potentials of the polar maritime and mid-latitude continental air masses, rather than differences in air-mass and frontal thunderstorms. However, the division will be made for both types.

Table 2 shows the result in a way similar to Table 1. Letter A denotes "air-mass", and A(W) means air-mass thunderstorms of the western nature. Similarly, F refers to the frontal cases. Year 1998 was really dominated by eastern thunderstorms, both air-mass and frontal. In addition, it had relatively few cases but a high number of flashes per case, especially in the eastern frontal storms.

Table 2. Classification of the annual thunderstorm systems into western (W) and eastern (E) air-mass (A) and frontal (F) types.

year		1998	1999	2000	2001	2002	total	mean
A(W)	cases	5	9	10	11	23	58	11.6
	flashes	8100	22800	14000	21400	45700	112000	22400
	fl/case	1620	2533	1400	1945	1987		1931
	fl %	8.6	20.8	14.1	28.6	38.4		22.5
A(E)	cases	12	8	10	5	4	39	7.8
	flashes	50700	20100	49900	37000	18700	176400	35280
	fl/case	4225	2513	4990	7400	4675		4523
	fl %	53.7	18.3	50.4	49.4	15.7		35.5
F(W)	cases	5	10	6	8	16	45	9.0
	flashes	10000	25200	10200	12500	43300	101200	20240
	fl/case	2000	2520	1700	1563	2706		2249
	fl %	10.6	23.0	10.3	16.7	36.4		20.4
F(E)	cases	5	10	7	3	3	28	5.6
	flashes	25700	41500	24900	4000	11200	107300	21460
	fl/case	5140	4150	3557	1333	3733		3832
	fl %	27.2	37.9	25.2	5.3	9.4		21.6
total	cases	27	37	33	27	46	170	34.0
	flashes	94500	109600	99000	74900	118900	496900	99380
	fl/case	3500	2962	3000	2774	2585		2923

For year 1999, eastern frontal storms were relatively intense and the three other types had equal weights. For years 2000 and 2001, eastern air-mass thunderstorms dominated clearly. Although year 2002 had one eastern-type day with about 20 000 flashes, most of the cases were of the western type, both air-mass and frontal. The mean of the five years (rightmost column) shows that most thunderstorms (21 out of 34) were of the western type, with nearly equal numbers (12 and 9) of air-mass and frontal cases. However, the highest amount of lightning (36 %) is associated with the fewer eastern air-mass thunderstorms, the number of flashes per case being double that of the western cases. The still fewer eastern frontal storms are also very intense on the average.

During these five years, there were 8 cases (5 air-mass, 3 frontal) with the number of flashes between 10 000 and 18 000, all of the eastern type and most of them associated with "hot" air (air temperature at least 25 degrees). The estimated record of the daily number of flashes, deduced from older lightning location data with a correction for the lower efficiency, is about 40 000 (June 29, 1988).

#### 6. *Monthly occurrence of thunderstorm types*

While lightning occurs occasionally outside the summer season in Finland, all cases exceeding the 700-flash lower limit here belong to the five-month season May-September. Even in May and September thunderstorms are rare although sometimes intense, and the main season really consists of the three summer months June-August.

Table 3 shows the monthly numbers of cases, summed for the five years (i.e. not as yearly means). On the average, there is roughly only one appreciable thunderstorm system per year in May and September. June is dominated by stationary-frontal cases. July is the high season of thunderstorms, but it differs from June mainly by the higher number of air-mass storm cases, both western (44) and eastern (35), and the fronts tend to be cold rather than stationary. In August, frontal thunderstorms decrease more rapidly than air-mass storms, and the eastern influence nearly disappears when the weather system returns to the normal course. The "total" rows at the bottom show that July has the highest number of cases and the highest number of flashes/case.

#### 7. *Local arrival directions of thunderstorms*

As a comparison with the early studies of Oksanen mentioned in the Introduction, we deduced the thunderstorm development directions from the lightning location maps, without considering the storm intensity. The total number of cases is less than that in our other analyses because we merged cases occurring within the same day whenever the directions were similar. The result is shown in Table 4. First, *Oksanen* (1921b) quoted an earlier result from 1887-1906, which shows that for the eight points of compass, the most frequent directions are SW (22 %) and S (20 %). She extended the data over 1907-1916 and found a very similar result: S (22 %), SW (19 %). *Oksanen* (1940) further considered the observed thunderstorms of 1936-1939 and found that the highest frequencies of the local directions of arrival were S (26 %), SW (23 %). However, for frontal thunderstorms the most frequent direction of arrival was SW (41 %). This proportion is very high compared with the other quoted results, which presumably contain also air-mass storms, but the distinction remains unclear. *Oksanen* (1940) did not consider the relative frequencies of air-mass and frontal storms. Our present result, whose period of five years is short compared with the early studies, is rather similar except for the high frequency of the direction SW (38 %). Some of the modest cases involve movements from the northern directions and their inclusion might slightly decrease the weight of the SW sector, but this possibility will not be studied

here. *Oksanen* (1921b) also cited the result that in Europe, W and SW together cover 51 % of the arrival directions.

Table 3. Monthly numbers of the different types of thunderstorm systems (summed over the five years).

<b>Month</b>		<b>May</b>	<b>June</b>	<b>July</b>	<b>August</b>	<b>Sept.</b>	<b>total</b>
cold fr	cases	1	8	16	5	3	33
	flashes	1200	13800	48400	21700	10100	95200
	fl/case	1200	1725	3025	4340	3367	2885
warm fr	cases	0	4	1	1	0	6
	flashes	0	13600	1800	900	0	16300
	fl/case	0	3400	1800	900	0	2717
ocl. fr	cases	0	4	4	3	0	11
	flashes	0	5700	7900	6100	0	19700
	fl/case	0	1425	1975	2033	0	1791
stat. fr	cases	3	13	7	0	0	23
	flashes	2400	58300	16600	0	0	77300
	fl/case	800	4485	2371	0	0	3361
front	cases	4	29	28	9	3	73
	flashes	3600	91400	74700	28700	10100	208500
	fl/case	900	3152	2668	3189	3367	2856
w-mass	cases	1	9	21	4	0	35
	flashes	700	15900	84600	14800	0	116000
	fl/case	700	1767	4029	3700	0	3314
polar	cases	0	8	16	8	1	33
	flashes	0	14600	30400	12400	700	58100
	fl/case	0	1825	1900	1550	700	1761
squall	cases	1	11	14	3	0	29
	flashes	5800	39100	61400	8000	0	114300
	fl/case	5800	3555	4386	2667	0	3941
air-mass	cases	2	28	51	15	1	97
	flashes	6500	69600	176400	35200	700	288400
	fl/case	3250	2486	3459	2347	700	2973
western	cases	4	29	44	22	4	103
	flashes	8200	50100	83100	61000	10800	213200
	fl/case	2050	1728	1889	2773	2700	2070
eastern	cases	2	28	35	2	0	67
	flashes	1900	110900	168000	2900	0	283700
	fl/case	950	3961	4800	1450	0	4234
total	cases	6	57	79	24	4	170
	flashes	10100	161000	251100	63900	10800	496900
	fl/case	1683	2825	3178	2663	2700	2923



Table 4. Distribution of thunderstorm arrival directions. Present data: yearly numbers of cases and the mean percentages. Data from Oksanen: the mean percentages.

<b>Present results</b>								
<b>sector</b>	<b>NE</b>	<b>E</b>	<b>SE</b>	<b>S</b>	<b>SW</b>	<b>W</b>	<b>NW</b>	<b>N</b>
year								
1998	3	1	5	3	6	1	0	1
1999	0	0	3	11	12	3	0	0
2000	0	3	9	5	7	4	0	1
2001	0	0	1	4	15	2	1	0
2002	1	0	0	7	13	7	5	5
total %	3	3	13	22	38	12	4	5
<b>Oksanen</b>								
1887-1906	6	7	13	20	22	15	10	7
1907-1916	6	10	15	22	19	14	10	6
1936-1939								
all	3	8	12	26	23	16	7	5
frontal	0	3	7	17	41	18	12	2

#### 8. *Thunderstorm durations*

While the typical lifetime of a single thunderstorm cell is of the order of an hour, the overall durations of the thunderstorm systems defined here are several hours. In the present data, the durations varied between 4 and 24 hours. For 117 of the 170 cases, the whole development took place (practically) within the country; for the rest 53 cases, a significant part of the system, usually the initial phase, took place outside the borders. The latter include many of the most spectacular eastern storms with fully developed lightning activity while entering the country. For thunderstorm systems wholly developed within the country, the beginning and end times of the lightning activity determine their true duration.

There is a wide variation of beginning times, durations and end times within all categories studied above; the standard deviations are 2-6 hours. As it may happen that a meager storm system lasts for several hours or an intense storm sweeps over very rapidly, it is understood that the number of flashes is not simply related to the storm system duration although it often happens that an intense system does last long. Hence, only the arithmetic means of the beginning and end times (UTC) are given and discussed for the front/air-mass and western/eastern categories, also resolving between the cases with whole/partial development within the country. Then each category consists of the averages of 10-46 cases. They are illustrated in Fig. 9.

For the cases with whole development within the country, the beginning times are rather uniform: both types of air-mass storms begin soon after 8 UTC and the frontal storms at about 9 UTC, i.e. near the local noon. Both of the eastern types end at nearly the same time, at about 19:30 UTC. The average duration of the eastern cases is thus

10-11 hours. This is evidently associated with the high flash activity of these systems. The western storms end before 18 UTC, having a duration of about 9 hours.

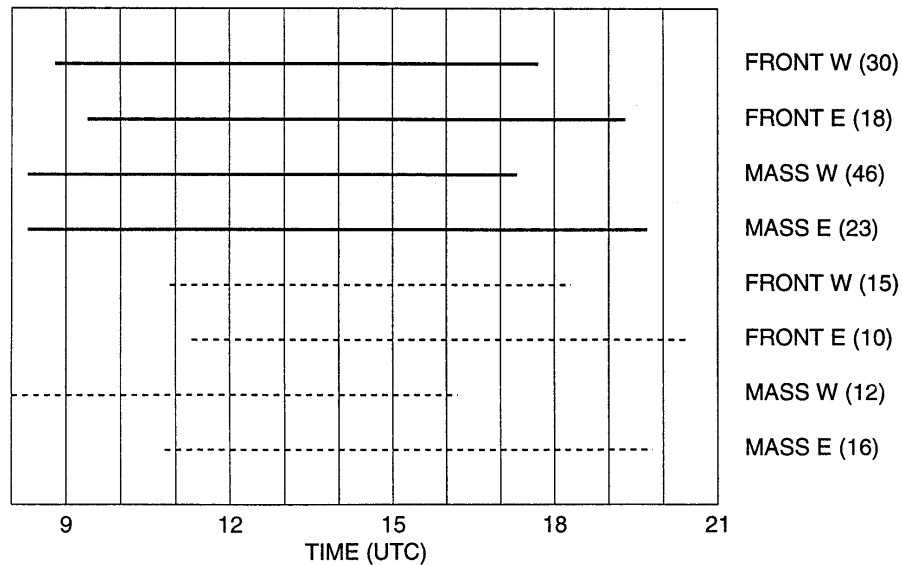


Fig. 9. Mean durations of four groups of thunderstorm types (mass = air-mass, W = western, E = eastern). Solid lines: whole development within the country, dashes lines: partial development within the country. The numbers of cases of each type are given in parentheses.

Storms with partial development outside the country, especially those associated with fronts, enter the country usually in a developing phase, and consequently the beginning times are relatively late: about 11 UTC for both types of frontal storms. The western frontal storms end after 18 UTC and the eastern ones after 20 UTC. This difference is similar to that of the storms with whole development within the country. Western air-mass storms, often approaching from southern or central Sweden over the warm late-summer Gulf of Bothnia (see Fig. 1a) or developing over the central Baltic Sea, enter Finland as early as 8 UTC and decay already at 16 UTC, i.e. they rarely survive long over the cooler land. The eastern air-mass storms, in turn, arrive at 11 UTC and last until 20 UTC. This end time is similar to that of the corresponding systems with whole development within the country because both types dissipate under similar conditions, i.e. after having proceeded far enough to the north.

## 9. Conclusions

We have suggested a method to classify the observed thunderstorms in Finland. This synoptic classification is justified by the position of Finland between two quite different source regions of air masses: the maritime North Atlantic and the continental eastern Europe and western Asia. The difference is also recognized in the everyday experiences of the people who, for example, feel the strongest awe of violent thunderstorms in association with the south-eastern hot, moist and hazy air mass. This study attempts to give some statistical basis to the connection between the nature of the

weather and its thunderstorm potential. It also tries to develop one more aspect to thunderstorm climatology, a subject that is usually limited to flash-density and thunder-day or thunder-hour statistics. It is hoped that the chosen degree of simplicity, i.e. the classification according to synoptic surface-weather conditions, is an advantage rather than an obstacle for the usefulness of the results. It would be relatively easy to add coming seasons to the tables and see e.g. possible trends not only in the amount of lightning but also in the synoptic character of thunderstorms. The period of five years is relatively short for a climatic study, but after ten years or more, averages and year-to-year variations, as well as trends and long-term periodicities, may gain statistical significance for climatic considerations.

Our primary expectation was that the most violent thunderstorms (measured by the amount of ground flashes) are associated with the continental air masses approaching from the Balkan – Black Sea region, and the results confirm this. The eastern storms have also the longest lifetimes. On the other hand, the major part of all thunderstorm systems, weak or heavy, are associated with western air masses, which reflects the dominance of the flow of air from the south-west. Years with relatively similar total thunderstorm activity, as happened for this period, may show large differences in the dominance of synoptic-weather and air-mass types.

Thunderstorm types might be compared with other weather or weather-related phenomena, such as precipitation (from radar data), lightning damages (especially forest fires) and thunderstorm-related wind damages. Variations in the frequency and violence of different thunderstorm types may be reflected in the damage statistics.

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