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On the Areal and Temporal Distribution of Thunder in Finland

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Abstract

The spatial and temporal distribution of the annual number of thunder days was studied in Finland on the basis of the means for the periods 1887–1936, 1931–50, 1970–86 and 1987–96. For all periods, values based on aural and visual observations were considered, with additional values based on an automatic lightning location system for the period 1987–96. In each case, regional means were calculated for the southern and middle boreal climatic zones. In addition, detailed spatial analyses were available for the period 1931–50, based on aural and visual observations, and on the automatic lightning location system for the period 1987–96. In the southern boreal zone there occurred more thunder than in the middle boreal, obviously because in the middle boreal zone there are more dry air masses of Arctic origin and fewer tall stands. The main threshold factors for the occurrence of air-mass thundering, such as the corona effect above tall stands and the contribution to the atmospheric moisture by local evaporation, are more effective in the southern region. The increasing number of tall trees and decreasing daily maximum temperatures from the 1930's to the present were also reflected in the temporal change of thundering. The automatic lightning location system detects lightning, and thence thunder days, more reliably than human observers, particularly for weak air-mass thundering. This methodological difference decreases northwards, which agrees well with the fact that the two factors launching weak air-mass thundering, mentioned above, also decrease northwards.

Key words: Thunder, thunder days, boreal climate

1. Introduction

In Finland, as in many other countries, there is a record of the annual number of thunder days over a period of more than 100 years. Considering that the threshold of thundering[1] observed varies appreciably from one station to another, the number of thunder days becomes somewhat underestimated, and the underestimation varies greatly as well. However, taking averages over large areas (of at least 15 stations and 30 000 km^2) and periods of duration of at least 10 years, a satisfactory picture of the main differences between regions and temporal changes can be observed. The modern lightning

[1]In the present context, in accordance with the traditional aural and visual observation method, the term "thunder" is used synonymously with "thunderstorm", and "thundering" with "occurrence of thunderstorms".

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location system appreciably improves the accuracy and spatial resolution of lightning and thunder days. With about 10 annual grid-square charts based on these modern observations so far, it is possible to make a more accurate analysis of the rather permanent spatial distribution of thunder days; observations since the year 1998 are no longer comparable because of a new lightning location system which observes essentially (about 3–4 times) more lightnings (*Tuomi*, 1997). The old system was found to fail to detect most of the weak flashes, but it detected all appreciable thunderstorms and hence practically all thunder days (confirmed by a comparison with visual-aural thunder days). In this study, the temporal and spatial distribution of the number of thunder days in Finland was studied, making use of both kinds of analyses, separately and together.

The part of Finland north of the Arctic circle was excluded because the network of traditional observations there is rather sparse, and the modern observation system does not extend so far north. One main aim of the study was to explain the reasons for the regional features of thunder days observed with the modern location system. Particular attention was paid to a belt within the boreal climatic zone, in which the gradient of the occurrence frequency of thunder days is especially great. This belt is situated around the boundary between the southern and middle boreal climatic zones, which is also the mean location of the polar front in summer. The predominant occurrence of the polar front around the boundary between the southern and middle boreal zones can be seen both by considering the frequency of the occurrence of cyclone centres and the mean air pressure; both in Europe and Northern America the belt of highest frequency of cyclone centres in summer (e.g. *Petterssen,* 1958) lies just there were the boundary between the considered zones (e.g. *Tuhkanen,* 1984) is situated. Everywhere in Northern Europe and Western Siberia the belt of lowest air pressure (*Solantie,* 1974, 1987) also falls well around the belt between the two zones. The monsoon effect of great continents naturally intensifies the polar front in summer, as does the shape of the Finnish peninsula (surrounded by the waters from northern end of Gulf of Bothnia to the northern corner of Lake Ladoga).

The boundary between the southern and middle boreal zone is also connected to the changes in such diverse factors as the occurrence of dry air masses of Arctic origin, evaporation and water vapour pressure in air, and the number of tall trees and the volume of growing stands per hectare. Trees may act as a threshold factor for the occurrence of thundering in two ways: First, they add air moisture by evaporation. The second mechanism is the so-called corona effect, contributing to the lower positive charge of the thundercloud. The strong earth surface electric field under a thundercloud generates corona discharges, especially at the tips of sharp and elevated objects. Tall trees on a high terrain may be especially effective in this respect. The corona ions, mostly positive, migrate towards the thundercloud (*Chauzy and Soula,* 1999) and are eventually attached to it. It is still not clear how much corona ions contribute to the lower positive charge, which is thought to be the region where most of the ground flashes are initiated. There are modelling results that prove the significance of the effect by roughness of the earth surface of this kind for the generation of lightning; this so-called corona effect is not alone effective enough to cause charges, but may launch lightning in cases in which it would not have occurred without this effect (*Chauzy and Soula,* 1999).

The density of tall stands per hectare is so well correlated with the amount of growing stock per hectare that only the values of the latter, denoted by K (m^3ha^{-1} on the total land area) are used to explain the temporal and spatial distribution of thundering. The temporal dependence of thundering was studied on the basis of means over 10 to 20 year periods of thunder days as observed by the traditional method. These changes in large regions are explained, on the one hand, by changes in the mean daily maximum temperatures reflecting the occurrence of air masses of Arctic origin and global radiation, and, on the other hand, by the corresponding changes of K.

2. Method

The mean annual number of thunder days according to visual and aural observations made at weather stations were considered for the Finnish mainland during four periods. The mean numbers of thunder days for the different periods are presented separately for the southern and middle boreal zones (Table 1). This separation is supported by observations of the number of thunder days, especially those obtained by the lightning location system, and by vegetational and climatic reasons. First, we can note that there is really a distinct difference between the zones in the number of thunder days in all four periods considered. Second, the number of tall trees, possibly enhancing the corona effect, is essentially greater in the southern boreal than middle boreal zone (Fig. 1). Third, the polar front, separating air masses of arctic origin with a rather small absolute humidity from moister air masses of more southern origin, passes in summer generally within the boreal zone so that the occurrence of moist air masses increases southwards. Additionally, a significant moisture gradient lies around the boundary between the two zones caused by the gradient of evaporation from trees and lakes in this belt.

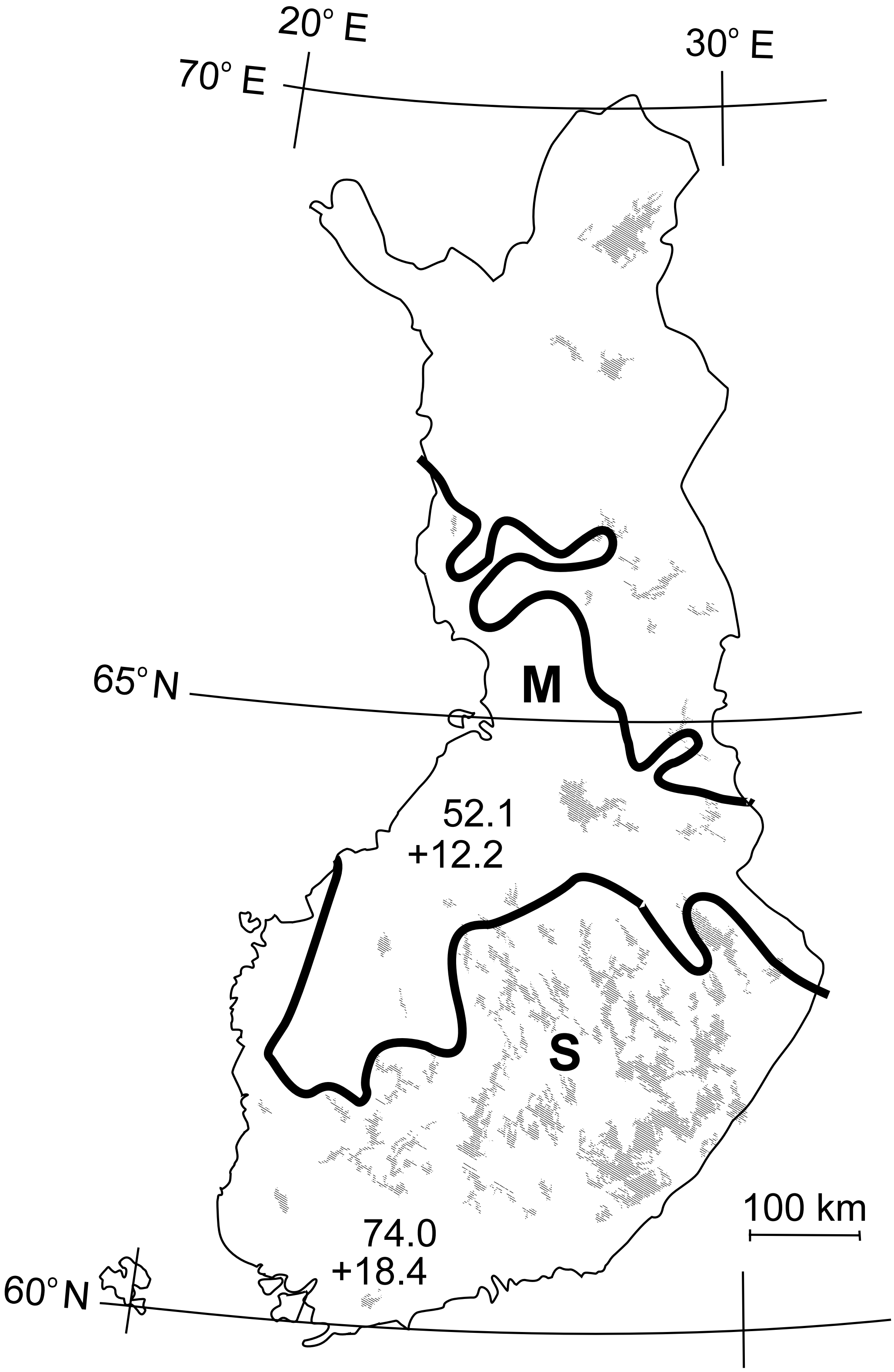

Fig. 1. The southern (S) and middle boreal (M) natural zones of Finland (*Kalela*, 1961) in the connection with the mean amounts of the growing stock in each (m^3 per hectare of total area, incl. inland waters) during the period 1983–93, and their changes from the period 1951–53.

The periods, the available materials for each period, and the various regional means calculated from these material are given below. In addition to regional means, spatial standard deviations of station-wise or gridded values, as well as the number of stations and grids are given. The grid-size was 50 x 50 km in the cases of aural and visual observations and about 30 x 40 km^2 in the case of the automatic lightning location system. Considering that the quality and kind of the basic materials changed from one period to another, the results are usually calculated in two ways to make the comparison between periods possible.

Period 1887–1936: Station-wise values and spatial isopleth analysis by *Oksanen* (1940); mean values for the southern and middle boreal zone were evaluated by graphical integration from the isopleth analysis, for the middle boreal area also south of the 65th latitude and for main watershed areas. In addition, arithmetical means of station-wise values were obtained for the southern boreal zone. These statistics (for maps as station-values) are based on selection of high-standard stations with 50-years' series, which means that weak thundering is more carefully observed than on the average (*Oksanen,* 1940).

Period 1931–50: Spatial isopleth analysis by *Venho* (1961): as for the period 1887–1936.

Period 1970–86: Mean values for the southern and middle boreal zone, for the middle boreal zone south of the 65th latitude, and additionally for main watershed areas were obtained as arithmetical means of all station-wise values. Observations were also selected and results of selected values were calculated.

Period 1987–96: As for the period 1970–86.

Furthermore, for the period 1987–96, the mean annual number of thunder days in both zones could be obtained from a chart based on another basic data source, namely the automatic lightning location system. Using this method, a thunder day is defined as the occurrence of at least one flash over an area of about 30 x 40 km^2, corresponding to the area of a circle with a radius of 20 km. The area, 30 km south–north and 0.75 degrees longitude, approximately corresponds to a regional map of a scale 1:100 000, which usually comprises 12 basic maps of 10 x 10 km. These regional "map-squares" have illustrative local names and are coded with 4-digit numbers. The area varies slightly with latitude but has only a little effect on the number of thunder days; the relative error due to this reason increases with latitude so that the number of thunder days at the 60th latitude are 4% too high compared with those at the 65th latitude. This error was corrected for the figures in Table 1. This method detects some of such weak air mass thunders which may be missed from aural and visual observing at stations of average accuracy.

We may therefore also augment the list of regional values with the additional results for the period 1987–96, based on that chart. As the location system did not reach north of latitude 65.5 °N, values for the middle boreal zone can only be given for the southern half of the area. For comparison, the values based on aural and visual observations for the period 1987–96 were calculated also for this particular area. Further, a chart was prepared showing the difference between two spatial fields of values, one for the period 1987–96 and the other for the period 1931–50.

3. *Results*

3.1 *The number of thunder days by periods and climatic zones*

The mean annual numbers of thunder days in the southern and middle boreal zones and around the main watersheds within the latter zone are given in Table 1 for the three periods considered, according to aural and visual observations, and according to the lightning location system for the period 1987–96.

Table 1. The mean annual number of thunder days in the southern and middle boreal zones according to visual and aural observations (V&A) during the periods 1887–1936 (from the chart in *Oksanen*, 1940), 1931–50 (from the chart in *Venho*, 1961), 1970–86 and 1987–96, and according to the automatic lightning location system (ALLS).

	1a. Based on all V&A-series						
	Southern boreal zone			Middle boreal zone			Main water-sheds
	Mean	St. dev.	n	Mean	St. dev	n	Mean
1931–50 (V&A)[1]	10.5	1.4	67	9.9	2.6	53	12.2
1931–50 (V&A)[1,3]				11.1	1.8	39	
1970–86 (V&A)[2]	10.0	2.8	54	9.0	2.9	26	10.1
1970–86 (V&A)[2,3]				9.1	3.1	20	
1987–96 (V&A)[2]	10.4	3.5	46	9.2	3.1	27	10.6
1987–96 (V&A)[2,3]				9.3	3.5	21	
1987–96 (ALLS)[1,3]				9.3	1.5	70	10.2

	1b. Based on selected V&A-series						
	Southern boreal zone			Middle boreal zone			Main water-sheds
	Mean	St. dev.	n	Mean	St. dev.	n	Mean
1887–1936 (V&A)[1]	11.4	2.0	67	10.3	1.7	53	11.9
1887–1936 (V&A)[2]	11.5	1.8	31	10.5	1.9	10	
1970–86 (V&A)[2]	11.8	2.2	31	10.2	2.3	18	11.5
1987–96 (V&A)[2]	12.7	2.2	27	10.8	2.5	21	12.2
1987–96 (V&A)[2,3]				11.1	2.6	18	
1987–96 (ALLS)[1,3]	12.3	3.0	116	9.3	1.5	70	

[1] the material is calculated from gridded values.
[2] the material is calculated from station values
[3] areas north of the latitude 65.5 °N are excluded

Part of the regional values are based on the station-values, part on gridded ones. The choice of the method does not significantly influence the regional means, which was shown for the data for the period 1887–1936 (Table 1) for which gridded values were obtained from the chart of *Oksanen* (1940) by the authors and the (selected) station-values given by Oksanen.

3.2 Statistical significance of differences between regions and periods

Let us begin with the statistics based on all (not selected) aural and visual observations for the periods 1931–50, 1970–86 and 1987–96. For these periods, we have rather good statistics of forests and climatic variables. During all these three periods, the significance for the difference in the number of thunder days between the southern and middle boreal zone, in the light of the two-tailed t-tests, is 80 to 90%, and during the last period according to the ALLS as high as 99%. The changes between the periods 1931–50 and 1970–86 in both zones are significant at the 80%-level, whereas in the northern boreal zone south of the latitude 65.5 °N the change is 99%-significant. The smaller changes from the period 1970–86 to 1987–96 are not statistically significant. (In the southern boreal zone, this change indicated by the selected material was, however, more significant.)

On the other hand, we may test the significance of the differences between the regions and periods on the basis of the annual (year-to-year) variation of the regional V&A means. The annual differences between the means in both zones has a standard deviation of 1.8 days. Applying the two-tailed t-test with this temporal variation, we found that the differences between the zones during the periods 1970–86 and 1987–96 (of 1.0 and 1.2 days) are significant at the 80% level, while the difference for the period 1931–50 (of 0.6 days) is not.

The standard deviation of the annual regional means is 2.5 days for the southern boreal zone and 3.2 days for the middle boreal zone. This means that the temporal standard deviation of the difference between 20 and 17 year means is 0.85 days in the southern boreal zone and 1.09 days in the middle boreal zone. Considering that 20% of the temporal variance of the number of thunder days is explained by temperature (Equations (2) and (3), section “Attempts to explain spatial and temporal variations of the number of thunder days”), the standard deviations accounting for unexplained variation are, respectively, 0.76 and 0.97 days. Using the latter value in the two-tailed t-test for the decrease of the number of thunder days in the main water shed areas from the period 1931–50 to 1970–86 (2.1 days) we found that the decrease is significant at the 95% level, and cannot be caused by irregular weather variations between summers. On the other hand, the changes of the number of thunder days between these periods (1931–50 and 1970–86) in the middle boreal zone as a whole, and in the southern boreal zone, cannot be shown to be significant in this way.

We also examined means of selected-station values for the periods 1970–86 and 1987–96 in order to follow the changes of the number of thunder days from the first period 1887–1936 to the last one. The selected stations comprise about 70 % of the total, and the number of selected stations is about the same for all periods. The standard deviations of the selected-station values are about 30% smaller and the means 15–20% (1.2 to 1.9 days) greater than those of all stations. During the period 1987–96, when materials based on (1) selected series, (2) all series and (3) ALLS values were available, the spatial standard deviation of the number of thunder days in Finland south of the 65.5th latitude was 3.5 for all series, 2.4 for selected series and 2.6 for ALLS-grids. Consequently, half of the spatial variance of all series is due to careless observation at about 30% of the stations. On the other hand, careful observers, e.g. those of the selected stations, should be able to produce spatial distributions as accurate as the old ALLS if only the network of observations were dense enough. Further we note that the spatial standard deviations of the selected-station values for the periods 1970–86 and 1987–96 are slightly greater than those for the period 1887–1936, which is expected because spatial variation slightly decreases with the smoothing out of single thunderstorms with the prolongation of the period considered. Altogether, we may consider all the three selected materials mutually comparable. The selected values for the southern boreal zone show that the mean number of thunder days increased from the period 1887–1936 through 1970–86 to the period 1987–96 in accordance with the fact that during the period 1887–1936 the daily temperature maxima were also rather low and the volume of growing stock in the major part of the southern boreal zone was smaller than any time after 1936 (*Ilvessalo,* 1930; 1957; 1960). In the middle boreal zone, the mean for the period 1970–87 is lower than that for 1887–1936 and 1987–96, particularly in the watershed areas, because of the extensive loggings mentioned before.

In the selected materials, the significance for the difference in the number of thunder days between the southern and middle boreal zones, on the basis of spatial variations, is 80% for the first period (1887–1936), 80% for the second (1970–86) and 95% for the third (1987–96). The change between the first and second periods is not statistically significant, while the change from the second to the third period in the southern boreal zone is 80%-significant (in the middle boreal zone, however, less significant).

We may further note that the mean for the period 1987–96 in the southern boreal zone, calculated from the selected values, is only slightly greater than the corresponding value obtained by the ALLS-method, without any significant difference between the values. On the other hand, in the middle boreal zone the selected V&A-values are appreciably larger with a significance of 99%, and sharp observers, ¾ of the total, observe more thunder days than the “old“ ALLS. This curious circumstance has a natural explanation: The concept “thunder day”, used for counting the number of thunder days from V&A-observations, is determined to change at 18 UTC which means 19.30 to 20.00 in solar hours. At this time, the diurnal thunder activity is still high particularly in the case of frontal thunderstorms: As a consequence, thundering in evening hours frequently accounts for two thunder days. On the other hand, according to the ALLS-registration, the thunder days change at 03 UTC which means 4.30 to 5.00 in solar hours, at which time the thunder activity has its minimum. The registration threshold of thundering by the ALLS-method in the middle boreal zone may also be slightly higher than in the southern boreal, also south of the 65th latitude.

The basis for comparisons between zones and periods is only of a satisfactory quality; therefore, a risk of false conclusions cannot be fully excluded.

3.3 Attempts to explain spatial and temporal variations of the number of thunder days

A decrease in the *mean* daily maximum and mean temperatures may either increase or decrease thundering. The decreasing maximum temperatures often indicate an increasing proportion of dry air masses of Arctic origin; such a fluctuation of the mean location of the polar front is highly possible at these latitudes. On the other hand, passing of cyclones and troughs both lower the daily maximum temperatures and enhance thundering. There are, however, several facts calling attention to the central role of the increase in the proportion of dry arctic-originated air masses.

The statistical relationship between air temperature and the number of thunder days on annual basis was studied by three regression Equations. The first Equation explains the annual values of the mean number of thunder days in the middle boreal zone according to V&A-observations 1970–86 (all stations included; not selected), denoted by t_M, as a function of the corresponding value in the southern boreal zone (t_S):

$$t_M = -1.5 + 1.06 \times t_S \; ; \tag{1}$$

correlation coefficient = 0.83.

The second Equation explains t_M as a function of the frequency of occurrence of thunder-day weighted mean temperature in summer at Sodankylä in northern Finland, denoted by m_{SOD}; the weights of June, July and August values for calculating m_{SOD} were 0.36, 0.47 and 0.17, approximating the frequency of occurrence of lightning in 1987–97 (*Tuomi*, 1997, p. 35).

$$t_M = -4.2 + 1.01 \times m_{SOD} \; ; \tag{2}$$

correlation coefficient = 0.44.

The third Equation explains t_S similarly:

$$t_S = -0.2 + 0.78 \times m_{SOD} \; ; \tag{3}$$

correlation coefficient = 0.43.

Considering mean changes over longer periods, we may note (Table 1) that in the southern boreal zone the number of thunder days during the periods 1931–50 and 1987–96 were about the same but in both these periods higher than during the period 1970–86. Let us try to explain such temporal development by the changes in climate and amount of growing stock. For both time steps we may form an Equation where the changes in the number of thunder days according to all (not selected) V&A-observations (ΔT) were explained by the corresponding changes in the mean daily maximum temperatures as a weighed mean of those in June, July and August ΔM, and the changes in the amount of growing stock per hectare of total land area (incl. inland waters) (ΔK) as

$$\Delta T = a \cdot \Delta M + b \cdot \Delta K. \qquad (4)$$

The weights of ΔM are those for m_{SOD} in Equations (2) and (3). Substituting the observed values for ΔT, ΔM and ΔK in the southern boreal zone for time steps 1 (from 1931–50 to 1970–86) and 2 (from 1970–1986 to 1987–96) as ΔT_1 = –0.5 days, ΔT_2 = +0.4 days, ΔM_1 = –0.62 °C, ΔM_2 = –0.18 °C, ΔK_1 = +9.4 m^3ha^{-1} and ΔK_2 = +9.0 m^3ha^{-1} (for climatic and forestall basic materials, see *Appendix*) we have

a = +2.1 days/ °C and b = +0.09 days/m^3ha^{-1}.

Correspondingly, for the middle boreal zone the observed values
ΔT_1 = –0.9 days, ΔT_2 = +0.2 days, ΔM_1 = –0.66 °C, ΔM_2 = –0.43 °C, ΔK_1 = +5.4 m^3ha^{-1} and ΔK_2 = +6.7 m^3ha^{-1} give

a = +3.4 days/ °C and b = +0.25 days/m^3ha^{-1}.

3.4 Thunder, air temperature and relative humidity

Equations (1), (2), and (3) show that the annual occurrence of thunder in the middle boreal zone reacts stronger to the temperature in northern Finland than in the southern. According to Equations (1) to (3), the difference in the number of thunder days between the zones during the coldest summers (m_{SOD} = 11 to 12 °C) or summers with least thunder (t_M = 4 to 6 days) is about 1.5, but during the warmest summers (m_{SOD} = 15 °C) or summers with most thunder (t_M = 13 to 15 days) it is about 0.5.

The value of parameter *a* in Equation (4) for the middle boreal zone is higher than for the southern boreal zone. This indicates, in accordance with coefficients of Equations (2) and (3), that the mean number of thunder days in the middle boreal zone has been more sensitive to the changes of mean daily maximum temperatures than in the southern boreal zone. The main reason for this may be that the daily maximum temperatures in the middle boreal zone actually more distinctly reflect the frequency of occurrence of dry air masses of Arctic origin, than farther south. It is in agreement with the fact that the frequency of occurrence of the dry air masses of Arctic origin in the middle boreal zone, and its variations, are also greater than farther south. Considering, however, that the values of *a* are rather rough, the zonal difference of parameter *a* may be partly caused by the inaccuracies of the variables involved. Consequently, the average a = 2.7 thunder days per °C applies well for both zones.

In both zones, daily maximum temperatures had a strong decreasing trend, the mean annual change in the middle boreal zone being –0.021 °C and in the southern boreal zone –0.016 °C. For the second time step, the decrease per year in the middle boreal zone was greater than for the first one, while the opposite holds for the southern boreal zone. The decreasing trend of daily maximum temperatures indicates the increasing proportion of air masses of arctic origin.

The central role of the increase in the proportion of dry air masses of arctic origin is also supported by observations of relative humidity: The mean values of the relative humidity in summer at Sodankylä observatory, situated between the middle boreal zone and the Arctic Ocean at 67.4 °N, as calculated with the number of thunder days as monthly weights, are for the consequential periods 1931–50, 1970–86 and 1987–96 67.4 %, 60.9 % and 62.3 %, respectively.

3.5 Thunder and forests

The volume growing stock has increased, which, according to Equation (4), has had a decreasing effect on the number of thunder days. According to Equation (4), the number of thunder days in the middle boreal zone seems to be more sensitive to the changes of the amount of growing stock than in the southern boreal. One reason for this may be the fact that in the middle boreal zone, tall tree stands have grown on totally or almost open mires due to the huge drainage measures while in the southern boreal zone trees have grown taller in forests that also earlier had rather tall stands.

Over the first time step, from 1931–1950 to 1970–86, the effect of the increasing volume of growing stock on the number of thunder days has been weaker than the opposite effect of climatic change towards lower daytime temperatures. Over the latter time step, from 1970–86 to 1987–96, the amount of growing stock increased about the same as over the first, from 1931–1950 to 1970–86, while daytime temperatures fell less. Consequently, over the latter time step, the effect of the increase of the amount of growing stock has exceeded the opposite effect of temperature. Considering that the volume of growing stock has increased faster in the southern boreal zone, the number of thunder days there has risen nearly to the level before the minimum, while in the middle boreal zone it has remained much below.

The zonal difference of the thunder days increased over both time steps, in the first by 0.4 from 0.6 to 1.0 and in the second by 0.2 from 1.0 to 1.2 days (all stations included). For both time steps the zonal difference of the amount of growing stock behaved similarly in time, increasing in the first step by 3.9 m^3ha^{-1} and in the second by 2.3 m^3ha^{-1}; thus, during both time steps, the increase in the difference of thunder days between the zones has been about 0.1 times the increase in the difference of the volume of growing stock (m^3ha^{-1}) between the zones.

From Table 1 we can note the exceptional behaviour of thundering around the main watershed regions of Suomenselkä, Maanselkä and Karjalanselkä. The mean decrease in the number of thunder days from the period 1931–50 to 1987–96 according to aural and visual observations at stations around those watersheds (for observation stations, see *Appendix*) was 1.9; the corresponding decreases are 1.8 in the middle boreal zone south of the 65th latitude (comprising the watershed areas), 0.7 in the middle boreal zone as a whole and 0.1 in the southern boreal zone. In these particular watershed regions, very old forests with tall stands still occurred till the early fifties – agreeing with a particularly high number of thunder days there during the period 1931–50 – but were logged later (Fig. 2). Note that also for the period 1887–1936 these watershed areas were distinguished from the surroundings as areas of great thundering.

During the period 1987–96, the results given by both methods, (V&A and ALLS) for the middle boreal zone as a whole, as well as in the main watershed areas within it, are practically the same. Thus we may compare the chart of the mean number of thunder days for the period 1987–96, based on the automatic lightning location system (Fig. 3), to the corresponding chart for the period 1931–50 by *Venho* (1961) (Fig. 4), based on aural and visual observations. The difference between the fields, i.e. the change between the periods, is seen in Fig. 5. The average decrease within the middle boreal zone is 1 day, but around the watersheds the decrease is about 3 days in the west (Suomenselkä), i.e. 2 days more than the average, and 4 days in the east (Maanselkä), 3 days more than average. Comparing with the chart of the decrease of the volume of growing stock per total land area (K) (Fig. 2), we found that in the former region K decreased by 20 m^3ha^{-1} and in the latter region by 30 m^3ha^{-1}. Consequently, in this case the effect of logging on the number of thunder days was about –0.1 thunder day per 1 m^3ha^{-1}. Considering that the number of thunder days within the southern boreal zone increased by 0.09 per increase of the volume of growing stock by 1 m^3ha^{-1}, it seems that this magnitude of the response (0.1 days per 1 m^3ha^{-1}) is generally valid as the forest area is unchanged, whereas the response of thundering to stands grown by afforestation, which occurred on the mires of the middle boreal zone during the few latest decades, seems to be ca. 2 to 3 times that.

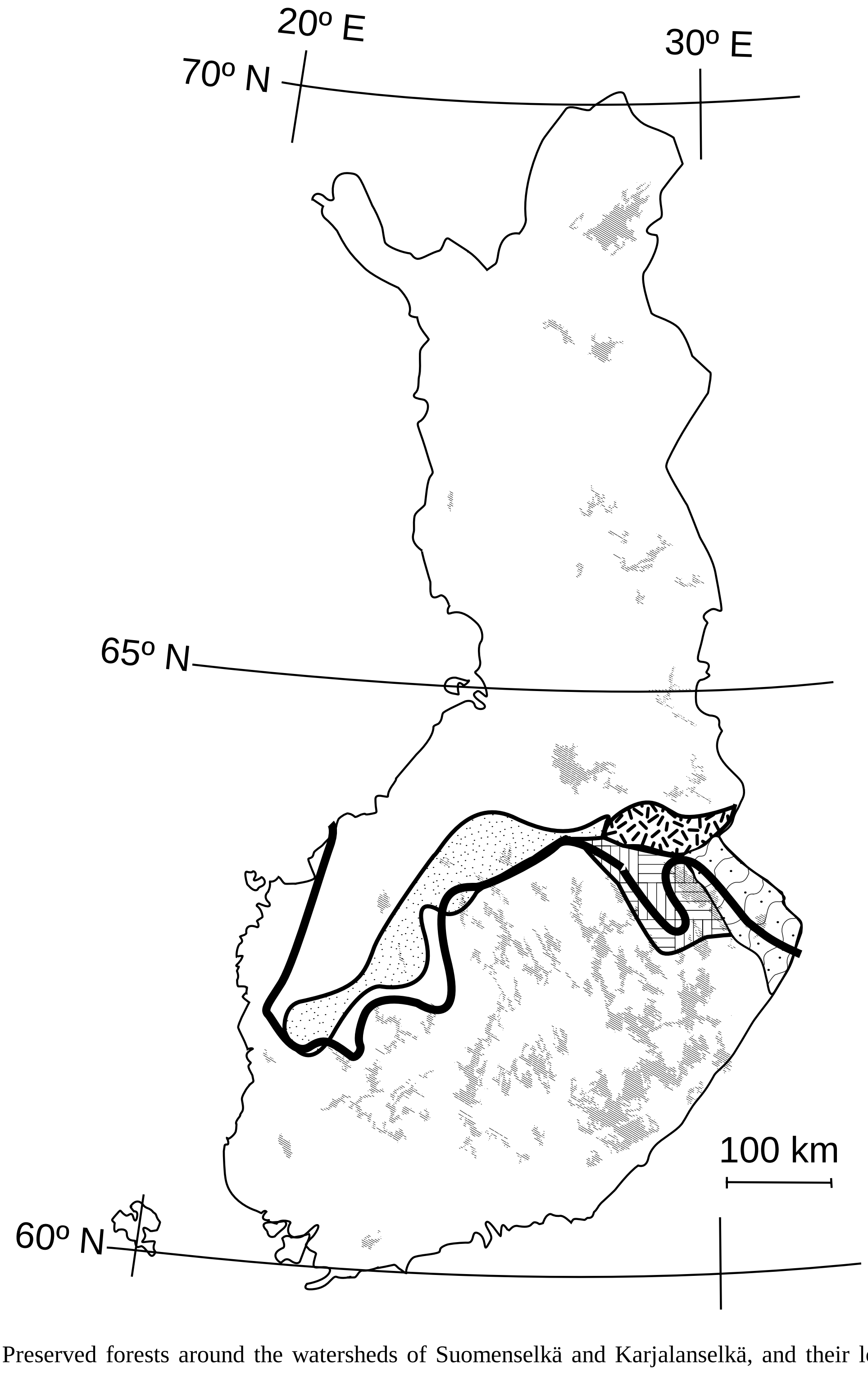

Fig. 2. Preserved forests around the watersheds of Suomenselkä and Karjalanselkä, and their loggings. The bold line denotes the boundary between the southern and middle boreal zones.

= Regions where the volume of the growing stock per a hectare of forest decreased from the period 1921–24 to 1951–53 by 30 m^3.

= Regions where the volume of the growing stock per a hectare of forest decreased from the period 1921–24 to 1951–53 by 20 m^3.

= Regions where the volume of the growing stock per a hectare of forest decreased from the period 1921–24 to 1951–53 by 15 m^3.

= Regions where very old forests (more than 160 years) dominated still 1951–53.

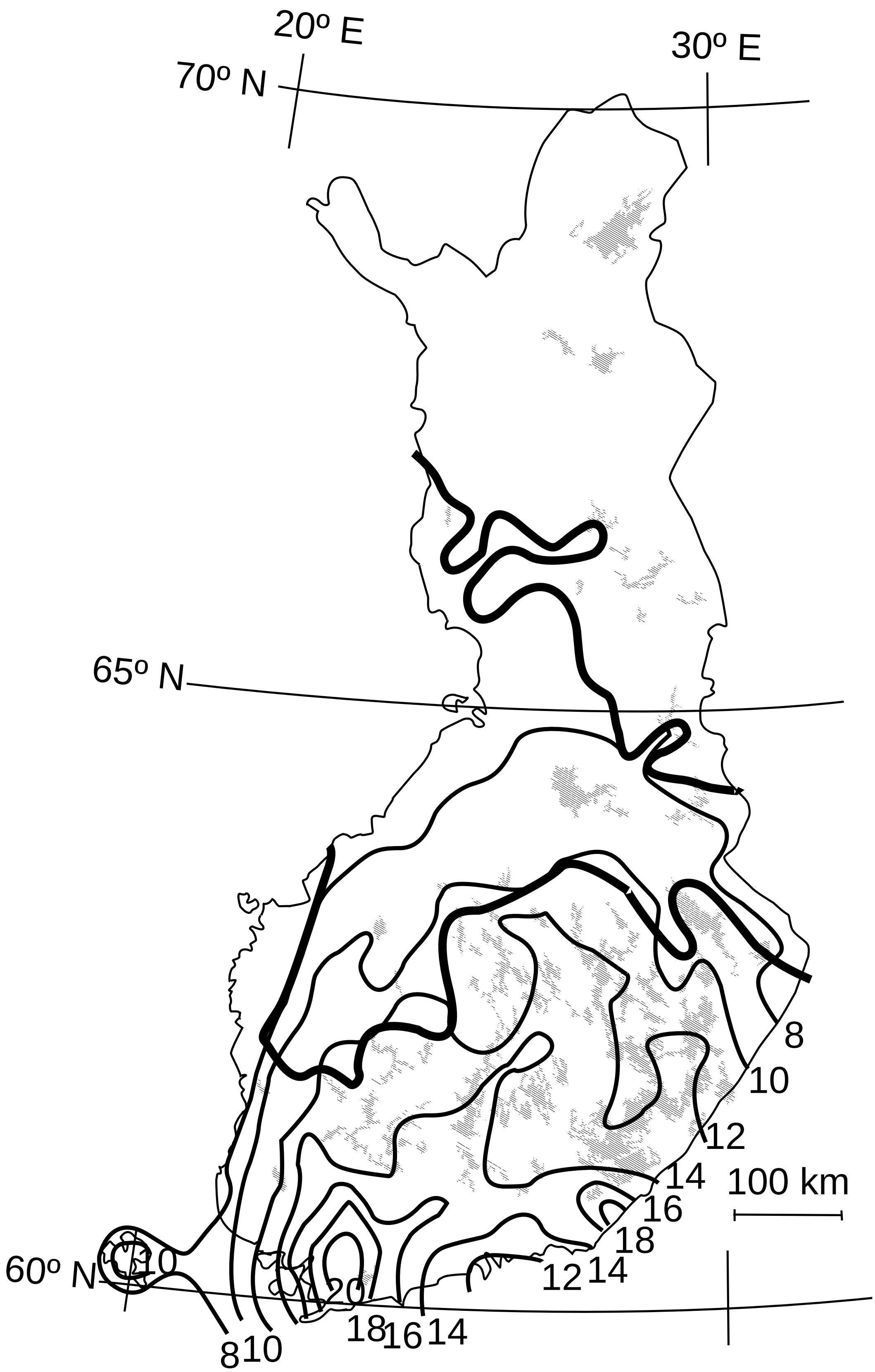

Fig. 3. The mean annual number of thunder days for the period 1987–96 based on the observations of the automatic lightning location system.

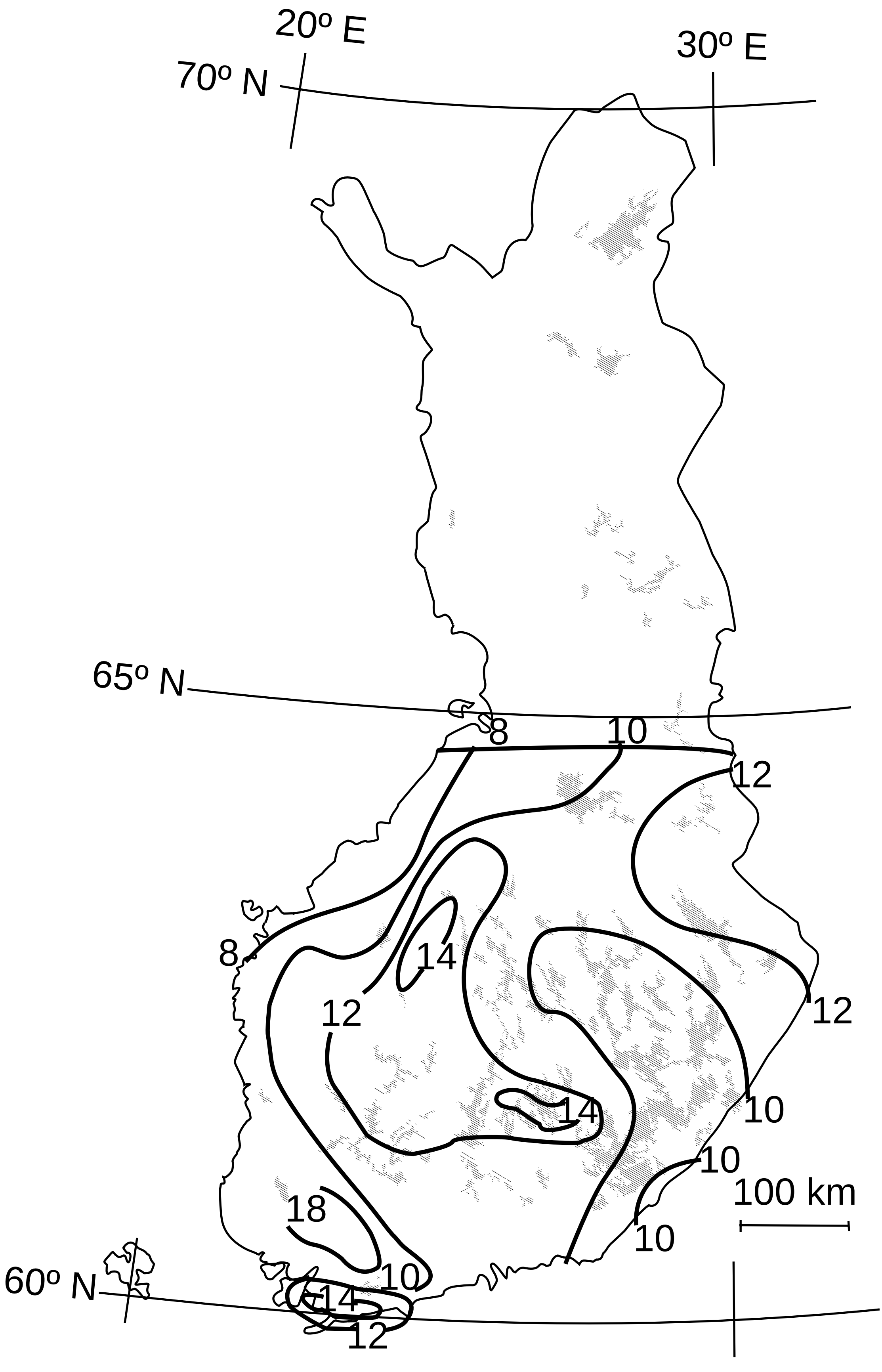

Fig. 4. The mean annual number of thunder days for the period 1931–50 based on aural and visual observations (*Venho*, 1961).

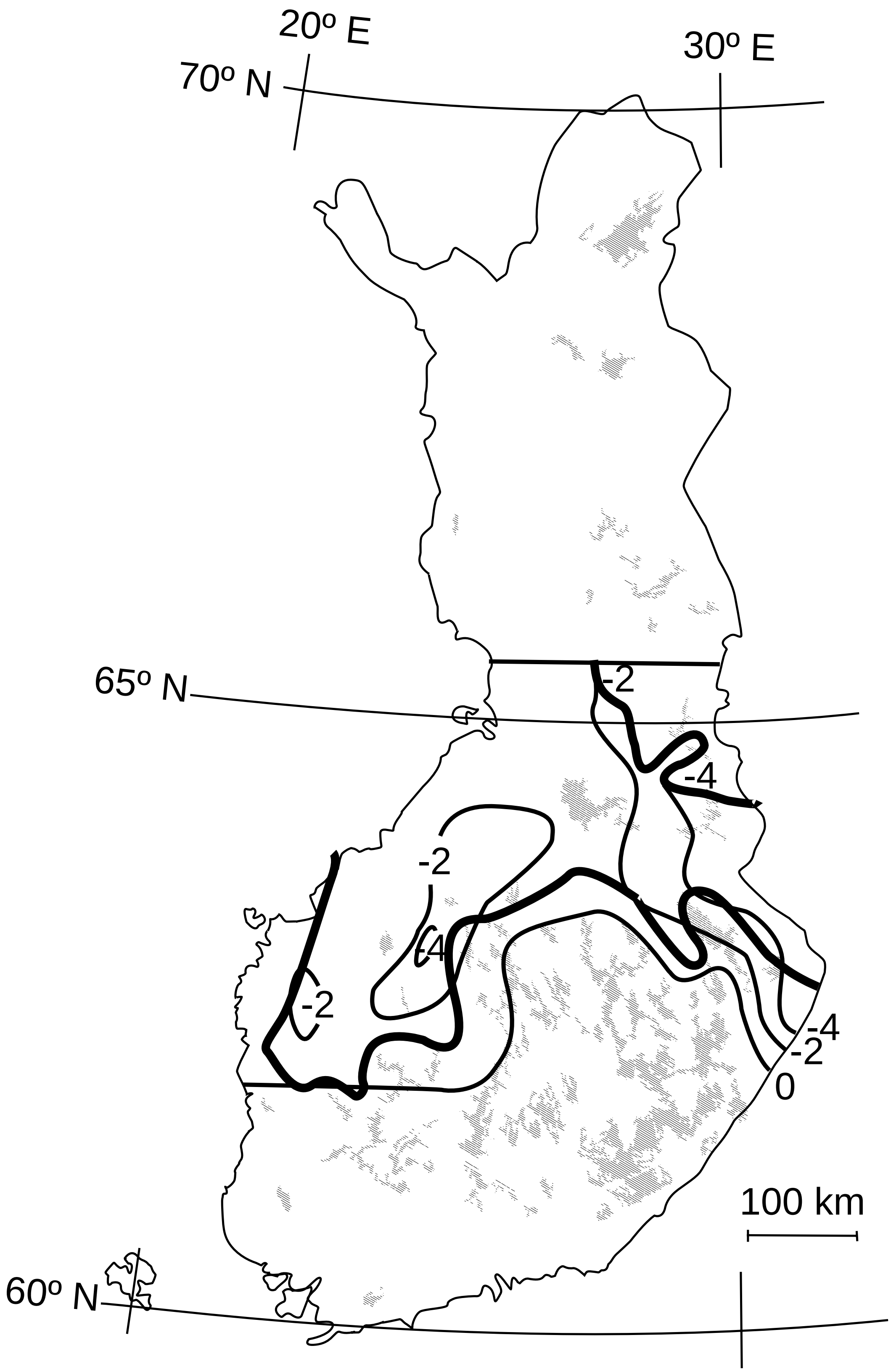

Fig. 5. The change of the mean annual number of thunder days from the period 1931–50 to 1987–96 in the middle boreal region south of the latitude 65.5°N, incl. the northern edge of the southern boreal zone. The boundaries between the zones are given as bold lines.

On the basis of the grid chart of the mean annual number of thunder days for the period 1987–96, based on the automatic lightning location system, the difference between the zones is as great as 12.3–9.3=3.0, which is statistically significant at the 99% confidence level. The flash density (referring to an unpublished chart) changes proportionately across the boundary between the southern and middle boreal zones even more than the number of thunder days, the zonal means being 20.9 and 12.5 flashes per 100 km^2; in the southern boreal zone, there were 1.71 flashes 100 per km^2 in a thunder day but in the middle boreal zone only 1.34 (these values of the flash density are underestimates but their relative values are considered to be correct. A new location system set up in 1997 detects much more lightning). According to this method, the number of thunder days in the southern boreal zone is greater by 1.8 while in the middle boreal zone it is the same as that given by aural and visual observations. This agrees well with the fact that local effects, such as the contribution to the atmospheric moisture by local evaporation and the corona effect above tall stands, are more effective in the southern boreal zone than in the middle boreal. They are threshold factors for the occurrence of air mass thundering more than for the frontal one. Thus, weak discharges that easily escape an observer's notice, seem to occur significantly more in the southern boreal zone than in the middle boreal. The flash density (a chart for the period 1987–98 by *Tuomi,* 1998) changes proportionately across the boundary between the southern and middle boreal zones even more than the number of thunder days.

3.6 Regional features

Let us consider the regional features of the number of thunder days in the light of the ALLS chart for the period 1987–96 (Fig. 3). Besides the difference between the two zones, we may note the small amount of thundering along the western coast; prevailing north-westerly winds in daytime direct dry air from the cold sea on the adjacent coastal mainland, and also dry air of arctic origin from northern Finland. We may also note a maximum occurrence of thunder in the southernmost corner of Finland with an accentuated coastal convergence. A similar maximum with convergence occurs in the south-eastern corner of Finland, an area between Lake Ladoga, the Gulf of Finland and Lake Saimaa. A weaker convergence line, observed only in the chart of flash density (*Tuomi,* 1998), can be noted around the watershed "Savonselkä" between the two large inland basins Vuoksi and Kymijoki.

4. Discussion

As a conclusion, the main features of the areal and temporal distribution of the occurrence of thunder in Finland can be satisfactorily found and explained by making use of both the traditional and modern observation systems. Strong although not fully convincing implications of the significant role of growing stock for the occurrence of thunder is also found, both for the temporal changes and the regional main features. The effect of the change in the amount of growing stock is comparable to the effect in the changes in the mean daily maximum temperatures. Generally, the rapid increase in the amount of growing stock, which has occurred particularly during the two last decades, has significantly eliminated the effect of the contemporary falling trend in daily maximum temperatures. Only around large water shed areas where old forests were logged from the 1930's to the 1950's, is a significant fall in occurrence noted, in agreement with decreasing effects for both the climatic and forestall reasons. It is also shown that there is a permanent belt of a steep gradient of thundering, and there are natural reasons for the existence of this boundary. This belt falls together, on the one hand, with the mean location of the polar front, which separates dry air masses of Arctic origin from the moister air masses originating in the south. On the other hand, this deep gradient of thundering falls together with the location of the boundary between the southern and middle boreal natural zones, at which the volume of growing stock steeply decreases northwards, more by natural reasons than due to forestry measures. This change of the volume of growing stock, in turn, is a natural adaptation of forests to the climate and the location of the polar front (*Solantie,* 1990). The decrease of growing stock northwards across this boundary belt accentuates the effect of polar front in two ways, first through the increase of evaporation with the amount of trees, and second, through the correlation between the occurrence of thundering and tall stands. If tall stands enhance thundering, as the results suggest, this promotes in natural conditions the renewal of mature forests while the risk of young forests to be destroyed by fire remains low. In the southern boreal zone forests stand for more frequent fires than in the middle boreal zone because they grow much faster.

These results are obviously more or less valid within the southern and middle boreal zones around the northern hemisphere, i.e. in Scandinavia, northern Russia, Siberia, Alaska and Canada. The general and regional features and behaviour of thundering in the boreal zone are still waiting for a more comprehensive understanding. Therefore, more studies on historical data in other countries of the boreal zone, and a more detailed study of old Finnish data, are desirable, in addition to the results from the new and more accurate observation systems. The new lightning location system, in operation since August 1997 will, within a few years, produce a very detailed picture of the distribution of lightning in the 2-km scale. Then, further and more accurate comparisons between thunder and the character of forests will be possible.

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Appendix

1. Forest statistics

In calculating the volume of growing stock, the middle boreal zone was represented by the area consisting of the forestry board districts of Pohjois-Pohjanmaa, Kainuu, Keski-Pohjanmaa and Etelä-Pohjanmaa, and the southern boreal zone by the area consisting of all the other districts farther south. The period 1931–50 was represented by the results of the third national forest inventory (NFI III) (*Ilvessalo*, 1957), the period 1970–86 by the mean results from NFI V (1964–68) (*Forest Research Institute*, 1974) and NFI VIII (1983–93) (*Aarne*, 1994) and the period 1987–94 by the results from NFI VIII.

2. Climatic stations used for the temporal changes of the daily maximum temperatures

The mean changes in the middle boreal zone were obtained as arithmetical means of changes for the climatic stations at Sodankylä, observatory (67.4°N, 26.6°E),Vaala, Pelso (64.5°N, 26.5°E), Ylistaro, (62.9°N, 22.5°E), Maaninka (63.1°N, 27.3°E), and Tohmajärvi (62.2°N, 30.3°E). The mean changes in the southern boreal zone were obtained as weighted means of changes for the climatic stations with weights as fractions in parentheses at Ylistaro (1/6), Maaninka (1/6), Tohmajärvi (1/6), and Heinola (1/2) (61.2°N, 26.0°E).

3. Climatic stations used for the regional mean of the number of thunder days around the main water shed areas of Suomenselkä, Maanselkä and Karjalanselkä 1970–86 and 1987–96

1970–1986: Karvia, Kuru, Ähtäri, Alajärvi, Nivala, Haapavesi, Kajaani, Kuhmo, Juuka, Lieksa and Ilomantsi; the stations are "selected", except Alajärvi and Kuhmo.

1987–96: Karvia, Kuru, Ähtäri, Alajärvi, Halsua, Nivala, Haapavesi, Pyhäntä, Vieremä, Kajaani, Kuhmo, Rautavaara, Valtimo, Juuka, Lieksa and Ilomantsi. The stations are "selected", except Kuru, Alajärvi, Kuhmo, Rautavaara and Valtimo.