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# The Characteristics of Lightning Occurrence in Southern Germany

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**Abstract**

For the first time, the temporal and spatial distributions of lightning in southern Germany are studied. Data is taken from a newly installed lightning location system (LPATS). The data base covers the years 1992–1994. Inside the observational are of 500 km × 430 km a mean value of 634,000 cloud-to-ground lightning strokes per year is detected. This corresponds to a lightning frequency of 1.2 per minute and a spatial density of 2.8 $yr^{-1}km^{-2}$. Most of the lightning events are confined to the summer months May–August with a mean number of 29 thunderstorm days per year. The diurnal cycle of lightning activity peaks at 1600–1700 local time with a subsequent slow decrease towards the minimum in the morning hours. A secondary maximum is found between 2100 and 2200 which is shown to be a propagation effect from distant thunderstorm source areas. The spatial lightning distribution confirms the well-known preference of certain areas for the development of thunderstorms. Such preferred areas are the leeward side of the Black Forest, the Allgäu and other parts of the Alpine foreland. Here lightning densities of more than 10 $yr^{-1}km^{-2}$ may occur. A comparison with routinely gathered thunderstorm data yields a good agreement.

**Zusammenfassung**

**Zur Charakteristik der Blitzverteilung in Süddeutschland**

Es wird die zeitliche und räumliche Verteilung von Blitzen in Süddeutschland untersucht. Die verwendeten Daten stammen von einem neu installierten Blitzortungssystem (LPATS) und umfassen den Zeitraum von 1992–94. Innerhalb des Beobachtungsgebietes mit einer Fläche von 500 km × 430 km wurden im Jahresmittel 634 000 Wolke-Erde Blitze registriert. Das entspricht einer Blitzfrequenz von 1,2 pro Minute und einer Flächendichte von 2.8 $yr^{-1}km^{-2}$. Die meisten Blitzereignisse sind auf die Sommermonate Mai–August konzentriert. Im Mittel treten im betrachteten Gebiet jährlich 29 Gewittertage auf. Der Tagesgang der Blitzaktivität erreicht das Maximum bei 1600–1700 Ortzeit und fällt danach stetig zum Minimum in den Morgenstunden ab. Ein sekundäres Maximum wurde zwischen 2100 und 2200 Ortszeit gefunden und auf die Wirkung langlebiger Gewitter zurückgeführt, die sich von den typischen Gewitterherden ausgehend über große Entfernungen ausbreiten können. Die räumliche Verteilung der Blitze zeigt die für häufige Gewitterauslösung bekannten Gebiete. Solche Gebiete sind die Leeseite des Schwarzwaldes, das Allgäu und andere Teile des Alpenvorlandes. Dort können Blitzdichten von über 10 $yr^{-1}km^{-2}$ auftreten. Ein Vergleich mit routinemäßig gewonnenen Gewitterbeobachtungen ergibt eine gute Übereinstimmung.

## 1 Introduction

In recent years lightning location systems have been installed in many countries (Holle and Lopez, 1993). Much has been learned from these systems, not only about the lightning activity itself but also about the thunderstorms causing the lightning. This resulted in an improved understanding of storm evolution and propagation. Due to hail, heavy precipitation, flooding, gusts and lightning, thunderstorms are one of the major cause of natural disasters in Central Europe. Improved forecasting of thunderstorms, therefore, is of vital interest. The combination of lightning data with radar observations presents new perspectives in the now-casting of convective storms as demonstrated by Stern et al. (1994). Because of the damage potential also insurance companies, building companies and electricity suppliers take a general interest in the characteristics of lightning occurrence. Lightning also plays a fundamental role in tropospheric chemistry as it produces nitrogen oxides (Franzblau and Popp, 1989). However, the global strength of this natural source is still uncertain by an order of magnitude.

Since 1992 data from a **L**ightning **P**osition **A**nd **T**racking **S**ystem (LPATS) is available for the southern half of Germany. The system is manufactured by Atmospheric Research Systems, Inc. (ARSI) (Bent and Lyons, 1984). It was installed by the two power supply companies Bayernwerk AG, München und Badenwerk AG, Karlsruhe (Fister et al., 1992). The original and main purpose for the LPATS installation is the monitoring of the lightning activity to allow for a timely replacement of potentially damaged power links and power stations. The system also allows to warn maintenance crews operating on electricity masts and towers.

Here we present a statistical analysis of data gained during the first three years of operation 1992–1994. A preliminary overview was already given by Fister et al. (1994), but a meteorologically-oriented analysis of lightning occurrence is still lacking. This is the primary objective of this paper.

In quite a few reports (e.g., Lopez and Holle, 1986; Reap and MacGorman, 1989; Orville, 1994) the characteristics of lightning in the United States are studied. There, ground-based lightning location networks have been in use since the mid-eighties. We will compare our findings with results from these networks. Our special scientific interest is the understanding of thunderstorm initiation and propagation in the Prealpine region. So far the most concise information on the characteristics of thunderstorms in southern Germany was provided by Alt and Weickmann (1910). It is based on the audible thunder monitored by 177 voluntary and official observers during the fifteen-year period 1893–1907. This early and carefully-written work not only gives the regional distribution of thunderstorm activity but also the diurnal cycle. Later Pelz (1984) used this data, together with other available historical material and routine observations and produced maps of annual thunderstorm days for whole of Germany. With the now-available data from lightning location systems it is possible to check these results on more objective grounds.

The paper is organized as follows. In Section 2 we give a short description of the lightning detection system and the data evaluation. In Section 3 we present the temporal distribution of lightning activity and in Section 4 its spatial distribution. Annual thunderstorm days are studied in Section 5 and the discussion follows in Section 6.

## 2 Lightning Detection and Data Evaluation

The lightning detection system consists of an array with 6 receiving stations distributed over southern Germany. Average separation between the stations is 200 km (Figure 1).

Each receiver detects the broadband (2–500 kHz) electrical component of the electromagnetic radiation emitted by the return stroke and assigns to it the time of arrival of its peak amplitude (Bent and Lyons, 1984). The common assumption is that this peak amplitude occurs when the upward streamer from the ground meets the downward moving stepped leader thus closing the lightning channel. This contact point is approximately 100 m above ground (Holle and Lopez, 1993). If at least four stations receive a pulse within a given time window and if the amplitude exceeds a detecting threshold value, a lightning discharge is identified. Differences in time of arrival between pairs of stations are calculated which then yield an unambiguous location of the lightning event. To achieve an accuracy of

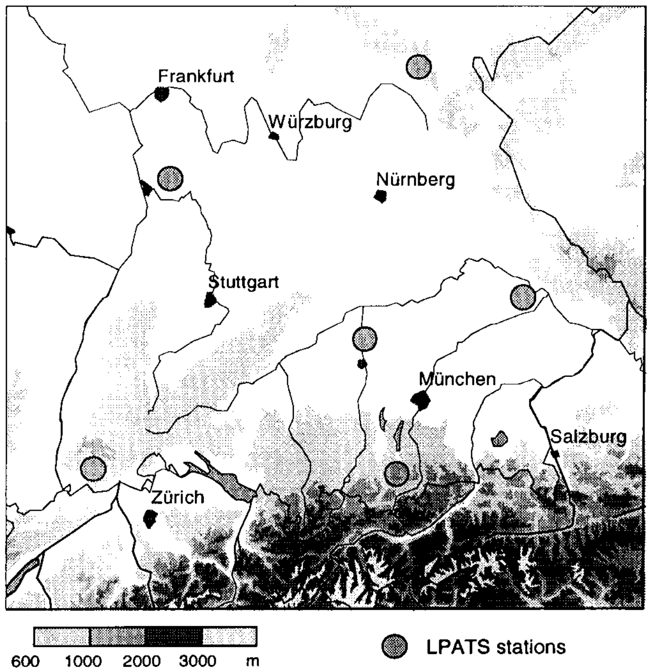


**Figure 1** The LPATS network of the Bayernwerk AG and Badenwerk AG in southern Germany. All lightning loci inside the shown area are evaluated. The area covers southern Germany and parts of the neighboring countries. Grey scale gives height in meters above sea level.

100 m, the time synchronization between all six stations must be better than 30 ns. For the given system this is presently realized using GPS (Global Positioning System) data and synchronization signals from television satellites.

The LPATS is designed to localize cloud-to-ground (CG) lightning and to ignore cloud-to-cloud (CC) discharges, though the latter are more frequent than CG-discharges. The ratio between the frequency of both lightning types depends on the geographical latitude. While in Prentice and Mackerras (1977) a factor of 3 is given for the midlatitudes, more recent observations (Mackerras and Darveniza, 1994) indicate a lower value of 1.3. Due to their general weaker amplitude CC-discharges are less frequently detected by LPATS. Also the waveform of the received signal differs between the two types of lightning discharges (Uman, 1987). The lightning detector uses this features for the identification of the type of discharge and rejects most of the contribution from the CC-lightning (Bent and Lyons, 1984). However this procedure removes some of the weaker CG-strokes as well.

The *detection efficiency* of the system depends on antenna and receiver characteristics, atmospheric propagation conditions, network geometry, the kind of discharge and some other factors. Usually, an overall detection efficiency of 70 % is quoted for the LPATS (Schütte et al., 1987). Position accuracy is better than 1000 m inside the network polygon (Bent and Lyons, 1984) and time resolution is about 15 ms. This is less than the typical time interval between subsequent strokes constituting a lightning flash. Thus, multiple strokes can be detected. Since, however, subsequent strokes have weaker amplitudes, some of them may not be detected by the LPATS and the multiplicity of flashes is underestimated. For the data analyzed in this study we derived a number of 1.4 strokes per flash, in contrast to the multiplicity of 2–3 strokes per flash which is generally observed at the midlatitudes (Reap and MacGorman, 1989; Uman, 1987). In the following, we ignore the multiplicity of flashes and focus solely on the distribution characteristics of *strokes*. One has to be aware of this fact when comparing the results with data from other lightning location systems. If data from magnetic direction finder (MDF) networks is used, usually the distribution of lightning *flashes* is examined, in contrast to this study.

A built-in algorithm estimates the peak current amplitude of the return stroke from the measured signal strength and the calculated location. However, the result is a crude estimate only, mainly because the relation between the electric radiation field and the resulting antenna voltage depends strongly on local, but unfortunately unknown, conditions. This should be kept in mind when interpreting peak current values.

The LPATS output is a record of lightning events ordered in time. Each record contains time, location and peak current amplitude for each identified and analyzed lightning discharge. Raw data were preprocessed (Fister et al., 1994) but no attempts were made to compensate for the detection efficiency as suggested by Orville (1991). With increasing distance from the array, the detection efficiency decreases, mainly because the signal amplitude decreases approximately with $1/r$. Evaluation of data, therefore, has to be limited to an area of approximate equal distances to at least four stations. For the given network we have chosen the area inside the coordinates 7°–14° E longitude and 46.8°–50.7° N latitude shown in Figure 1. Nearly 97 % of all loci within this area have distances to at least four stations of less than 350 km. Size of the area is about 500 km × 430 km = $215 \cdot 10^5$ km$^2$. Besides southern Germany, also Liechtenstein and parts of France, Switzerland, Austria and Czechia are covered.

The set of $N$ lightning positions can be represented as an empirical density function of space and time

$$f(t, \vec{r}) = \sum_{i}^{N} \delta(t - t_i)\, \delta(\vec{r} - \vec{r}_i), \tag{1}$$

where the $t_i$ and $\vec{r}_i$ denote the time and location of the $i$th detected stroke. The Dirac function $\delta(t - t_i)$ and $\delta(\vec{r} - \vec{r}_i)$ are used in their conventional meaning. For the statistical analysis of this paper we examine the properties of this function and its integrals over some sub-intervals in time and area. To determine e.g. the number of lightning events which occurred during the time interval $\Delta t$ around the central time $t$ and inside the area $\Delta F$ around the location $\vec{r}$ we integrate

$$N(t, \vec{r}; \Delta t, \Delta F) = \int_{\Delta t, \Delta F} f(t + \tau, \vec{r} + \vec{\rho})\, d\vec{\rho}\, d\tau. \tag{2}$$

## 3 Temporal Distribution

To study the temporal distribution of lightning activity, we consider time integrals over three years, one year, one month, one day and 10 minutes and integrate over the complete area $F$ shown in Figure 1

$$N(t; \Delta t, F) = \int_{\Delta t, F} f(t + \tau, \vec{r} + \vec{p})\, d\vec{p}\, d\tau. \qquad (3)$$

### 3.1 Total Number of Lightning Events

Within the analysis region the total numbers of lightning events counted are 544,000 in 1992, 587,000 in 1993, and 771,000 in 1994. This gives a mean number of about 634,000 lightning strokes per year and a mean lightning frequency of 1.2 per minute. If only the period from May to August is considered, when the most thunderstorms occur, the frequency increases to 3.6 per minute. And if we look at the lightning activity during storms and focus on time intervals with more than 5 strokes per minute, we get an average value of 9.3 per minute. We compared this value with the global lightning frequency, which is approximately 100 $s^{-1}$ (Orville and Spengler, 1979), i.e. we tried to estimate the contribution of storms in southern Germany to the global value and found a percentage value of 0.2 %. The distribution of lightning events is strongly inhomogeneous in time and space. During single intense storms lightning frequencies may exceed the above mean values by orders of magnitude. This will be discussed below. In the following we examine the temporal structure of lightning activity.

### 3.2 The Annual Cycle

To characterize the annual cycle, we calculated both the daily and monthly total numbers of strokes. Results are shown in Figure 2 for each of the three years together with the average over the three years. As expected, a well-expressed annual cycle is found. About 95 % of all lightning events were observed in the four summer months May to August. The lightning number increases from April to July and reaches its maximum in July or August. The sharp

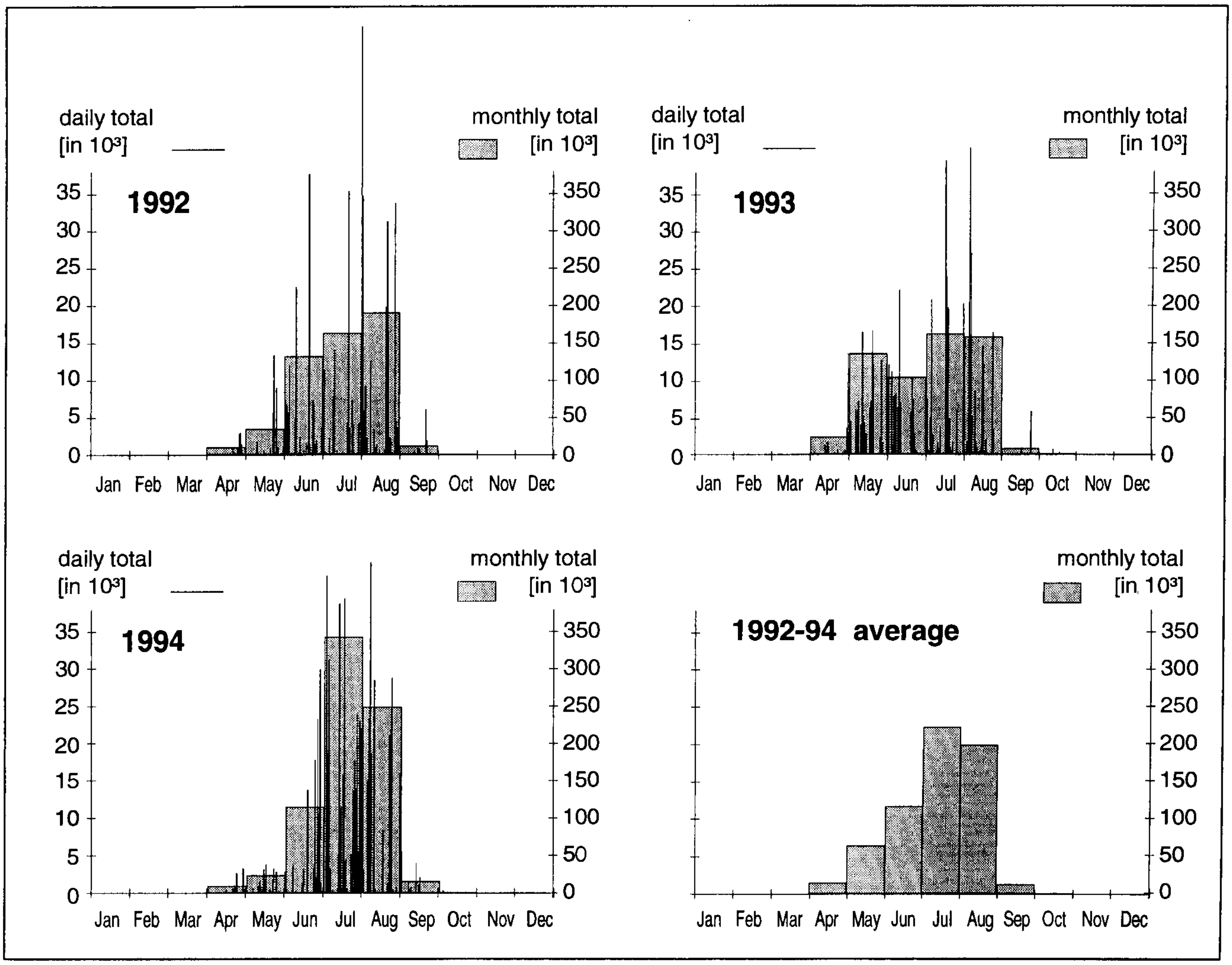


**Figure 2** Annual cycle of lightning for 1992–1994. Narrow, isolated columns denote daily totals while the shaded columns represent monthly totals.

decrease after August marks the end of the storm period. In September the last thunderstorm days are typically ended by abrupt changes in synoptic weather conditions.

Thunderstorm activity exhibits a strong year-to-year variability. This goes parallel with the variability of synoptic flow conditions favourable for the development of thunderstorms. For Central Europe the dominant situation is a south-westerly flow of humid air from the Mediterranean Sea. As, generally, synoptic conditions change on a time scale of 3–5 days, we find days with high thunderstorm activity clustered in groups of a few days while during the remaining days much less or no storms are found. Clustering of thunderstorm days can also be identified by a relative minimum of the autocorrelation function (Figure 6) at three days. Other features of the autocorrelation function are discussed below.

Monthly sums (Figure 2) hide the temporal variability of favourable synoptic flow conditions as the latter vary on shorter time scales. To reveal this fine-scale structure we, therefore, plot additionally in Figure 3 the running monthly totals for the year 1992. Quite surprisingly a minimum in the middle of July appears. In 1993 this minimum shows up for June in the column presentation as well. This minimum is caused by high pressure weather systems with suppressed thunderstorm activity. Flohn (1942) discussed this feature already and referred to it as a minimum between two ‚monsoon waves'. If this or similar features are of interest, the use of running monthly totals is strongly recommended instead of the totals for fixed months.

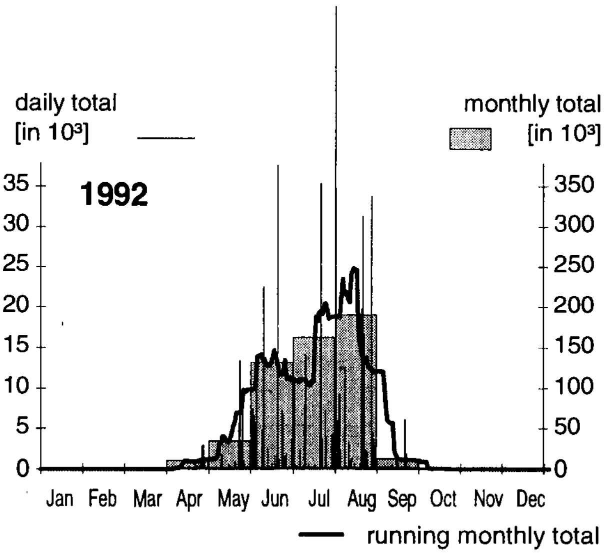


**Figure 3** The 1992 annual cycle of lightning activity in terms of daily totals (single small columns) and monthly totals. Shaded columns are identical with those of Figure 2. In addition now the running sum over 30 days is shown (thin line). Note the fine-scale structure, especially the minimum in July.

The relation of lightning activity to certain synoptic flow conditions also implies, that, whenever the respective conditions prevail, then the thermodynamic atmospheric background is very similar in the whole observational area. The structure of the annual cycle in terms of monthly total numbers, therefore, does not change significantly between various sub-areas. The Alps, however, exert an impact on the synoptic flow pattern. We observe in the Northern Alpine front range significant differences from the other parts of southern Germany (not shown). Lightning activity is low in early summer until June. Then more and more areas at higher altitudes are involved in the thunderstorm evolution processes and the storm frequency increases. Finally, we look at the distribution of daily totals of lightning strokes among the thunderstorm days. Again a clustering is found. Most contribution comes from only a few days with strong lightning activity. In 1993, with a total number of 52 days with thunderstorms over the observation area, for instance, 12 days (= 23 %) with more than 15,000 lightning events occurred, contributing with 49 % to the annual sum. In 1992, 9 from 39 thunderstorm days (≙ 23 %) contributed to 53 % of all strokes, and similarly 1994, 22 from 57 days (= 39 %) gave 72 % of the detected strokes.

### 3.3 Diurnal Cycle

To study the diurnal cycle of lightning activity, we choose as a suitable integration period a time interval of 10 minutes. In Figure 4 the number of all lightning strokes per year which where detected during the 10-minute intervals are shown as function of daytime.First we note, that there is little scatter between the individual years. Diurnal cycles averaged over the years are more alike than the corresponding annual cycles. There is a general structure common to all diurnal cycles. From a minimum in the morning hours lightning activity increases to a maximum at about 1600 followed then by a slow decrease to the early morning minimum. This minimum is observed between 0700 and 1100 local time. Only 6 % of all lightning events is observed in this time interval. It represents the contribution of lightning from frontal thunderstorms. The latter are approximately homogeneously distributed over the day. Their contribution to the diurnal cycle is, therefore, more or less constant over the day, but

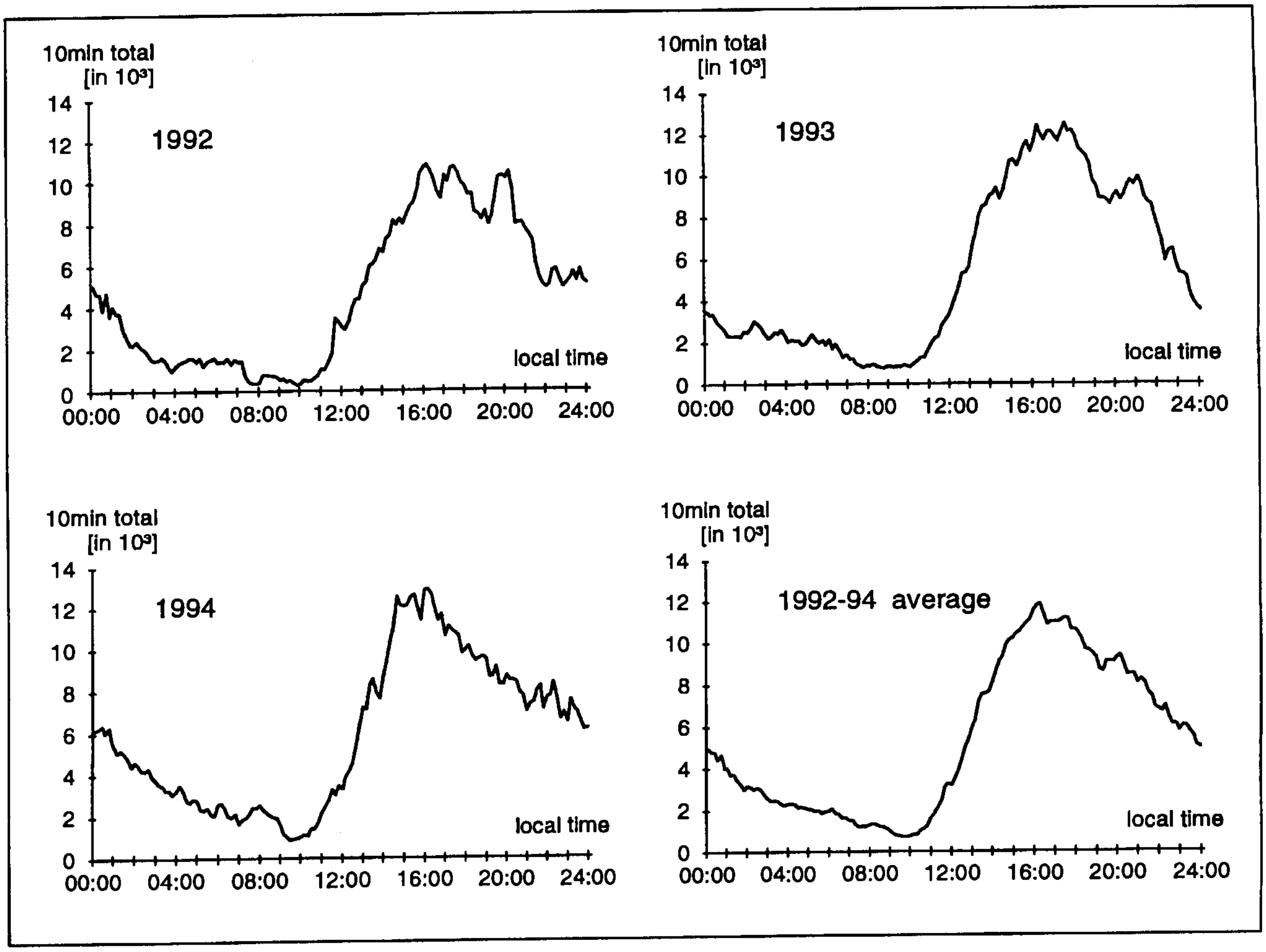


**Figure 4** Diurnal cycle. 10-minute sums of all strokes observed per year in the analysis region as a function of time of the day. Besides the maximum in the afternoon about 1500–1900 local time, a secondary maximum at about 2100 is notable.

appears as the sole lightning source in the absence of convectively-forced storms. The steep and rising flank of the afternoon maximum follows the diurnal, radiatively-forced heating cycle of the atmospheric boundary layer (Stull, 1988). The initiation of deep convection requires a well-mixed state of the fully developped boundary layer which usually is the case at about 1100 in the morning. While this storm initiation time is more or less the same for all locations in space, later storm evolution including the dissipation show considerable scatter of time scales. This also explains the fact that the rising flank is steeper than the falling flank.

One special and significant feature is the secondary maximum between 2000 and 2400. It was first reported and also in principle explained by Alt and Weickmann (1910) using data from nearly 200 observers for 13 years. They found the bimodal behaviour to be more common for the eastern regions of southern Germany with a shift of the maximum position due to the propagation time. With the lightning data we can now show that long-lasting storms which propagate from their south-westerly source areas in predominantly easterly to north-easterly directions cause the secondary maximum. An eye-inspection reveals that most of the strong storms travel typically over 200–300 kilometers and last 4–6 hours. We note that for single years only 2–3 intense storms, mostly in the southern part of the considered region, may generate already the secondary maximum. This small required number of strong storms explains also the observed great interannual and also regional variability. Our conclusions follow similar ideas proposed by Fankhauser and Wade (1982) who analyzed convective precipitation over the Great Plains. They showed that the time of maximum thunderstorm activity is shifted according to the distance from the mountains and concluded that the nocturnal maximum is caused by travelling storms originating at or near to the mountains.

### 3.4 Minute Sums

Finally, we ignore for a while the precise time of a recorded stroke and consider the distribution of lightning on the base of minute sums. The question is raised: how often do we observe a specific number of strokes per minute within the observational area? The frequency distribution of minute sums is shown in Figure 5 on a logarithmic scale. For convenience we included the zero value which is, not surprisingly, the most frequent one: during the most time of the year 1993 (91 %) no lightning was recorded.

The frequency distribution is steadily decreasing. Moreover, for 48 % of the thunderstorm time five strokes per minute or less are observed. Only for 2.7 % of the thunderstorm time intense lightning with more than 60 strokes per minutes is found. These numbers characterize the lightning activity in southern Germany. They are governed (i) by the lightning activity of a single storm, and (ii) by the number of simultaneously occurring storms. If the lightning events are all *independent* the frequency distribution of the minute sums follows a Poisson distribution (see e.g., Feller, 1968). A $\chi^2$-test, however, reveals clearly, with 99 % confidence, that this distribution deviates from a Poisson one. In contrast, it fits quite satisfactorily a Gamma-distribution

$$f(x) = \frac{\alpha^{\nu}}{\Gamma(\nu)} x^{\nu-1} e^{-\alpha x} \quad (4)$$

with the parameter values $\alpha = 0.04$ and $\nu = 0.37$. The fit is shown as a solid line in the Figure 5. The cause of this frequency distribution is not considered further but is seen to be related to the two forementioned reasons.

In order to find the typical time scales of lightning activity in the observational range, we examined the *autocorrelation function* of the time series of minute-sums. Figure 6 shows the normalized autocorrelation function. We note a nearly exponential decrease for time lags shorter than 8 hours. The *e*-folding time is approximately 4 hours, which corresponds to the typical duration of thunderstorm activity. This fact is also reflected in the shape of the diurnal cycle of lightning activity (Figure 4). One should note that the lifetime of individual storms ranges between 2–7 hours. The daily periodicity of lightning activity itself finds its expression in the maxima at multiples of a day. The amplitudes of the first three daily maxima are decreasing. Thus, the aforementioned time scale of three days can be derived. It marks the duration of thunderstorm periods. We note that the ‚daily' period is slightly shorter than 24 hours. This

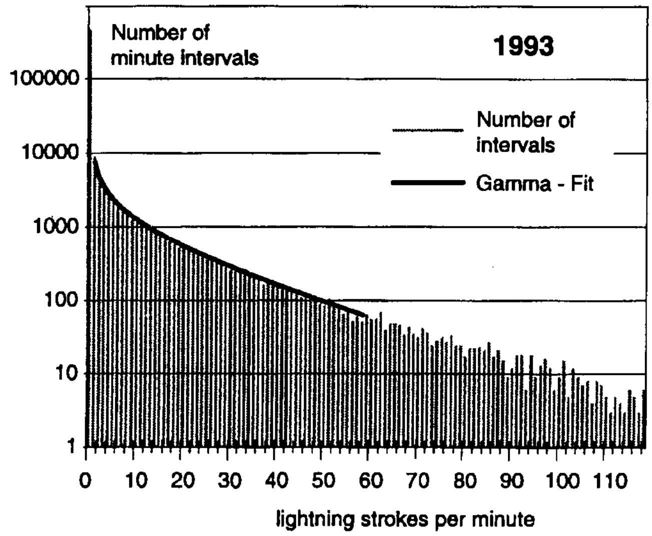


**Figure 5** Frequency distribution of minute sums of lightning strokes. Data is taken for the whole observational area in 1993. Minutes with no strokes are included, comprising the majority observed. Note the logarithmic scaling.

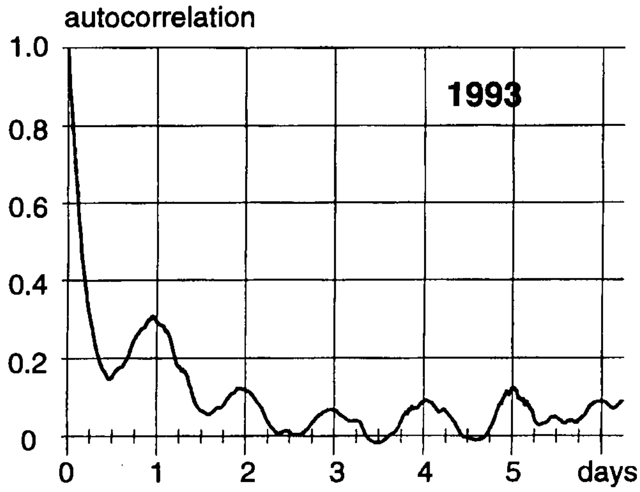


**Figure 6** Normalized autocorrelation function of the minute-sum time series.

points to the process of conditioning: On subsequent days with thunderstorm activity, storm evolution starts on the average earlier than on the preceding day.

### 3.5 Peak Current Amplitudes

As described above, the LPATS calculates the current amplitude of the return strokes using the detected electric radiation field and the determined strike position. This calculation is more difficult than the lightning localization. An exact calibration of the antennas is required and assumptions on the return stroke and signal propagation must be made. Additionally the current statistics is affected by

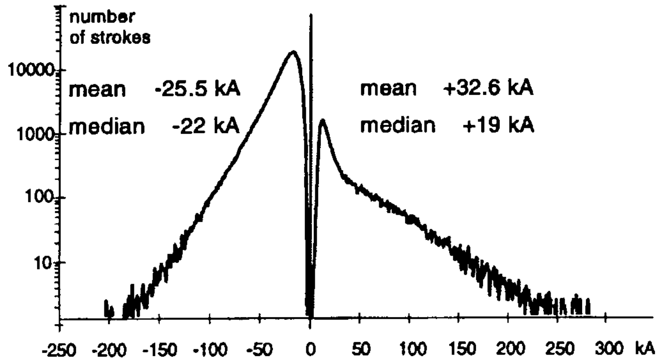


**Figure 7** Frequency distribution of the return stroke currents averaged over the years 1992–93. Note the logarithmic scaling. At zero amplitude we displayed the strokes, which were classified by the LPATS as CC-strokes.

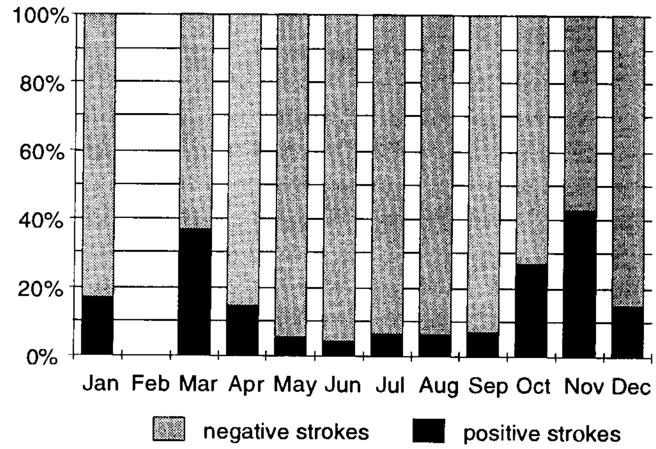


**Figure 8** Seasonal variation of the proportions of positive and negative strokes for the years 1992–93. Strokes with zero amplitudes were omitted. In February of both years no lightning strokes were detected. For each of the months November–March less than 1000 strokes were counted.

internal system parameters such as detection thresholds and the network geometry (Diendorfer et al., 1994). Therefore, the resulting current amplitudes must be interpreted with more caution than the lightning position parameters. A comparison of the current statistics between different networks and even more between different location methods requires the knowledge of the system parameters.

The averaged frequency distribution of stroke amplitudes is depicted in Figure 7. Mean current amplitudes were found at – 25.5 kA for the negative strokes and at 32.6 kA for the positive strokes. The interannual scatter was smaller than 7 %. These mean values are lower than those observed in northern Australia by Petersen and Rutledge (1992) (39 kA for positive and negative flashes), but are close to the results of Berger et al. (1975) for Switzerland (– 30 kA and + 35 kA). As mentioned in the previous section we did not distinguish between first and subsequent strokes constituting a lightning flash. Since the current amplitude for subsequent return strokes is smaller than for the first stroke our estimate for the mean values should be lower compared to results from magnetic direction finder networks where usually only the first strokes are considered.

Remarkable is the different shape of the distribution function (Figure 7) for negative and positive strokes. The decay at large amplitudes is slower for the positive strokes. There is a high number of weak (< 20 kA) positive strokes. These features were also found and discussed by Lopez et al. (1991) analyzing observations of a magnetic direction finder network. The large proportion of weak positive strokes gives rise to the low median value of 19 kA. For the negative strokes, in contrast, the median (– 22 kA) is close to the mean amplitude.

Positive strokes are much less frequent than the negative ones. Only 5.1 % of all detected strokes were positive. This value agrees well with the value 3.1–4.0 % reported by Orville (1994) for the USA. A proportion of 12.6 % strokes was classified as CC-strokes. It is supposed, however, that this quantity contains some weak CC-strokes of both polarity as well. Figure 8 shows the seasonal variation of the monthly averaged ratio of positive to negative flashes. During the summer months May–August the positive strokes contribute only about 5 % to the total stroke number, whereas this percentage increases significantly in the colder seasons of the year. The relative high number of positive discharges in winter thunderstorms is a common observation (e.g. Orville et al., 1987; Hojo et al., 1989). Thunderstorms occurring in the colder season mostly take place in a sheared environment and do not extend to large altitudes. Under these conditions more positive streamers proceeding from the upper, positive charge center of the cloud can reach the ground (see e.g. Brook et al., 1982; Takagi et al., 1986).

We established a good agreement of our observations with previously reported current statistics. In view of the mentioned problems with the accuracy of the peak current values, we refrain from discussing the differences to other observations in detail.

## 4 Spatial Distribution

### 4.1 Density of Lightning Strokes

We integrate Eq. (2) over the time period of one year. The result then is smoothed over areas of 16 km × 16 km. This gives the spatial distribution of the yearly sums of lightning strokes. Figure 9 shows the annual density of lightning strokes in the observational area for each year 1992–94 and the average over all three years.

First we note that there are preferred areas of lightning activity. They show up very clearly in all three subsequent years despite a significant year-to-year variability. Stroke densities range from values of about 2 $yr^{-1}km^{-2}$ found in most parts of southern Germany to 10 $yr^{-1}km^{-2}$, or even more, in the Black Forest. The maximum densities of 10 $yr^{-1}km^{-2}$ compare well with values found in subtropical regions. Orville (1994) e.g. reported for Florida flash densities of 9–13 $yr^{-1}km^{-2}$.

The pattern of the spatial lightning distribution is clearly related to orography. So the area of maximum lightning density in the Southwest is fixed to the Black Forest mountains. All the other mountainous areas can be identified in the lightning patterns, although not in every year: Spessart, Taunus, Bavarian Forest, to mention some. The high correlation of the distribution of thunderstorms to the main orographic features was also found by Pelz (1984) for the whole of Germany. We note that the maxima of lightning density are shifted to the leeward sides with respect to the prevailing south-westerly flow. Storms are initiated in the mountains, as the elevated heat sources, and propagate with the

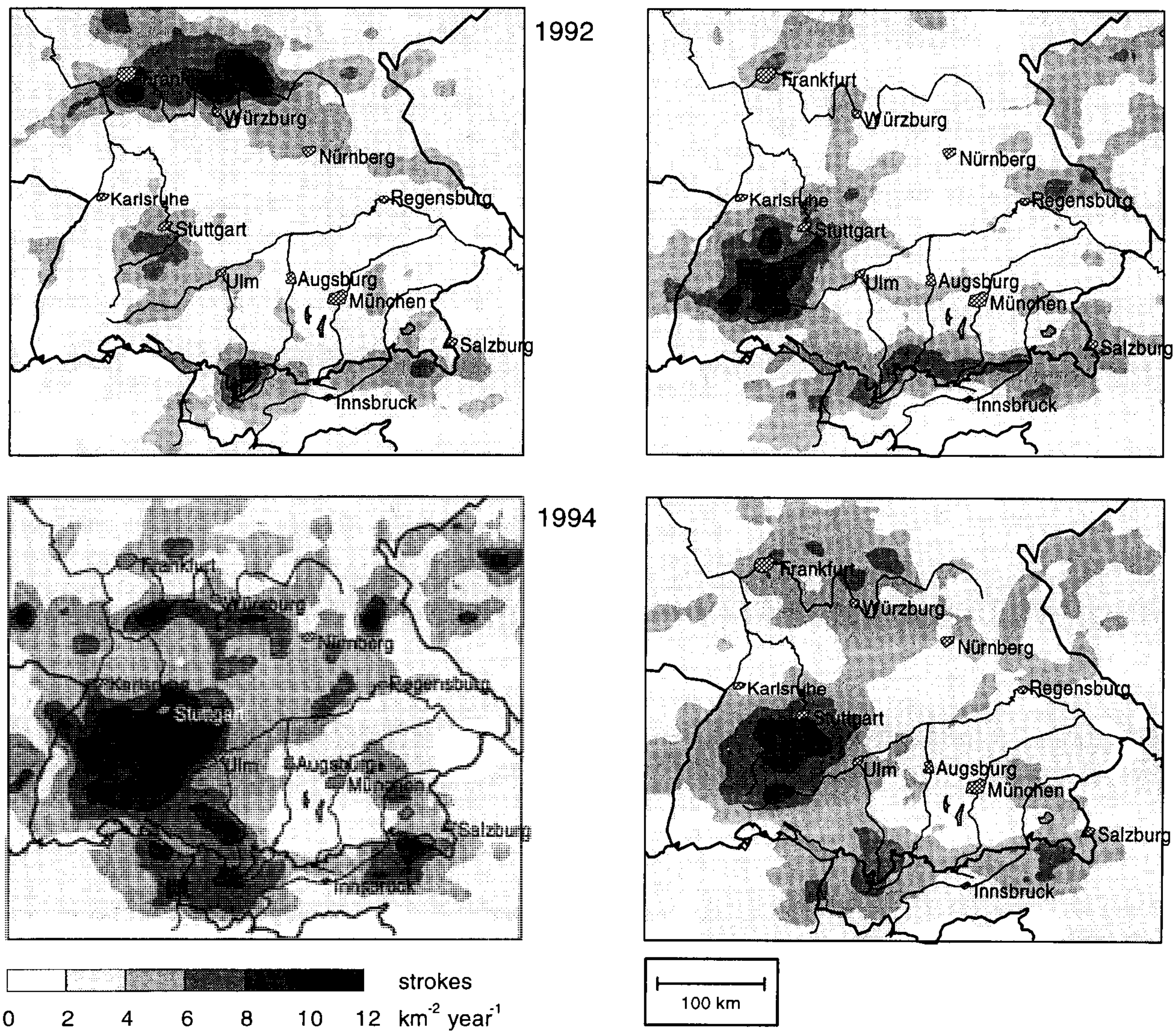


**Figure 9** Spatial distribution of lightning activity. Annual sums are given for each individual year and also as a three-year average. Maximum stroke densities are found in the Black Forest and the Bavarian Prealps.

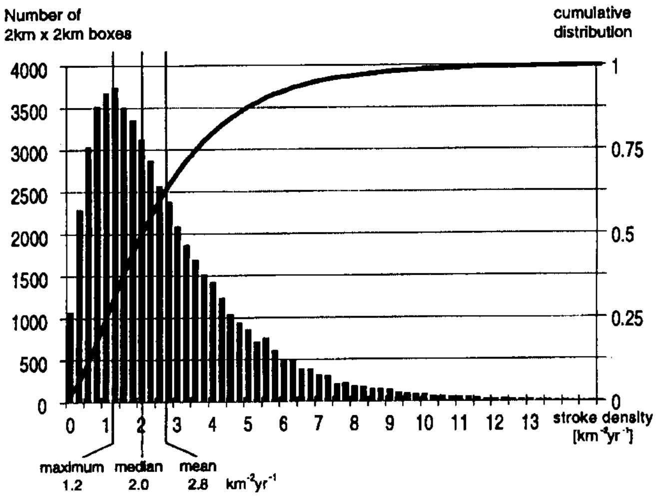


**Figure 10** Frequency distribution of stroke densities. Strokes are counted in boxes os 2 km × 2 km for 1993. The number of boxes with a specific stroke density in units of $yr^{-1}km^{-2}$ is shown on the vertical axis. The solid line depicts the normalized cumulative distribution. Maximum, median and mean of the distribution are given below. The median value, for instance, shows that the half of the observational area has a lightning density of more than 2.0 $yr^{-1}km^{-2}$.

mean flow. Another area of high stroke densities is the Prealpine Region. It is a well-known effect that many storms develop in the Alpine mountains close to the front range. Then they propagate into the lower areas north of it where sufficient moisture is available. The lack of moisture also explains the well-documented minimum of storm and lightning activity in the inner Alps.

If individual years are considered (Figure 9), again a considerable year-to-year variability appears. Although the distribution of relative maxima and minima remains, absolute numbers differ quite substantially. This is seen by comparing the plates for the years 1992 and 1994. Regional maxima may be caused by only single but strong storm events and, hence, vanish in the other years. In 1992, for instance, the highest stroke densities of 12 $yr^{-1}km^{-2}$ are found in the Spessart mountains north of Würzburg. A closer inspection showed that these high values are dominated mainly by four strong thunderstorms. In the following years, where such extraordinary strong storms where absent, densities of only about 4 $yr^{-1}km^{-2}$ were observed for the same area.

To study the distribution of lightning strokes at small spatial scales, we consider the number of strokes inside boxes of 2 km × 2 km size. The frequency distribution of boxes with a specific lightning density is shown in Figure 10. This distribution is strongly asymmetric with a maximum at 1.2, median at 2.0 and mean at 2.8 $yr^{-1}km^{-2}$. It is notable that only 2 % of all 2 km × 2 km boxes are empty. This implies that within a radius of 1.1 km around any given point in southern Germany the probability of observing at least one lightning stroke per year is 98 %. This can also be seen as a measure for the lightning risk. Square boxes with lightning densities larger than 6.0 $yr^{-1}km^{-2}$ are also rare (9 %).

## 4.2 Thunderstorm Days

The common measure of thunderstorm activity is the number of thunderstorm days per year. By definition a day is called a thunderstorm day when an observer heard thunder. As no instruments are required, long-term climatologies of thunderstorm days exist (Changnon, 1985; Wang, 1984; Alt and Weickmann, 1910; Pelz, 1984) and it is worthwhile to compare this data with that of the lightning location systems. For that purpose, the lightning-based thunderstorm day is defined as a day when at least one lightning stroke was detected inside an properly defined 'audible' range. A side-length of 30 km was chosen for the grid-cells. This corresponds roughly to a range of audibility of about 15–

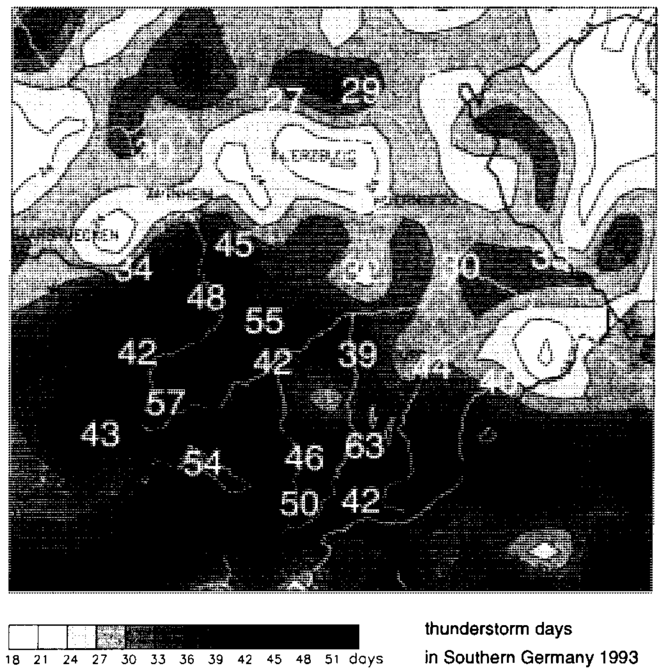


**Figure 11** Thunderstorm days for 1993. A comparison between two methods: thunderstorm days based on audible thunder (white overlayed numbers, at selected sites with synoptic observations) and based on lightning data (gray code and isolines; for definition see text).

20 km in agreement with the literature (Changnon, 1989).

In Figure 11 we plotted the contours of equal number of thunderstorm days for the year 1993 as derived from the lightning data together with the number of thunderstorm days counted at selected synoptic stations. The latter data was taken from synoptic weather reports. What are the dominant features? The annual number of thunderstorm days increases from about 30 in the North to values above 40 in the South. Averaging over three years we found a mean annual number of 29 thunderstorm days for the region of southern Germany. Alt and Weickmann (1910) reported a mean number of 31 thunderstorm days for approximately the same area. The spatial patterns of thunderstorm days resemble the picture found in the spatial distribution of lightning (Figure 9). The Black Forest and the Prealpine region with maximum values at about 50 thunderstorm days, and some other mountainous areas can be identified.

The comparison of the number of thunderstorm days obtained from lightning data with the synoptic observations (Figure 11) demonstrate a satisfying agreement in the spatial structure. Minimum numbers agree better than maximum numbers, as some stations report significantly more thunderstorm days than indicated by the lightning data. There are mainly two reasons for the difference. Firstly, due to the limited detection efficiency, particularly for CC-lightning, thunderstorms with low and mostly intracloud lightning activity may remain undetected by the lightning network. Secondly, the human observation is affected by local conditions of audibility and sound propagation and additionally suffers from subjective factors. So an enhanced audible range is typical for mountain sites, such as the Hohenpeißenberg with 63 thunderstorm days reported for 1993. On the other hand, observation stations located in cities frequently report less thunderstorms due to high urban noise. These problems are well known and indicate an advantage of lightning location systems for defining thunderstorm days. They have a rather uniform spatial detection characteristic and, although some of the less active storms are missed, effectively detect the CG-lightning, which is mostly relevant for practical applications. For more details of this intercomparison problem we refer to Changnon (1993).

## 5 Discussion

In this paper we gave a first and preliminary analysis of the characteristics of lightning in southern Germany. Data come from a newly installed lightning positioning systems (LPATS). Three years of data were analysed. Emphasis was laid on the temporal and spatial distribution of lightning within the observational area.

Lightning is necessarily linked to the existence of thunderstorms. Its appearance is often considered as synonymous to storm appearance. The understanding of the basic characteristics of lightning occurrence, therefore, requires the study of storm evolution. Four elementary factors have to be considered:

- certain *synoptic-scale and mesoscale conditions* favour the development of thunderstorms,
- initiation of first storms during the day are tied to the *diurnal heating cycle* of the boundary layer,
- the *electric activity* varies considerably from storm to storm, and
- *lifetime and propagation* of a storm is defined by the set of lightning loci and the covered time interval.

Necessary conditions for the development of thunderstorms are strongly tied to synoptic-scale and mesoscale weather situations, including the conditionally unstable stratification of lower tropospheric layers with respect to moist convection. These conditions are specific for each region. In Central Europe thunderstorms develop preferably in a southwesterly flow, occasionally also in a southeasterly flow, when moisture-enriched air is brought in from the Mediterranean Sea. The southwesterly flow is very often associated with the eastern flank of a pressure trough approaching southern Germany. Additional synoptic-scale lifting favours the development of strong storms, especially squall-lines. The well-known organization of deep convection on the mesoscale was studied by Höller (1994) in southern Germany in terms of cell structure (single, multi-cell, super-cell). He used six years of data from an advanced polarimetric radar and found a considerable scatter in type as well as in frequency from year to year. Huntrieser (1995) did a similar analysis for Switzerland. So far only a few storms in the area of southern Germany and Switzerland have been studied in such detail and could be satisfactorily related to mesoscale and synoptic scale conditions. A typical storm which developed in the warm sector air mass ahead of a cold front was studied by Höller et al. (1994). Under similar conditions a severe squall-line developed over Switzerland and southern Germany on July 21, 1992 causing great damage (Haase-Straub et al., 1994). We conclude with the authors of the forementioned examples that a great variability of storms can be expected in type as well as in occurrence.

The same variability can also be expected for the lightning activity and it is evident in the variability of the annual cycle (Figure 2), the diurnal cycle (Figure 4), and the spatial distribution (Figure 9). This required, for instance, to present the results for each individual year as well as the average of all three years together. Locally, differences in lightning occurrences of 100 % may be observed. This confirms the well-known necessity of having at least an observational period of thirty years for climatological studies. Nevertheless it is still a valuable exercise, also with respect to climatological questions, to present results from the seemingly short time interval of three years only. The basic features of temporal and spatial distribution are believed to be significant. This hypothesis is supported by the comparison of our results with the work of Alt and Weickmann (1910) hundred years ago, based on 15 years of eye-observation 1893 to 1907 for the same range in southern Germany. Agreement is found with respect to the mean number of thunderstorm days, the annual and diurnal cycle, and the source regions of storms. Differences, however, also appear which can be explained in differences of the synoptic settings between the two observation periods (not shown).

The required necessary link to environmental conditions make thunderstorms, at least in mid-latitudes, rare events. Only on 50 days of the year (14 %) can thunderstorms be observed somewhere in the observational area. As the duration of storm activity is usually much shorter than one day, the proportion of minutes where lightning appears is confined to only 9 % of the minutes of the year.

The dependency on synoptic scale conditions causes a clustering of lightning activity in time with the typical synoptic time-scale of three days. This fact is clearly indicated by the autocorrelation function.

The diurnal cycle of lightning activity is a well-expressed feature. Its increase in the morning hours is strongly tied to the heating of the boundary layer and the development of shallow convection. Once storms have developed in an area, the further formation of new storms is not necessarily linked to boundary layer forcing but might be caused by the cold-air outflow of existing storms or other processes such as gravity waves. It can be clearly seen, that the link to the heating cycle disappears in the course of the day. The maximum of lightning activity is reached in the late afternoon while the minimum appears in the early morning hours. The slow decrease of lightning activity in the late afternoon and in the evening reflects the differences in life-time of previously formed storms. Storms can propagate over distances of several hundred kilometers during their life-time. The latter varies from one hour to 6–8 hours. A striking feature which was already studied by Alt and Weickmann (1910) is the appearance of a secondary maximum in the evening between 2100 and 2200. In the data considered here this secondary maximum was produced by a few strong storms which propagate from typical source regions in northeasterly directions. Propagation causes a shift with time according to the travel time from the source region. The Munich hail storm of 1984 (Höller and Reinhardt, 1986) is a famous example of this type of storm.

Lightning activity on a daily base shows great variability from day-to-day due to the various number of storms but also due to varying electrical activity of the storms. It should be noted that in this paper we always considered the observational area as a whole. Statements concerning the characteristics of individual storms require the identification of single storms and will be considered in a forthcoming paper.

The spatial patterns of lightning activity emphasize the eastern, leeward part of the Black Forest and the Prealpine region as main thunderstorm centres. Low lightning stroke densities are found in the middle of the observational area. One important result was the high stroke densitiy in parts of the observation area. While the average value is 2.8 $yr^{-1}km^{-2}$, maximum stroke densities exceed 10 $yr^{-1}km^{-2}$ and are thus comparable to values reported from Florida (Orville, 1994). As the number of thunderstorm days in Florida is roughly twice as high as in southern Germany, it is concluded that the storms here produce slightly more lightning than the Florida ones. At least, we may conclude that storms in southern Germany are typical representatives of the global acting storms. During their lifetime they contribute in equal amounts to the global averages. It seems reasonable that the same statement holds for all the Central European thunderstorms.

Derived spatial distribution of thunderstorm days agrees well with the observations at synoptic stations.

A systematic bias at the high numbers of thunder days however is noted, where human observations reveal more thunderstorm days than the lightning location system. It is argued that the reasons for this deviation are varying conditions of sound propagation and reception but also the low detection efficiency of the lightning network with respect to intracloud strokes.

The time range of three years considered in this paper is too short with respect to climatological studies. As the usefulness of lightning location networks is without doubt, they will be continuously operated in future and thus enable the update of the preliminary results of this paper. Statistical analyses, similar to those in this paper, may be used in future as a tool for diagnosing climatic trends. The model calculations of Price and Rind (1994) showed, that regionally-specific changes in thunderstorm activity are one possible consequence of global warming. They stated that a global temperature increase of 1 K will result in a 6 % increase of the global lightning frequency. Monitoring the lightning activity over a long time allows the detection of climatic trends on the global as well as on the regional scale.

As discussed in the first section, the lightning location system suffers from some inaccuracies. This concerns mainly the absolute number of monitored lightning strokes. The analysis did not give hints for a regional sensitivity of the whole system. We, therefore, believe that the spatial patterns, as well as the diurnal cycle are unaffected by the forementioned deficiencies. Absolute numbers might be checked by comparison with other ground based systems and also with the lightning mapping systems operating from satellites such as DMSP (Orville and Henderson, 1986) or the more recent OTD satellite (Christian et al., 1989). A combination with 3-dimensional lightning location systems with spatial resolutions down to a few hundred meters and covering the cloud scale of 30 km (Richard et al., 1986; Rhodes et al., 1994) is also desirable.

Valuable information can be gained if the lightning data is combined with radar signatures (Goodman, 1991). Because radars sense the hydrometeors and thus completely-different characteristics of a storm, both systems supplement each other and should be viewed in a coordinated way, especially for nowcasting purposes. This is already done in the United States (Stern et al., 1994) and might also be a promising technique in Central Europe and Germany. For such purposes as tracking and monitoring of strong convective storms, both systems provide adequate information and there is no principal superiority of one or the other system. Lightning systems, however, are less expensive than radars, require less maintenance and manpower, and have lower data rates. This may become an important factor when, in future, e.g. the installation in tropical regions is considered.

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