Cloud-to-ground Lightning in Austria: A 10-year Study using Data from a Lightning Location System

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Abstract

In this paper we present lightning statistics for more than three million cloud-toground (CG) flashes located during the 10 year operation period 1992-2001 of the Austrian lightning location system (LLS) called ALDIS (Austrian Lightning Detection and Information System). Like a majority of other lightning systems operated worldwide, ALDIS underwent configuration changes and continuous performance improvement. Since these changes can alter the lightning statistics, we also relate the variation of the individual lightning parameters during the period of operation to changes in ALDIS configuration and performance. This analysis should be useful to other network operators and data users. Flash densities in Austria are normally between 0.5 and 4 flashes km⁻² yr⁻¹ depending on terrain. Flash densities higher than 4 flashes km⁻² yr⁻¹ are typically related to mountain tops or high towers on elevated sites. Flashes are classified as negative, positive or bipolar (both negative and positive strokes comprising the flash). 17% of the flashes were classified as positive (90% single strokes and 10% multistrokes), and 2.3% of the total number of flashes were bipolar. 50% of the positive multiple-stroke flashes were bipolar flashes with positive first stroke -- this influences the positive flash multiplicity and interstroke interval statistics. Compared to many other networks, the ALDIS network reports much lower median negative peak currents. For 2001, the median first-stroke peak current for negative flashes was 10kA. We show that even when using the same configuration parameter as used in the U.S. National Lightning Detection Network (NLDN), the median first-stroke peak current in an NLDN region with similar climate is about 30% higher than in Austria. Some of this difference is likely due to better detection efficiency (DE) in the ALDIS network. Estimated multiplicity of negative flashes for the 10-year period is affected by the algorithm that groups strokes into flashes, as well as the improved DE of the network as a result of the integration of ALDIS into the European LLS (EUCLID). This performance improvement also

resulted in a higher number of single stroke flashes. Interstroke interval and median first-stroke peak current show a clear correlation with multiplicity for negative flashes, irrespective of DE. Negative flashes with higher multiplicity show smaller average interstroke intervals and larger first stroke median peak currents. No correlation between interstroke interval and stroke order was found. On average, regions with higher flash density show slightly higher flash multiplicity.

1. Introduction

Cloud-to-ground (CG) lightning parameters and the spatial distribution of lightning flashes are of fundamental interest for the design of lightning protection systems, and are of increasing importance for weather forecasting and climatology. Prior to the late 1980's, CG lightning parameters were studied mainly at single locations such as elevated towers or triggering sites, and the spatial distribution was estimated from thunderstorm days monitored by the meteorological services or lightning counters. With the introduction of lightning location systems (LLS) [Krider et al., 1980] it became possible to determine statistically meaningful area densities of flashes and lightning parameters over large contiguous areas.

Since the late 1980's, temporal and spatial lightning distributions and CG lightning parameters have been studied in many areas based on lightning location system data. Some specific examples are Brazil [Pinto et al., 1999a; Pinto et al., 1999b], Japan [Shindo and Yokoyama, 1998], Canada [Burrows et al., 2002], southern Germany [Finke and Hauf, 1996], France [LeBoulch and Plantier, 1990] and Spain [Terrandella, 1997]. The most detailed reports are available for the U.S. National Lightning Detection Network (NLDN) [Huffines and Orville, 1999; Orville and Huffines, 1999; Orville and Huffines, 2001; Zajac and Rutledge, 2001]. The largest region of analysis has been the combined U.S. and Canadian network – the North American Lightning Detection Network (NALDN) [Orville et al., 2002].

Austria has what would be considered as moderate lightning incidence. The highest flash density observed in the U.S., in Tampa, Florida, is about 14.5 flashes $km^{-2} yr^{-1}$ for 1995 to 1999 [Zajac and Rutledge, 2001]. This is somewhat higher than the 9 flashes $km^{-2} yr^{-1}$ value reported by Orville and Huffines [2001] for the period 1989-1998 in the same area. Although both studies used the same grid size, they did

not correct for flash detection efficiency (DE), which is lower in the 1989-1994 time period. Nevertheless both flash density values are more than a factor of two higher than the highest lightning densities found in Austria. Orville et al. [2002] have shown that for the largest LLS in the world - the NALDN - some lightning characteristics e.g. flash density, median first-stroke peak current and multiplicity, exhibit a large variation with region. Due to the almost homogenous performance of the NALDN, those variations are not attributable solely to instrumentation. They are thought to reflect variations in climate and terrain.

In numerous papers related to lightning characteristics determined by LLS, too little attention has been paid to critical performance characteristics and processing algorithms of LLS systems and this can easily lead to misinterpretations of the data. When comparing lightning characteristics from different LLS in different countries, it is important to consider the following issues:

- Some networks measure signal strength using electric field sensors that are not calibrated in absolute field strength (V/m units). Typically, these networks will "normalize" the amplitude measurement of each individual sensor so that they are consistent with all other sensors (this is essential), and then the overall field strength is set so that it is identical with the median negative flash peak current measured at towers (e.g. 30 kA). This prevents the identification of low flash DE and valid comparisons with data in other regions.
- The region of investigation may not be limited to a region of high and uniform performance of the LLS. An example is the inclusion of large regions outside the network in the data analysis. In these cases, the statistics are biased towards higher lightning peak currents because small amplitude strokes are not detected at large distances. This will also result in lower flash density values in those areas and will also affect all other measured lightning parameters.
- Whenever networks have different sensor baselines, sensor gains, sensor waveform parameters, sensor thresholds or central processing algorithms, it is likely that they will report different subsets of the lightning discharges.
- Different algorithms to group strokes into flashes have been used at different times in different networks. For example, in some systems the flash peak current is defined as the peak current of the first stroke [Orville and Huffines, 2001; Cummins et al., 1998] and in others it is the maximum peak current of any

stroke in the flash. In some papers, even a mix of both versions is presented e.g. Bernardi et al. [2002] where the maximum stroke amplitude is used till 1999 and first stroke amplitude after 1999.

Given these issues, it is not easy to compare published lightning characteristics directly or to conclude that lightning characteristics are indeed different in different countries and climates. A clear example of this problem is the change in median first-stroke peak current over several years as shown by Orville and Huffines [2001]. The improvement of NLDN performance produced a decrease in the median first-stroke peak current of negative flashes from 30 kA to 20 kA over a 10-year period.

It is our assumption throughout this paper that peak current statistics, and most other lightning parameters, do not significantly vary from year-to-year within a region that is large enough to experience 10's of thousands of flashes per year. This is based on multiple one-year statistics observed in sub-regions of the U.S. during periods of stable performance. However, we do know that ground flash density, even within a large region, is one lightning parameter that does vary from year to year.

Some lightning characteristics, e.g. diurnal cycle of lightning activity, are not as sensitive to flash DE as the peak current distributions. Also, some parameters only require high storm DE from an LLS. Even a LLS that detects only half of the CG flashes will be able to detect most thunderstorms, since they are usually comprised of several flashes. For other parameters, e.g. peak current and multiplicity statistics, it is necessary to detect each individual stroke and therefore high stroke DE is required to accurately estimate these parameters.

This paper provides a detailed analysis of 10 years of lightning data collected in Austria using the Austrian LLS called ALDIS (**A**ustrian **L**ightning **D**etection and Information **S**ystem), a LLS with comparably small baselines, low sensor threshold settings and therefore very high stroke and flash DEs. To the best of our knowledge this is the first report of a 10-year lightning dataset for any European country. The ALDIS network has undergone a number of changes over its 10-year history, and therefore the analysis of these data serves to illustrate many of the system-related issues that we discussed earlier in this section. Accordingly, Sections 2 and 3 include a comprehensive description of ALDIS and the resulting changes in the available data over the 10-year period. Section 4 provides detailed spatial, temporal, and summary statistics on lightning incidence, peak current distributions, flash multiplicity, and interstroke intervals. Relationships between these parameters are also explored. For each parameter, the effect of network configuration and performance is discussed, and comparisons are made with other published studies. We further explore "peculiar" data subsets (bipolar flashes, small positive flashes, misplaced events, etc.) in our lightning database which are related to the lightning location technology used at that time. We assume that similar data have been obtained by other networks using the same technology. The evaluation of these data provides additional information about the quality of LLS data, and implications about the quality of similar statistics published for other networks. Finally, key findings are summarized and discussed in Section 5.

2. ALDIS Description and Evolution

ALDIS was installed in the summer of 1991 and officially started operation in January 1992. All equipment used was manufactured by Lightning Location and Protection, Inc. (LLP) or Global Atmospherics, Inc. (GAI), which are now part of Vaisala. The network was initially composed of eight magnetic direction finding sensors (Model ALDF 141). Sensor site error corrections [Hiscox et al., 1984] were provided by the manufacturer, resulting in an estimated median location accuracy of 1-2 km during these early years. These early sensors were only able to report CG flashes (first strokes) and measured the angle to the flash, the amplitude of the flash and the multiplicity (number of strokes) of the flash. The corresponding position analyzer (APA 280, Advanced Position Analyzer) located flashes using angle information only. Figure 2.1 shows the ALDIS network and the eight sensor locations. The distances between the sensors in Fig. 2.1 are in the range of 120km, which provides a highgain lightning location system with the smallest sensor baselines in the world. The angle-based algorithm to group strokes to flashes used in these early years (see Cummins et al. [1998] for a description of the grouping algorithms) introduced some measurement errors in the peak current and multiplicity distributions and a slight over-counting of the number of detected flashes.

In 1994 the sensors were upgraded to the so-called IMPACT type (ALDF

141T). The advantages of IMPACT sensors are the time-synchronization using GPS satellite time signals (resulting in better time-correlation and improved location accuracy) and the ability to process and report each individual stroke in the flash. The upgraded position analyzer (APA 280T) used the time information to locate the first stroke in the flash and then assigned all other strokes to the same location (ASR – all stroke reporting). At this time the grouping of strokes into flashes was accomplished using only angle information [Diendorfer et al., 1998]. No maximum interstroke interval was considered, but the total flash duration was limited to 1 second in the ASR grouping algorithm. The amplitude of the flash was changed to be the largest amplitude of any component stroke, rather than just the first stroke.

Prior to the 1998 storm season, another major upgrade of the network was carried out by replacing the APA 280T with a software package called LP2000 (Lightning Processor 2000). The LP2000 can process all the available sensor information in real time, and can therefore compute a separate location for each individual stroke in the flash. With this software a new grouping of strokes to flashes was introduced which is based on a time and a distance criterion [Cummins et al., 1998]. The grouping assigned the estimated peak current of the first detected stroke as flash peak current. A further difference from the previously used APA 280T was that the algorithm allowed a maximum interstroke interval of 0.5s. The total flash duration remained at a maximum of one second.

The last major improvement of the Austrian LLS occurred before the 1998 storm season, with the integration of ALDIS into the European Lightning Location network called EUCLID (EuUropean Cooperation for Lightning Detection). With this integration, the DE in the western part of Austria was improved considerably. From 1998 to 2001 more and more sensors around Austria were integrated into the EUCLID network and the majority of LPATS III sensors located in neighboring countries were upgraded to LPATS IV sensors.

Since the evolution of this network has had a large impact on the detected and reported lightning information, these changes are summarized in Table 2.1. The *1% Peak Current* column represents the 1% value of the cumulative peak current distribution of detected negative flashes. This value should correlate well with the

relative DE from year to year. The method to group strokes to flashes called Flash Algorithm has a considerable effect on the estimated multiplicity. The Lightning Classification Method reflects changes in the way that the sensors discriminate between CG and cloud discharges(CC), and can affect the misclassification of cloud discharges as CG discharges. The IMPACT and ALDF sensors employed a proprietary set of waveform classification parameters to exclude cloud discharges. One of these criteria, referred to as the minimum width waveform criterion, is a measure of the time from the initial peak to the threshold crossing time after the peak ([see Diendorfer et al., 1998 for details)]. This criterion was reduced to a smaller value (narrower width) early in the 1995 storm season. This improved detection of small positive and negative strokes, but it also resulted in the misclassification of some cloud discharges as positive CG strokes [Cummins et al., 1998; Wacker and Orville, 1999a,b]. In 1998, the integration with EUCLID allowed LPATS sensors in Germany (the BLIDS network operated by Siemens) to contribute to lightning detection in Austria. These sensors detect all waveforms crossing that cross the sensor threshold, and send their data to the LP2000. The LP2000 employs a very simple single CC:CG classification parameter known as PTZ (peak-to-zero). PTZ is a measure of the time from the initial peak field until the waveform crosses zero. PTZ values below a specified level (10 microseconds in this case) were classified as cloud discharges. Due to this simple classification method, the LLS misclassifies some cloud discharges as small positive CG strokes. The Positive Detection Threshold reflects the ability of individual sensors to report small positive CC or CG discharges. Finally, the Source of Flash Peak Current will effect the measured distribution of estimated peak currents.

3. Data

For this analysis, all flash data provided by ALDIS from 1992 to 2001 have been examined. Negative and positive flashes are discussed separately for most of the analyses. Unless otherwise stated, data were within a rectangular area around Austria with longitudes between 9.50° and 17.5° East and latitudes between 46.00° and 49.25° North. Data at greater distances from the Austrian border are strongly biased by DE and therefore are excluded. Geographical plots are made with a spatial resolution of 1x1 km or 10x10 km.

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It is worth noting that all measurements provided by an LLS will have some degree of error and/or limitations. Knowledge of these errors and limitations helps to prevent misinterpretation or over interpretation of the data. For the peak current estimates, the combination of measurement errors and model limitations restrict the errors to about 20-30%, assuming that the sensors are properly calibrated [Cummins et al., 1998]. There are two issues related to estimated peak currents for positive flashes. First, the accuracy of peak current estimates has not been independently validated with a large data set, given the difficulty in obtaining tower strikes and rocket triggered lightning for positive flashes. Second, the positive flash statistics are contaminated by misclassified cloud discharges, to varying degrees, as discussed above. This has been reported for the US network [Cummins et al., 1998] and for the Brazilian network [Pinto et al., 1999a]. Due to the small baselines in Austria we are able to detect strokes that have amplitudes as low as 2-3 kA [Diendorfer et al., 2002]. Therefore we expect to have an even higher percentage of misclassified discharges in our data set which will contaminate the distribution of positive peak currents. The stroke location accuracy can also affect the analysis of lightning data. The ALDIS network (since 1994) has been shown to have a median stroke location accuracy of about 500 meters [Diendorfer et al., 2002], and therefore location accuracy does not pose a problem in these analyses.

The final performance-related issue is the flash and stroke DE. A low stroke DE will affect flash multiplicity, could produce low flash DE, and will bias the estimated distributions of peak currents towards larger values. In this analysis, we do not apply any correction for DE to the data. The DE of ALDIS varied somewhat from year to year and also from region to region for the following reasons:

- Due to the shape of the Austrian territory (see Figure 2.1) it is almost impossible to setup a LLS with uniform performance with sensors located inside Austria only. From 1992 to 1998, when ALDIS utilized only sensors located inside Austria, the network DE in the western region was lower than in the eastern part of Austria. Since 1998, additional sensors located around Austria have been integrated into the analysis (as a part of the EUCLID project) and the result has been an increased DE in the western part of Austria.
- The factory threshold setting of 100mV was not used in the ALDIS network. Prior to 1999, the threshold of all sensors were set to 50 mV for most of the year and

70 mV in the summer because of the limited processing capabilities of the APA 280 and APA 280T used at that time. Since 1999, all sensors are permanently set to a threshold of 50 mV. Compared to the factory setting of 100 mV, which is used in many other networks, the reduction of the threshold to 50 mV doubles the sensitivity of the sensor. Of course this change requires a low background noise level at the sensor site. Given that the threshold was higher before 1999, we would expect better DE since 1999. This is shown in the 1% peak current (Table 2.1) and in many of the figures.

Although the Austrian sensors have had a very high uptime percentage, there were occasional sensor failures that could not be repaired within a few days. These failures were randomly distributed over the 10 year study. During these periods the DE was temporarily decreased in the region around the failed sensor. Because the average sensor availability was above 98% for each year, this is assumed to be a negligible effect.

Given all these factors, the DE was not uniform throughout Austria until 1998 (estimated to vary between 80-90% for flash DE based on model calculations), but should be close to uniform and exceeding 90% since 1998. Even for the early years, the ALDIS flash and stroke DEs are much higher than the DE of most networks worldwide because of the small sensor baselines and the low threshold settings.

As a last issue, integration of ALDIS in the EUCLID network allows it to detect some cloud discharges inside Austria, because some of the sensors located around Austria (sensor types LPATS III, LPATS IV and IMPACT ESP) are able to detect and report this type of discharge. All discharges that were identified as cloud discharges by the LP2000 have been excluded from the following analyses.

4. Results and analysis

4.1 Temporal statistics

Figure 4.1 shows the annual counts of CG flashes and strokes in Austria over the 10 year period. Lightning activity varied from year to year, ranging from about 200,000 flashes in 1992 to about 450,000 flashes in 1993 and 2000. In Figure 4.1 there is no dependency of the annual flash number on the performance improvements of the LLS, other than the fact that the year with the lowest count (1992) had the largest 1%

peak current threshold (see Table 2.1). Interestingly, the maximum number of flashes in one year was detected in 1993 -- a year with somewhat low detection efficiency. A total of 3,272,031 flashes were detected in Austria during the 10 year time period. Although the system was upgraded to detect individual strokes starting in 1994, the lightning database only contains these data since the beginning of 1996.

The distribution of the mean monthly flash counts is shown in Figure 4.2. 96 % of all the detected flashes occurred during the period from May through September. This illustrates the importance of solar radiation in forcing deep convection and therefore for the formation of thunderstorms. We will refer this period as the convective season. The maximum number of flashes occurred in July and the minimum in December.

In Figure 4.3 the diurnal flash counts as a function of local time show the typical lightning frequency variations. There is an increase from 10h to a maximum in the afternoon at about 16h, followed by a slow decrease. The shape of the diurnal flash count plot is almost identical for the convective and nonconvective seasons (not shown), although the lightning frequency in the convective season is about 25 times higher. Interestingly, lightning activity occurs throughout the day, although one might expect a time with no lightning activity. This continues "background" activity in Austria stems from thunderstorms embedded in frontal systems that pass through the area of investigation [Kann, 2001].

A similar behavior for the diurnal flash counts is reported for other countries, e.g. Southern Germany [Finke and Hauf, 1996], Catalonia in Spain [Terrandellas, 1997], Spain [Soriano et al., 2001], Brazil [Pinto et al., 1999b], Colorado and Florida [Lopez and Holle, 1986] and the western US [Reap, 1986]. The results by Lopez and Holle [1986] and by Reap [1986] are interesting in the sense that their data are from one of the first LLS with much lower performance compared to the current state of the art. Obviously the pattern of diurnal flash counts is rather insensitive to LLS performance. Zajac and Rutledge [2001] reported a variation of the summertime lightning activity over the central U.S. that depended on longitude with a large amount of nocturnal lightning activity occurring over the eastern Great Plains and upper Midwest. Contrary to the findings of Finke and Hauf [1996], who used stroke

data, we see no secondary peak in the diurnal counts, even when we plot the data in 10 min intervals and even if we use stroke data (not shown). This is interesting because Finke and Hauf [1996] used data from a region in southern Germany that also covered the western part of Austria. They analyzed data from only three years and they observed large differences between the individual years (e.g. for the 1994 data no secondary maximum was present in their analysis).

Diurnal cycles of lightning activity in different sub-regions in Austria (central Alps, border of Alps, foothills of the Alps) are almost identical [Troger, 1998]. Lightning rates start to increase at 10h (local time) in all the three sub-regions, with the only difference being that the maximum is about three hours later in the foothills of the Alps. Also in this five year investigation (1992-1996), no secondary peak was present.

4.2 Flash density

Prior to the installation of ALDIS the flash density for locations in Austria was estimated from thunderstorm day statistics using Eq. (4.1). Eq. (4.1) originally published by Anderson et al. [1984] is recommended by IEC and CENELEC [ENV 61024, 1995] for risk evaluations for lightning protection systems if there are no LLS data available.

$$N_{g}=0.04*T_{d}^{1.25}$$
 (4.1)

A 30-year average isoceraunic map of Austria [Cehak, 1980] shows peaks of lightning activity of 30 to 40 thunderstorm days per year in the regions around the cities of Graz and Klagenfurt. With the lightning location data we also found the highest mean annual flash densities in the regions around these cities (see Figure 4.4). However, local values of N_g calculated from the thunderstorm days using Eq. (4.1) differ by more than 100% from values derived from the lightning location system data in some regions of Austria [Diendorfer et al., 1995]. The major reason for these differences is that the observed "thunderstorm day" does not accurately reflect for the severity and duration of the lightning activity in the storm.

Figure 4.4 shows the 10-year mean annual measured ground flash density

derived from 3.3 million CG flashes, using a 1x1 km grid size. Most of the sites in Austria with flash densities exceeding 4 flashes km⁻² yr⁻¹ are related to summits and radio towers on mountains. Meteorological and topographical conditions favour the areas south of Carinthia (region 4 in Figure 4.4), the border between Tyrol and Bavaria (region 1 in Figure 4.4) and the southeastern parts of Austria (region 3 in Figure 4.4) as the hot spots for lightning activity in Austria. The main Alpine crest (region 2 in Figure 4.4), however, is marked by a pronounced minimum in the flash density. The glaciated areas with their high albedo and absence of an adequate moisture source in the inner Alpine dry area (Frei and Schär, 1998) are responsible for this feature.

The area with the highest lightning activity detected by ALDIS is just to the south of Austria (region 4 in Figure 4.4) close to the border of Italy and Slovenia. In this area a mean flash density of more than 15 flashes km⁻² yr⁻¹ was observed (1x1 km grid). This is also one of the areas with the highest lightning activity for all of Europe [Schulz and Diendorfer, 2002]. Not all grid points within this region exhibit such high flash density, therefore increasing the grid size decreases the measured density by averaging over a larger area. Calculating densities in this region based on a 20x20 km grid size still shows a small region with more than 6 flashes km⁻² yr⁻¹. This is about 30% lower than the maximum in the US in Tampa, Florida of 9 flashes km⁻² yr⁻¹ [Orville and Huffines, 2001], which was calculated using the same (20x20 km) grid size. It is also worth noting that during the period 1992-1997 the DE of ALDIS was lower in this region than inside Austria. Analysis of the period 1998-2001 resulted in a measured flash density in this region just under 7 flashes km⁻² yr⁻¹, when using a 20x20 km grid size.

4.3 Lightning polarity

Even in the early years of lightning location systems it was observed that the ratio of negative to positive flashes increases during summer time and that this ratio shows significant variations from storm to storm [Orville et al., 1987]. Figure 4.5 shows the mean polarity distribution in Austria for the 10-year period for the individual months. In Austria we observe an increase in the percentage of negative flashes in summer time, similar to the reports for the NLDN [Orville and Huffines, 1999; Orville and Huffines, 2001].

The changes in instrumentation and the increase in sensitivity of ALDIS during the last decade (discussed in Section 2 – Table 2.1) are clearly illustrated in Figure 4.6, which shows the percent of positive flashes each year. There is an increase in the percentage of positive flashes starting in 1995 after the change in the waveform width criterion, and there is a large increase in 1998 after integration with EUCLID. The steady increase in the percentage of positive events after 1999 is thought to reflect a steady enlargement and improvement (e.g. change of LPATS III to LPATS IV) of EUCLID. Many of these flashes are misclassified cloud discharges as discussed in Sections 2 and 3. Often attempts are made to limit the influence of the misidentified discharges by neglecting positive strokes below 10 kA, because it appears that over 90% of all positive events less than 10 kA are cloud discharges and that most positive events above 20 kA are CG strokes (based on video validation in Texas – Krider, personal communication, 2003). This approach is a compromise because the misclassification of cloud discharges occurs over a wide range of amplitudes. In addition, the limit of 10 kA is somewhat arbitrary, and may be related to network configuration and climate. Nevertheless we also use this approach in Figure 4.6 to be able to compare values with other studies. All other analyses in this paper do not exclude reported positive stroke less than 10 kA. As a result of the exclusion of small positive events the maximum percentage for positive flashes (year 2001) decreased from about 23% to about 13%. In the NLDN data the percentage of positive flashes above 10 kA ranged from 3% before 1995 upgrade to 9% after 1995 upgrade [Orville and Huffines, 2001]. In addition there is a regional variation of the percentage of positive flashes in the NLDN data from 2% to more than 20% [Orville et al., 2002]. Much of this variation is thought to be due to climate, as discussed further by Carey and Rutledge [2003].

Flashes with subsequent strokes of opposite polarity to the first stroke are called bipolar flashes. In 1998 the algorithm for grouping strokes into flashes was changed due to the installation of the LP2000. Unlike the grouping algorithm of the previously used APA 280T the new grouping algorithm allows strokes of different polarities to be grouped in the same flash, as long as they meet the spatial and temporal requirements [Cummins et al., 1998].

In this study, the bipolar flashes were separated into positive and negative bipolar flashes according to the polarity of the first stroke in the flash. Table 4.1 shows an increase in the percentage of negative bipolar flashes from 1998 to 2001 that may be attributable to generally increasing performance during these years. Unlike Pinto et al. [1999b], we think that the existence of these bipolar flashes in the LLS data is not an artifact of the criteria for grouping strokes into flashes, because this type of flash has also been observed using direct current measurements at the Gaisberg tower [Schulz and Diendorfer, 2003] and other towers [Rakov, 2000; Rakov and Uman, 2003]. A bipolar flash recorded at the Gaisberg tower was correctly detected by ALDIS [Schulz and Diendorfer, 2003]. Nevertheless 50% of the positive multistroke flashes in our data are positive bipolar flashes. We note that this percentage is independent of the peak current of the first (positive) stroke. We can exclude ionospheric reflections as the reason for the bipolarity, given that the interstroke interval between strokes which change polarity is generally much longer than 200 microseconds, and is comparable to non-bipolar flashes. We therefore infer that the majority of positive bipolar flashes are the result of a "true" positive first CG stroke followed by one or more negative CG strokes. We note that these events are only called positive flashes because the first stroke is positive. One might question whether this type of discharge should be called a positive or a negative flash, or whether separate classes of positive and negative bipolar flashes should be employed in lightning statistics.

4.4 Lightning peak current

In the Austrian network peak current values are inferred from fields using to Eq. (4.2) [Diendorfer et al., 1998] using a field to current conversion factor of 0.23. This factor originally supplied by the manufacturer of the LLS was theoretically derived assuming a transmission line model [Uman and McLain, 1969] with a return stroke velocity of 1/3 of the speed of light.

$$I[kA] = 0.23 * \overline{RNSS}$$
 (4.2)

The range normalized signal strengths (RNSS) of the individual sensors are calculated using Eq. (4.3) (see also Cummins et al. [1998]). In this equation SS is the raw signal strength¹ and r is the distance from the sensor to the stroke in km. We use

¹ This signal strength is either calibrated magnetic field for IMPACT and ALDF sensors, or is "normalized" to be equivalent to magnetic field strength in the case of LPATS sensors.

for our RNSS calculations b=1.0 and a λ =10,000,000 km, resulting in a simple inverse-distance relation. No attenuation constant of b=1.13 as proposed by Orville [1991] or b=1.09 as proposed by Idone et al. [1993] is used due to the small sensor baselines of ALDIS.

$$RNSS = SS * \left(\frac{r}{100}\right)^{b} * exp\left(\frac{r-100}{\lambda}\right)$$
(4.3)

The small baselines and the low sensor threshold result in a high DE for the Austrian network. With this system it is possible to detect strokes in Austria down to peak currents of about 2 kA [Diendorfer et al., 2002]. Table 4.2 gives the mean and median estimated peak current values for positive and negative flashes for each of the 10 years. The highest mean and median peak currents were detected in the year 1992. This is a clear indication of the influence of DE on the lightning peak current statistics determined with lightning location networks. During this first year of network operation, numerous sensor outages degraded the DE of the network. Since an improvement of the sensor power supply and the overvoltage protection of the sensor communication in winter 1992/1993, the DE became much more stable inside Austria. This poor performance in 1992 can also be seen in the 1% peak current value for 1992, provided in Table 2.1. This value of -7.9 is nearly twice as high as any other year. For a correct interpretation of the results it is also necessary to recall that the data are extracted for a rectangular area around Austria. Therefore due to the connection of EUCLID sensors located around Austria and the steady improvement of the EUCLID network the overall DE increased steadily since 1998. It can be seen from Table 4.2 that this increase in DE results in a further reduction of the mean and median negative peak currents to -13 kA and -10 kA respectively. These improvements are also reflected in the 1% peak current values in Table 2.1.

Figure 4.7 shows the median peak current for each year of operation. The median positive peak current decreased over time more quickly than the median negative peak current. We assume that this is a result of the more frequent misclassification of small cloud discharge as positive CG strokes with increasing DE, as discussed earlier. We postulate that the decrease of the median peak current for both negative and positive flashes is not related to any changes in the lightning characteristics during the 10 year period -- these changes are a result of the

improved performance of the network, of changing the criteria for the assignment of a flash amplitude (see section 2) and an underestimate of propagation effects since the inclusion of EUCLID in 1998 (see below). Given the inclusion of misclassified cloud discharges, all the mean and median positive peak current values given in Table 4.2 and Figure 4.7 are biased towards smaller values, particularly since 1997-1998. Taking into account that from 1998-2001 a large number of CC flashes reduce the median peak current of positive flashes, we conclude from Table 4.2 and Figure 4.7 that on average the peak currents of first strokes of (real) positive CG flashes are greater than negative first strokes. This is in qualitative agreement with observations on instrumented towers [Berger et al., 1975, Garbagnati and Lo Piparo, 1982].

To evaluate the influence of the bipolar positive flashes on the overall median statistics, the median peak currents of positive nonbipolar flashes are also plotted in Figure 4.7 for the period from 1998 to 2001. This curve is almost identical to the curve for all positive flashes. For negative flashes the influence of negative bipolar flashes is even smaller and therefore not shown in Fig. 4.7.

To estimate the influence of the flash amplitude criterion (first or largest stroke peak current - see section 2) and the field attenuation constants in equation 4.3 [see Herodotou et al., 1993 or Idone et al., 1993], we have recalculated lightning data in the whole region for August 2001, using various attenuation constants and flash amplitude assignment criteria. About 60,000 negative flashes and about 20,000 positive flashes occurred in the selected region in August 2001. The results of the recalculation are shown in Table 4.3. The recalculation with the amplitude criteria set to assign the largest stroke amplitude as the flash amplitude (instead of the first stroke amplitude) shows an increase in the median peak current from -9.9 kA to -11.3 kA (+14%) for negative flashes, and from 8.1 kA to 8.4 kA (+4%) for positive flashes. These changes are caused by subsequent strokes having larger peak current than the first stroke [see Rakov and Uman, 1990].

Due to the enlargement of the LLS in early 1998, sensors at larger distances from the region of investigation were able to contribute to the amplitude calculation in this region. As a result of the setting of the attenuation exponent b=1.0 and the e-folding length for attenuation λ =10,000,000 km (thereby no propagation attenuation is

assumed), signal levels provided by those distant sensors serve to bias the resulting peak current estimates towards lower values. To evaluate this influence, we recalculated the August 2001 dataset with various attenuation parameter values. Results are shown in Table 4.3. Using the attenuation exponent setting b=1.13 as used in the NLDN [Cummins et al., 1998], the median estimated peak current increases from -9.9 kA to -11.0 kA (+11%) for negative flashes and from 8.1 kA to 9.2 kA (+14%) for positive flashes. The NLDN also employs an e-folding length for attenuation of λ =10,000 km. A recalculation with b=1.13 and λ =10,000 km resulted in a further small increase in the mean and median estimated peak currents as shown in Table 4.3.

Herodotou et al. [1993] have shown that an attenuation model with an efolding length is the best approximation of finitely conducting ground. To determine the optimum e-folding length for Austria, data from August 2001 were recalculated with e-folding lengths ranging from 500 km to 1200 km. The optimum is determined by evaluating the deviation of the individual sensor's RNSS to the mean RNSS for all sensors that report a stroke. The mean of those deviations ("Mean" in Table. 4.4) should be as close as possible to "1" and the relative standard deviation (relative to the mean) should be a minimum. Table 4.4 also shows the calculated mean and relative standard deviation for the different b and λ combinations in Table 4.3. The recalculation with b=1.00, λ =1100 km has a mean closest to 1 and the smallest relative standard deviation for all the 4 different propagation parameters used in this paper. Therefore the consistency between the individual measurements is best for b=1.0 and λ =1100 km. An e-folding length of λ =1100 km further increases the median peak currents from -9.9 kA to -11.5 kA (+16%) for negative flashes and from 8.1 kA to 9.5 kA (+17%) for positive flashes, as compared to b=1.0 and λ =10,000,000 km (see Table 4.3).

The lightning peak currents reported by lightning location systems are inferred from electric and magnetic field measurements, and therefore the absolute calibration regarding peak current estimates is often questioned. In Austria the validity of the peak current for negative strokes was confirmed by means of directly measured lightning peak currents from flashes to an elevated tower. A correlation of ALDIS peak current estimates with directly measured peak currents for 295 current pulses (peak currents ranging from 2 kA to 35 kA) out of 66 flashes to the tower (only two of the flashes were initiated by downwards leaders) yielded

$$I_{ALDIS} = 0.95 * I_{Tower}$$
 (4.4)

with a correlation coefficient r=0.954 [Diendorfer et al., 2002]. The 5 closest sensors are between 32 and 205 km from the tower. It is important to note that the ALDIS data were calculated with field to current conversion factor of 0.23 and assuming infinite ground conductivity (b=1.0 and λ =10,000,000 km). With b=1.0 and λ =1100 km the resulting median and mean peak currents of negative flashes are increased by about 16% and 24% respectively (see Table 4.3). Therefore reducing the field to current conversion factor from 0.23 to 0.185, a value that was derived from rocket triggered lightning [Cummins et al., 1998] and is used in the NLDN, would result in about the same relation between the ALDIS peak currents and the tower measurements as shown in Eq. (4.4).

As a final observation related to peak current, an investigation of the spatial distribution of the mean peak current (both for positive and negative flashes) showed little variation inside the Austrian territory. It indicates that the network DE is fairly uniform over the region and that there is little variation in peak current characteristics between the Austrian Alps and the eastern plains.

4.5 Flash Multiplicity

The number of strokes per flash (flash multiplicity) is a parameter that is very sensitive to both the detection efficiency of an LLS and the algorithm used to group strokes to flashes. Since the change to the LP2000 and its new flash algorithm in 1998, the ALDIS flash multiplicity is no longer limited to 15 strokes per flash. The highest flash multiplicity reported thus far with ALDIS is 32 strokes in a single flash. This was a flash to a tall radio tower and therefore likely to be an upward initiated discharge. This type of discharge commonly has high multiplicity. We note that the location system does not distinguish between return strokes and similar fast-rising current pulses superimposed on the initial continuing current of upward initiated discharges.

Figure 4.8 shows the variation in annual mean flash multiplicity over the 10 year period. For 1992 and 1993 data from the old ALDF system were used and processed by an APA280. This system assigned the highest multiplicity reported by one of the corresponding sensors as the flash multiplicity. From 1994 to 1997 the all stroke reporting (ASR) was used to group strokes into flashes (APA 280T) [Diendorfer et al., 1998]. Both of these angle-based algorithms tend to report higher multiplicities compared to the location-based algorithms used since the beginning of 1998 (LP2000) and described by Cummins et al. [1998]. On the other hand the integration of sensors from the EUCLID network around Austria in early 1998 resulted in an increased DE and therefore partly compensated for the effects of the change to the LP2000 in 1998.

To separate the DE and flash algorithm effects, raw data for the months of July and August 1997 and July and August 1998 were reprocessed using the LP2000, employing different network configurations. Results are shown in Table 4.5. The reprocessed 1997 data show the influence of the change in the grouping algorithm from APA 280T to LP2000, and the 1998 data shows the influence of the larger network when we compare the results to the Austria-only configuration. The angle-based grouping algorithm of the APA 280T produced a negative flash multiplicity of 2.59, whereas the result for the location-based LP2000 algorithm was 2.10 -- about 23% lower. The difference in positive flash multiplicity was less, changing from 1.30 to 1.16 - a 12% reduction with the LP2000 algorithm. Table 4.5 also shows that the mean multiplicity for negative flashes increased from 2.25 to 2.54 when neighboring EUCLID sensors are used. This is presumable due to the improved DE resulting from the integration of additional (EUCLID) sensors in the network.

As shown in Figure 4.8 the annual mean value of the multiplicity for negative flashes decreased steadily from 1998 to 2001. A related increase in the number of single stroke flashes is obvious in Figure 4.9. These effects are thought to result from the incremental network improvements and expansion after the initial integration into the EUCLID network. The result may seem counterintuitive, since the detection of low peak current events will also increase the number of detected subsequent strokes, and should thereby INCREASE multiplicity. However, we show in Section 4.7.1

(Figure 4.12) that single stroke flashes also have very small peak currents, and therefore the improvements also result in better detection of single stroke flashes. This in turn DECREASES multiplicity. The balance between these two effects will depend on actual DE (minimum detectable peak current) and the true distribution of the data. Finally, Figure 4.8 also shows that the multiplicity of all positive flashes is moved toward higher values due to the high multiplicity for positive bipolar flashes.

It is conceivable that the same changes in classification method that resulted in the misclassification of cloud discharges as small positive CG discharges is also the reason for the increase in single-stroke negative flashes in later years. It is this concern that caused E.P. Krider and his associates to assess small, single-stroke negative flashes during their video validation studies in Texas (Krider and Biagi, personal communication, 2003). In an evaluation of 16 small negative single stroke flashes reported by the NLDN (functionally the same instrumentation as used in ALDIS), they could confirm that at least 14/16 (87%) of them had a clear channel to ground. The other two events showed no clear channel in their video recordings, but they may have simply been out of the field-of view or too faint to see. These findings, in stark contrast with the analysis of small positive events, provide us with some confidence that the small single-stroke negative flashes seen by ALDIS are real CG flashes.

The integration into the EUCLID network also resulted in an increasing number of so called "fake flashes" or "outliers" in the network. These flashes result from random (noise-based) time correlations between sensors, and occur most frequently in large networks composed of different types of sensors. These flashes are typically single stroke flashes and therefore bias the multiplicity distribution. We can calculate the multiplicity including outliers (m_o) from the assumed fraction of outliers (F_o) and the real measured multiplicity (m) by Eq. (4.5)

$$m_o = (1 - F_o)^* m + F_o$$
 (4.5)

With small transformations, the fractional error (E) depending on the real multiplicity m is given by Eq. (4.6)

$$E = \left(1 - \frac{m_o}{m}\right) = F_o * (1 - \frac{1}{m})$$
 (4.6)

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Eq. (4.6) shows that the error in multiplicity is less than the fraction of outliers and gets smaller as m gets smaller. Assuming a fraction of outliers of $F_0=1\%$ and a real multiplicity of m=2.5 results in a fractional error of 0.6%. Therefore the effect of the outliers on the multiplicity statistics is small.

Figure 4.10 shows the spatial distribution of the multiplicity of negative flashes for Austria. It clearly shows a maximum of multiplicity inside the alpine region. The spatial distribution of the percentage of single stroke flashes (figure not included) shows similar but opposite spatial dependencies, when compared to the spatial distribution of multiplicity in Figure 4.10. One might infer that these results indicate poor DE outside of Austria, but this is not the case. The spatial pattern shown in Figures 4.10 exists both before and after integration with EUCLID in 1998. A possible reason for the small regions with highest multiplicity (>3.0) and small percentage of single strokes (<40%) in the alpine region could be the presence of several places (towers and/or mountain tops) which favor upward initiated flashes. A more detailed analysis of the multiplicity on a 1x1 km resolution (figure not included) shows several squares with a 10 year average multiplicity of more than 5 strokes (according to the LLS) per flash, many of them in coincidence with radio tower locations and mountain tops.

4.6 Interstroke intervals

Because stroke data are only available in our lightning database since 1996, the following analysis is done for the period from 1996 to 2001. During this 5-year period, the algorithm to group strokes to flashes was changed, as discussed in Section 2. In order to minimize algorithm effects on the interstroke interval statistics, we have evaluated the relevant differences. The flash algorithm used in the APA 280T (used for the 1996 and 1997 data) allowed interstroke intervals greater than 0.5s. Less than 2% of the strokes exhibited an interstroke interval greater than 0.5s during 1996 and 1997 and therefore we conclude that the influence of this parameter change is marginal.

For the period of 1998-2001 (LP2000 flash algorithm) about 2% negative and 9% positive strokes of flashes with a multiplicity greater than one had very small interstroke intervals (< 0.1 ms). These constituted about 2% of the total data. An

investigation with NLDN data [Cummins, personal communication, 2003] has shown that there are almost no flashes with interstroke intervals between 0.7 ms and 0.1 ms, and that the events with interstroke intervals in the range of 0 - 0.1 ms are related to duplicate ground-wave events and ionospheric reflections that do not occur with the APA280T algorithm. We therefore exclude interstroke intervals below 0.1 ms. We found that the negative bipolar flashes had interstroke interval statistics that were indistinguishable from non-bipolar negative flashes, so these data are presented as one dataset. However, positive bipolar flashes influenced the positive interstroke interval statistics and are therefore also excluded in this analysis.

Arithmetic and geometric mean interstroke intervals are shown in Figure 4.11, both for positive and negative flashes. The geometric mean interstroke interval for negative flashes is in the range of 60 ms, and does not have a large dependence on year. Rakov et al. [1994] reported a geometric mean of 60 ms for the interstroke interval of all negative multistroke flashes. Berger et al. [1975] reported a median interstroke interval for negative downward flashes of 33 ms based on a sample size of 133 strokes measured at the tower on the Monte San Salvatore. Taking into account that Berger et al. [1975] may have analyzed the so called "no current interval" [Fisher et al., 1993], the actual interstroke interval should be higher than 33 ms. Our results are also consistent with optically measured interstroke intervals obtained using a high speed camera, as reported by Saba et al. [2003]. Saba et al. measured a mean interstroke interval of 96 ms (arithmetic mean) what is close to the values presented in Figure 4.11.

Interstroke intervals for positive flashes show a clear year-to-year variation. Although we have excluded positive bipolar flashes and flashes with unrealistic small interstroke intervals (< 0.1 ms) from this analysis, this trend is clear. It is unlikely that this effect is related to annual changes in climatological conditions because the interstroke interval statistic for negative flashes does not have a large year to year dependence. Therefore we conclude that this effect is related to the misclassification of small positive cloud discharges, as discussed above. The reason for the increase of interstroke interval of the positive nonbipolar flashes in 2001 is unknown.

4.7 Relation between lightning parameters

4.7.1 Flash peak current as a function of multiplicity

Orville et al. [2002] reported an increase in median first-stroke peak current with increasing multiplicity for negative flashes detected by the U.S. NLDN. As noted by Orville et al. [2002], this might suggest that the key factors determining the charge in the lower portion of the lightning channel (which determines first-stroke peak current) are also related to the total charge available for producing all the strokes in a flash.

Figure 4.12 shows median flash peak current as a function of multiplicity for the periods 1992-1993, 1994-1997, 1998-2001, as well as the 10-year average 1992-2001. As expected, there are large differences between the individual periods, related to the algorithm that groups strokes to flashes and the performance enhancement of the network. However, all periods show a dramatic increase in the median flash peak current with increasing multiplicity. It is interesting to note that even during the period 1994-1997, when the largest (rather than the first) stroke determined the flash peak current, this same dependence exists. These results are in agreement to Rakov and Uman [1990] who noted that first strokes in multi-stroke flashes exhibit a significantly higher initial field peak than single stroke flashes

The results in Austria show an even greater dependence of flash peak current on multiplicity than was found in the U.S. This is illustrated by the fact that the ratio of the median peak current for negative flashes with multiplicity 10, as compared to the value for a negative single stroke flash, is 2.3 in Austria and was about 1.7 averaged over the NLDN region [Orville et al., 2002].

The relationship between the median first-stroke peak current and flash multiplicity for positive flashes does not show such a clear trend (Figure 4.13). As in the previous sections only nonbipolar flashes are considered for the period from 1998 to 2001. Contrary to the findings of Orville et al. [2002], we see no decrease in the median positive peak current with increasing multiplicity. We attribute the variability in Figure 4.13 to the algorithm that groups strokes to flashes and the misclassification of small positive events. It should be noted that the bins for positive flashes with a multiplicity greater than five contain sample sizes of less than 100 flashes.

4.7.2 Interstroke interval versus flash multiplicity and stroke order

Only data from 1996 to 2001 were available for this analysis. In addition, strokes with interstroke intervals less than 0.1 ms are excluded. Figure 4.14 shows the geometric mean of the interstroke intervals of negative flashes, as a function of flash multiplicity. These values monotonically decrease from 68 ms (multiplicity=2) to 34 ms (multiplicity=15). The decrease of interstroke interval with increasing multiplicity may be related to regions in clouds with higher charge concentration. It is possible that flashes developing from those regions exhibit more strokes with shorter intervals.

Due to the DE improvements over the six-year period (1996-2001) we expect the additional detected return strokes to result in a lower average interstroke interval for the year 2001. We expect a further reduction in interstroke interval for the sub area within a radius of 200 km around sensor 4 (Niederöblarn) (see Figure 2.1), which is the area with the highest DE in Austria. The results presented in Figure 4.14 support our hypothesis. The interstroke interval in 2001 around sensor 4 is about 5% lower than the six-year average (1996-2001). For 2001 the results of limiting the data to a sub region around sensor 4 are similar to those for the complete region, indicating a more or less uniform performance of the network over the entire area.

The nonbipolar positive flashes have smaller interstroke intervals, when compared to the negative flashes. Similar to negative flashes, their interstroke intervals decrease with increasing multiplicity. There is not a sufficient number of nonbipolar positive flashes with multiplicity greater than 5 to calculate the interstroke interval for this data set. For positive nonbipolar flashes, there is no apparent relationship between interstroke interval and stroke order. Given the small sample set, any interpretations would not be statistically meaningful.

Figure 4.15 shows the geometric mean of the preceding interstroke interval as a function of stroke order. For negative flashes there is a slight decrease in the preceding interstroke interval for increasing stroke order. It is interesting to note that the geometric mean of the interstroke intervals reported by Rakov et al. [1994] for stroke orders 2-4 is 66 ms and therefore higher than the value of 59 ms determined with the ALDIS network. This is somewhat unexpected because the limited DE of the LLS means that not all strokes will be detected, and thus the interstroke interval should be biased toward larger values. The values measured by Rakov et al. [1994] were obtained from summer thunderstorms in Florida. We have not assessed the variation of the interstroke intervals from storm to storm, region to region, or from season to season. At this time the source of this difference is unknown.

5. Discussion

This analysis of a 10 year period of the lightning data in Austria provides, for the first time, comprehensive insight into the lightning activity and the lightning parameters in Austria. It is also important to note that these data were recorded using a LLS with small baselines, low sensor thresholds and therefore high performance. Nevertheless all results presented in this paper have to be viewed with the limitations of the specific lightning location technology that was used.

We have shown that the applied algorithm that groups strokes to flashes has an effect on the multiplicity and the peak current statistics. By changing from the APA 280T to the LP2000 flash algorithm the mean multiplicity for negative flashes decreased by about 23% (from 2.59 to 2.10 - see Table 4.5 summer 1997 data). By changing the assignment of flash peak current from the largest stroke peak current to the first stroke peak current, the median peak current for negative flashes decreased by about 12% (from 11.3 kA to 9.9 kA – see Table 4.3).

The peak current and multiplicity statistics in Austria are quite different from the values obtained with most of the other LLS throughout the world. This could be caused by regional climate differences or by differences in the performance of the lightning detection systems. In an effort to separate out these factors, we have identified a region in the U.S. which has a similar latitude, climate and mountainous terrain (Western Montana: 45 - 49N, 111 - 116W) and a region in the U.S. which has completely different climate and terrain (Southern Louisiana: 29 - 31.5N, 89.5 - 93.0 W) compared to Austria. In Table 5.1 we have summarized three-year averages for some of the key lightning parameters for the U.S. (NLDN) regions and Austria. For this comparison we use Austrian data from 1999-2001 because during this period ALDIS performance was the highest and most uniform.

It is clear from Table 5.1 that the lightning parameters of Louisiana are quite different from the values in Montana and Austria. This result indicates that regions with similar climate and geography may have similar lightning parameter values. It is interesting to note that the mean and median peak currents in Montana are lower than in Louisiana even with a higher 1% value, given that this 1% value is an indicator of the DE in the region. The (smaller) difference in peak current values between Austria and Montana may be due to true regional differences or network differences. The median value of -13.5 kA of the NLDN in Montana is calculated with a field to current conversion factor of 0.185, which is about 20% smaller than the value of 0.23 used in Austria (see Eq. 4.2). On the other hand attenuation parameter b=1.13 and λ =10.000, as used in the NLDN, increase the median value by about 13% compared to the Austrian settings b=1.0 and λ =10.000.000 - see Table 4.3. Taking into account both effects the median peak current in Austria for the 1999-2001 period of -10.6 kA would change to -9.6 kA and is therefore about 30% smaller than in Montana. This difference could be related to the smaller baselines of ALDIS resulting also in the smaller value for the 1% peak current. This presumed better DE in Austria may also account for the slightly higher mean interstroke interval in Montana (63.5 ms), as compared to Austria (56 ms).

A review of the findings of Burrows et al. [2002] shows that negative flash multiplicity can vary significantly with region. Burrows et al. [2002] analyzed almost 2 years of data for Canada and reported a multiplicity of negative flashes of 3-6 for western Canada. Although the DE of the LLS in Canada is assumed to be lower than in Austria, the multiplicity reported for Canada is generally much higher. We note that multiplicity not only varies with region -- it also varies strongly from day to day [Diendorfer et al., 1998], and appears to be related to storm phase and type. It was also shown by Diendorfer et al. [1998] that the percentage of single stroke flashes varies from storm to storm.

It is generally accepted in the literature that median negative first stroke peak current is approximately two times larger than subsequent stroke peak current in the same channel [Berger et al., 1975; Garbagnati E. and Lo Piparo, 1982]. A similar result has been found in Florida for range-normalized peak fields [Rakov and Uman, 1990]. In a previous study in Austria by Diendorfer et al. [1998], no such relationship was found in data from ALDIS. There are several possible reasons for this discrepancy, including real climatological differences, the exclusion of small subsequent strokes due to limited DE of the ALDIS network prior to 1998, or the fact that the ALDIS data is covering an entire year with all types of thunderstorms and stages of storm development. Two findings in this paper shed additional light on this topic. First, the median first stroke peak current for single stroke negative flashes are about half as big as those for flashes with at least four or more strokes (Figure 4.12). Second, the percentage of single stroke flashes is extremely high in the ALDIS network, and increased even further (from about 40% to about 60%) as the network improved and expanded (Figure 4.9). These results suggest that the lack of difference in first versus subsequent stroke estimated peak current in the ALDIS network may truly be a climatological difference from other regions, and that this difference is related to the percentage of single stroke flashes.

Rakov and Huffines [2003] compared the percentage of single stroke flashes detected by the NLDN with the percentage of single stroke flashes determined from correlated electric field and television (video) records. They concluded from their data that the NLDN misses many small subsequent strokes because the percentage of single stroke flashes in their measurements is smaller than the one reported by the NLDN. This may be true in a network with a somewhat high detection threshold, but it is in contradiction to our observation that with increasing performance of the LLS (above some minimum level) the percentage of single stroke flashes increases and the mean multiplicity decreases (see Figure 4.8 and Fig 4.9). It is further interesting to note that the mean interstroke interval measured in Austria is in the same range as those determined by field and camera measurements [Diendorfer et al., 1998; Saba et al., 2003; Miranda et al., 2004] but it should be higher if the LLS misses a considerable number of small subsequent strokes. We note that although the reported absolute values of the interstroke intervals are influenced (increased) by the slightly limited DE of the LLS, the relationship between interstroke interval and multiplicity or stroke order should be fairly insensitive to this limitation. These findings make it clear that there is more to learn about the subtle interactions between LLS performance and regional lightning parameters.

We have shown that lightning data processed with the LP2000 (1998-2001) contains a large number of positive bipolar flashes which do not influence the peak current statistics but influence the interstroke intervals and the multiplicity statistics. 50% of the positive flashes with multiplicity greater than one are bipolar flashes. A similar relation between the percentage of positive bipolar flashes and multiplicity is found in the data of the U.S. NLDN network. The majority of positive bipolar flashes appear to be the result of a positive first CG stroke followed by one or more negative CG strokes. In this case there is the question whether this type of discharge should be called positive or negative flash or if a separate class of bipolar flashes should be introduced for lightning statistics.

Lightning data calculated with the LP2000 also contains about 2% negative and 9% positive multi stroke flashes with an unrealistic small interstroke interval as a result of limitations in the currently used location algorithm. These events constitute about 2% of the total data set. The events with unrealistic interstroke intervals in the range of 0 - 0.1 ms are related to duplicate ground-wave events and ionospheric reflections.

Because positive flashes include a large fraction of bipolar flashes, are contaminated by cloud discharges and include strokes with unrealistic small interstroke intervals, published statistics about multiplicity and interstroke intervals of positive flashes should be interpreted with caution. Whenever other weather phenomena, e.g. severe storm reports, are related to the located number of positive flashes, a careful examination of the positive flash reports seems appropriate.

We think that we have analyzed the data recorded with ALDIS as carefully as possible, and that ALDIS has better performance than the majority of networks in the world. Nevertheless we have to keep in mind that all the sensors of an LLS have a detection threshold, and assuming a monotonic relationship between increasing peak electromagnetic field and lightning peak current, we have to conclude that all LLSbased lightning peak current statistics are over-estimates of the actual mean/median lightning peak current, and that the true average multiplicity is higher than the estimated (measured) one.

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The availability of LLS data has considerably advanced our knowledge of lightning incidence and our understanding of regional variations in lightning parameters, as well as providing critical information for real-time and operational applications. However, the specific performance level (location accuracy and detection efficiency), flash algorithms, and system "peculiarities" (classification errors and miss-location behaviors) must be considered and controlled in order to produce results that can contribute to our understanding of true regional and climatological differences throughout the world.

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References

Anderson R.B., Eriksson A.J., Kröninger H., Meal D.V., Smith M.A.: Lightning and Thunderstorm parameters. In Lightning and Power Systems, London, IEE Conf. Publ. No. 236, 1984.

Berger K., Anderson R.B., Kröninger H.: Parameters of lightning flashes, Electra, No. 41, p. 23-37, 1975.

Bernardi M., Pigini A., Diendorfer G., Schulz W.: Long Term Experience on Lightning Acquisition in Italy and Austria and Data Application to the Improvement of Lightning Performance, CIGRE Session Paris, 2002.

Burrows William R., Patrick King, Peter J. Lewis, Bohdan Kochtubajda, Brad Snyder and Viateur Turcotte: Lightning Occurrence Patterns over Canada and adjacent United States from Lightning Detection Network Observations, Atmosphere-Ocean, Vol. 40, p. 59-81, 2002.

Cehak K.: Zur Gewitter- und Hagelklimatologie von Österreich, Tagungsbericht der 15. Internationalen Tagung für alpine Meteorologie in Grindelwald. Veröffentlichung der SMA, 40, 316-319, 1980

Carey D.L., Rutledge A.S., Petersen A.W.: The relationship between severe storm reports and cloud-to-ground lightning polarity in the contiguous United States from 1989 to 1998. Monthly Weather Review, Vol. 131, p. 1211-1228, 2003.

Cummins, K. L., Murphy, M. J., Bardo, E. A., Hiscox, W. L., Pyle, R. B., Pifer, A. E.: A combined TOA/MDF technology upgrade of the U. S. National Lightning Detection Network, J. Geophys. Res. Vol. 103, No. D8, p. 9035, 1998.

Diendorfer G., Schulz W., Hofbauer F., Stimmer A.: Thunderstorm days versus ground flash density. ISH, Graz, 1995.

Diendorfer G., Schulz W., Rakov V.: Lightning characteristics based on data from the Austrian lightning location system. IEEE Transactions on EMC, Vol. 40, No. 4, 1998.

Diendorfer G., Hadrian W., Hofbauer F., Mair M., Schulz W.: Evaluation of Lightning Location Data Employing Measurements of Direct Strikes to a Radio Tower. CIGRE Session Paris, 2002.

ENV 61024: Protection of structures against lightning part I: General Principles, 1995.

Finke U. and Hauf T.: The Characteristics of Lightning Occurrence in Southern Germany, Beiträge zur Physik der Atmosphäre - Contributions to Atmospheric Physics, Volume 69, No. 3, August 1996.

Fisher R.J., Schnetzer G.H., Thottappillil R., Rakov V.A., Uman M.A., Goldberg J.D.: Parameters of triggered lightning flashes in Florida and Alabama, J. Geophys. Res, Vol. 98, No. D12, 1993.

Frei C., and C. Schär: A precipitation Climatology for the Alps from high-resolution rain-gauge observations. *Int. J. Climatol.* 18, 873-900, 1998.

Garbagnati E. and Lo Piparo G.B.: Parameter von Blitzströmen, ETZ, Bd. 103, 1982.

Herodotou N., Chisholm W.A., Janischewskyj W.: Distribution of lightning peak stroke currents in Ontario using an LLP system, IEEE transactions on Power delivery, Vol. 8, Nb. 3, July 1993.

Hiscox W. L., Krider E. P., Pifer A. E. and Uman M. A.: A systematic method for identifying and correcting "site errors" in a network of magnetic direction finders, paper presented at the International Aerospace and Ground Conference on Lightning and Static Electricity. Natl. Interagency Coord. Group. Natl. Atmos. Electr. Hazard Program. Orlando, Fla.. June 26-28. 1984.

Huffines G. R. and Orville R.E.: Lightning Ground Flash Density and Thunderstorm Duration in the Continental United States: 1989-96, Monthly Weather Review, 1999.

Idone V.P., Arsalan S.B., Henderson R.W., Moore P.K. and Pyle R.B.: A Reexamination of the Peak Current Calibration of the National Lightning Detection Network, J. Geophys. Res. Vol. 98, No. D10, p. 18,323-18,332, 1993.

Kann A.: Klimatologie konvektiver Systeme in den Ostalpen anhand von Blitzdaten, Diplomarbeit Institut f. Meteorologie und Geophysik Univ. Wien, 2001.

Krider E.P., Noggle R.C., Pifer A.E., Vance D.L.: Lightning direction finding systems for forest fire detection, Bull. Am. Meteorol. Soc., 61, 980-986, 1980.

LeBoulch M. and Plantier T.: The Meteorage thunderstorm monitoring system: A tool for new EMC protection strategies. ICLP, Interlaken, 1990.

Lopez R.E. and Holle R.L.: Diurnal and Spatial Variability of Lightning Activity in Northeastern Colorado and Central Florida during the Summer, Monthly Weather Review, Vol. 114, p. 1288-1312, 1986.

Miranda F., Pinto O., Saba M.: GPS Time synchronized analysis correlating electric field observations, fast camera images and lightning detection system measurements in Brazil. GROUND 2004 & 1st LPE, 2004.

Orville R.E.: Calibration of a Magnetic Direction Finding Network Using Measured Triggered Lightning Return Stroke Peak Currents, J. Geophys. Res. Vol. 96, No. D9, p. 17,135-17,142, 1991.

Orville R.E., Weisman R.A., Pyle R.B., Henderson R.W., Orville R.W.: Cloud-to-Ground Lightning Flash Characteristics from June 1984 through May 1985, J. Geophys. Res. Vol. 92, No. D5, p. 5640-5644, 1987.

Orville R.E. and Huffines G.R.: Lightning Ground Flash Measurements over the Contiguous United States: 1995-97, Monthly Weather Review, 1999.

Orville R.E. and Huffines G.R.: Cloud-to-Ground Lightning in the United States: NLDN Results in the First Decade, 1989-98, Monthly Weather Review, 2001.

Orville R.E., Huffines G.R., Burrows W.R., Holle R.L., Cummins K.L.: The North American lightning detection network (NALDN) – first results: 1998-2000, Monthly Weather Review, 2002.

Pinto O. Jr., Pinto I. R. C. A., Gomes M. A. S. S., Vitorello I., Padilha A. L., Diniz J. H., Carvalho A. M., Filho A. C.: Cloud-to-ground lightning in southeastern Brazil in 1993, 1, Geographical distribution, J. Geophys. Res. Vol. 104, No. D24, p. 31369, 1999a.

Pinto I. R. C. A., Pinto O. Jr., Rocha R. M. L., Diniz J. H., Carvalho A. M., Cazetta Filho A.: Cloud-toground lightning in southeastern Brazil in 1993, 2, Time variations and flash characteristics, J. Geophys. Res. Vol. 104, No. D24, p. 31381, 1999b.

Rakov V.A.: Positive and bipolar lightning discharges: a review. 25th ICLP, Rhodes, 2000.

Rakov V.A., G.R. Huffines: Return-Stroke Multiplicity of Negative Cloud-to-Ground Lightning Flashes, J. of Applied Meteorology, Vol 42, Oct. 2003.

Rakov V.A., Uman M.A., Thottappillil R.: Review of lightning properties from electric field and TV observations, J. Geophys. Res. Vol. 99, No. D5, p. 10,745-10,750, 1994.

Rakov V.A. and Uman M.A.: Some properties of negative cloud-to-ground lightning flashes versus stroke order. J.Geophys.Res., Vol. 95, D5, 5447-5453, 1990.

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

Reap R.M.: Evaluation of Cloud-to-Ground Lightning Data from the Western United States for the 1983-84 Summer Seasons, Journal of Climate and applied Meteorology, Vol. 25, p. 785-799, 1986.

Saba M.M.F., Naccarato K.P., Pinto O., Cabral G.F.: Imaging atmospheric discharges with high-speed cameras. VII International Symposium on Lightning Protection-SIPDA, Brazil, November 2003.

Schulz W. and Diendorfer G.: EUCLID network performance and data analysis, 17th International Lightning Detection Conference, Tucson, October 2002.

Schulz W. and Diendorfer G.: Bipolar flashes detected with lightning location systems and measured on an instrumented tower. VII International Symposium on Lightning Protection-SIPDA, Brazil, November 2003.

Soriano L.R., Pablo F., Diez E.G.: Cloud-to-ground lightning activity in the Iberian Peninsula: 1992-1994, J. Geophys. Res. Vol. 106, No. D11, p. 11891-11901, 2001.

Shindo T., Yokoyama S.: Lightning Occurrence Data Observed with Lightning Location Systems in Japan: 1992 – 1995, IEEE Transactions on Power Delivery, Vol. 13, No. 4, 1998.

Terrandellas E.: Main features of the distribution of the atmospheric electric activity in Catalonia and the surrounding Mediterranean area. INM/WHO International symposium on cyclones and hazardous weather in the Mediterranean, Palma de Mallorca, Spain, 1997.

Troger W.: Die Einbeziehung des österreichischen Blitzortungssystems ALDIS in die meteorologische Analyse von Gewittern. Diplomarbeit Leopold-Franzens Univ. Innsbruck, 1998.

Uman M,A. and McLain D.K.: Magnetic field of the Lighting Return Stroke, J. Geophys. Res. Vol. 74, 1969.

Wacker, R. S., and R. E. Orville, 1999a: Changes in measured lightning flash count and return stroke peak current after the 1994 U.S. National Lightning Detection Network upgrade. Part I: Observations. J. Geophys. Res., **104** (D2), 2151–2157.

Wacker, R. S., and R. E. Orville 1999b: Changes in measured lightning flash count and return stroke peak current after the 1994 U.S. National Lightning Detection Network upgrade. Part II: Theory. *J.* Geophys. Res., **104** (D2), 2159–2162.

Zajac B.A. and S.A. Rutledge: Cloud-to-Ground Lightning Activity in the Contiguous United States from 1995 to 1999, Mon. Weather Rev., Vol. 129, 10833-10841, 2001.

TABLE CAPTIONS

Table 2.1: ALDIS network performance changes from 1992-2001

Table 4.1: Number of located bipolar flashes 1998 – 2001

Table 4.2: Mean and median peak currents for positive and negative flashes

Table 4.3: Influence of different configuration parameters for August 2001 on the peak current

Table 4.4: Influence of different attenuation parameters on the agreement of the individual sensors (First stroke amplitude assigned as flash amplitude).

Table 4.5: Influence of different configuration on average multiplicity for the summer months July and August 1997 and 1998.

Table 5.1: Lightning parameters of negative flashes in similar and different climatological areas

| Year | Sensor | 1% Peak | Flash | Liahtning | Positive | Source of | Comments |
|-------|--------------------|---------|-----------|------------------------------|----------------------|------------------------|-------------|
| . oui | Type(s) | Current | Algorithm | Classification | Detection | Flash neak | Commonito |
| | 1,200(0) | | Aigontinn | Method | Threshold | current | |
| 1000 | | | Avanla | | | det Otrelie | |
| 1992 | ALDF | -7.9 | Angle | LLP parameters | 350 mv | 1st Stroke | |
| 1993 | ALDF | -3.9 | Angle | LLP parameters | 350 mV | 1st Stroke | |
| 1994 | IMPACT | -3.9 | Angle | LLP Parameters ¹ | 350 mV | Largest | |
| | | | - | | | stroke | |
| 1995 | IMPACT | -3.4 | Angle | LLP Parameters ¹ | 350 mV | Largest | |
| | | | Ū | (reduced width) ² | | stroke | |
| 1996 | IMPACT | -3.7 | Angle | LLP Parameters ¹ | 350 mV | Largest | |
| | | | - | (reduced width) ² | | stroke | |
| 1997 | IMPACT | -3.5 | Angle | LLP Parameters ¹ | 350 mV | Largest | |
| | | | - | (reduced width) ² | | stroke | |
| 1998 | IMPACT; | -3.4 | Spatial | LLP Parameters ¹ | 350 mV ³ | 1 st Stroke | EUCLID |
| | LPATS ⁵ | | - | (reduced width) ² | ~200 mV ⁴ | | Integration |
| 1999 | IMPACT; | -2.8 | Spatial | LLP Parameters ¹ | 350 mV ³ | 1 st Stroke | EUCLID |
| | LPATS ⁵ | | - | (reduced width) ² | ~200 mV ⁴ | | Integration |
| 2000 | IMPACT; | -2.5 | Spatial | LLP Parameters ¹ | 350 mV ³ | 1 st Stroke | EUCLID |
| | LPATS ⁵ | | - | (reduced width) ² | ~200 mV ⁴ | | Integration |
| 2001 | IMPACT; | -2.7 | Spatial | LLP Parameters ¹ | 350 mV ³ | 1 st Stroke | EUCLID |
| | LPATS ⁵ | | | (reduced width) ² | ~200 mV ⁴ | | Integration |

Table 2.1: ALDIS network performance changes from 1992-2001

¹ A proprietary set of waveform parameters that exclude cloud discharges. These parameters are only used by IMPACT and ALDF sensors. LPATS sensors only employed width as a classification method. ² width was reduced in March, 1995 (early in the storm season).

³ for IMPACT sensors inside Austria ⁴ for IMPACT ES and LPATS sensors outside Austria ⁵ LPATS sensors outside Austria only

Table 4.1: Number of located bipolar flashes 1998 – 2001

| Year | Total neg. Flashes | Total pos. Flashes | Neg. bipolar Flashes | Pos. bipolar Flashes | % neg. bipolar from total neg. Flashes | % pos. bipolar from total pos. Flashes |
|-----------|-----------------------|-----------------------|-------------------------|-------------------------|--|--|
| 1998 | 321,320 | 50,342 | 1422 | 2537 | 0.4 | 5.0 |
| 1999 | 216,742 | 34,367 | 1721 | 2955 | 0.7 | 8.6 |
| 2000 | 368,355 | 75,574 | 6088 | 6058 | 1.7 | 8.0 |
| 2001 | 261,320 | 76,563 | 6224 | 5559 | 2.4 | 7.3 |
| 1998-2001 | 1,167,737 | 236,846 | 15,455 | 17,109 | 1.3 | 7.2 |

Table 4.2: Mean and median peak currents for positive and negative flashes

| Year | mean neg. peak current [kA] | median neg. peak current [kA] | mean pos. peak current [kA] | median pos. peak current [kA] |
|------|--------------------------------|----------------------------------|--------------------------------|----------------------------------|
| 1992 | -31 | -24 | 72 | 55 |
| 1993 | -20 | -15 | 46 | 32 |
| 1994 | -20 | -16 | 39 | 30 |
| 1995 | -17 | -13 | 35 | 25 |
| 1996 | -18 | -14 | 38 | 28 |
| 1997 | -17 | -13 | 30 | 20 |
| 1998 | -17 | -14 | 22 | 13 |
| 1999 | -16 | -13 | 24 | 16 |
| 2000 | -13 | -10 | 19 | 12 |
| 2001 | -13 | -10 | 16 | 10 |

Table 4.3: Influence of different configuration parameters for August 2001 on the peak current

| | Neg. flashes | | Pos. fl | ashes |
|---|--------------|----------------|--------------|----------------|
| | Mean [kA] | Median [kA] | Mean [kA] | Median [kA] |
| First stroke amplitude assigned as flash amplitude b=1.00, λ =10,000,000 km | -12.3 | -9.9 | 12.5 | 8.1 |
| Maximum stroke amplitude assigned as flash amplitude b=1.00, λ =10,000,000 km | -13.8 | -11.3 | 13.4 | 8.4 |
| First stroke amplitude assigned as flash amplitude, b=1.13, λ =10,000,000 km | -14.0 | -11.0 | 14.9 | 9.2 |
| First stroke amplitude assigned as flash amplitude, b=1.13, λ =10,000 km | -14.3 | -11.2 | 15.3 | 9.4 |
| First stroke amplitude assigned as flash amplitude, b=1.00, λ =1100 km | -15.3 | -11.5 | 16.7 | 9.5 |

Table 4.4: Influence of different attenuation parameters on the agreement of the individual sensors (First stroke amplitude assigned as flash amplitude).

| | Mean | Relative standard deviation [%] |
|-------------------------|------|---------------------------------|
| b=1.00, λ=10,000,000 km | 1.21 | 14.1 |
| b=1.13, λ=10,000,000 km | 1.11 | 14.4 |
| b=1.13, λ=10,000 km | 1.09 | 14.3 |
| b=1.00, λ=1100 km | 1.01 | 13.0 |

Table 4.5: Influence of different configuration on average multiplicity for the summer months July and August 1997 and 1998.

| | | Mean multiplicity | Mean multiplicity |
|--------|-----------------------------------|-------------------|-------------------|
| | | neg. flashes | pos. flashes |
| Summer | 8 sensor ALDIS network (APA 280T) | 2.59 | 1.30 |
| 1997 | 8 sensor ALDIS network (LP2000) | 2.10 | 1.16 |
| Summer | 8 sensor ALDIS network (LP2000) | 2.25 | 1.17 |
| 1998 | Complete EUCLID network (LP2000) | 2.54 | 1.20 |

Table 5.1: Lightning parameters of negative flashes in similar and different climatological areas

| | Louisiana | Montana | Austria |
|--|-----------|-----------|-----------|
| | 2000-2002 | 2000-2002 | 1999-2001 |
| 1% peak current [kA] | -3.5 | -5.5 | -2.6 |
| Median peak current [kA] | -20.5 | -13.5 | -10.6 |
| Mean peak current [kA] | -25.6 | -17.9 | -13.6 |
| Mean multiplicity | 2.8 | 2.1 | 2.1 |
| Single stroke flashes [%] | 38.6 | 53.8 | 56.3 |
| Geometric mean interstroke interval [ms] | 71.9 | 63.5 | 56.0 |

FIGURE CAPTIONS

Figure 2.1: The locations of the sensors in ALDIS

Figure 4.1: Annual CG flash and stroke counts in Austria

Figure 4.2: Mean monthly flash counts (1992-2001). Bars represent ±1 standard deviation.

Figure 4.3: Mean diurnal flash counts (1992-2001)

Figure 4.4: Mean annual flash density in Austria 1992-2001 (1x1km resolution)

Figure 4.5: Mean monthly polarity distribution in Austria 1992-2001

Figure 4.6: Percent positive flashes from total flashes versus year

Figure 4.7: Median peak currents for negative and positive flashes versus year

Figure 4.8: Mean flash multiplicity over the 10 year period

Figure 4.9: Percentage of single stroke flashes. Bipolar flashes are included.

Figure 4.10: Multiplicity distribution of negative flashes over Austria (1992-2001, 10x10km resolution)

Figure 4.11: Interstroke intervals versus year (only intervals greater 0.1ms are included)

Figure 4.12: Median flash peak current versus flash multiplicity for negative flashes

Figure 4.13: Median flash peak current versus flash multiplicity for positive flashes

Figure 4.14: Geometric mean of interstroke interval versus multiplicity

Figure 4.15: Geometric mean of preceding interstroke interval versus stroke order



Figure 2.1: The locations of the sensors in ALDIS



Figure 4.1: Annual CG flash and stroke counts in Austria



Figure 4.2: Mean monthly flash counts (1992-2001). Bars represent ±1 standard deviation.



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Figure 4.4: Mean annual flash density in Austria 1992-2001 (1x1km resolution)



Figure 4.5: Mean monthly polarity distribution in Austria 1992-2001



Figure 4.6: Percent positive flashes from total flashes versus year



Figure 4.7: Median peak currents for negative and positive flashes versus year



Figure 4.8: Mean flash multiplicity over the 10 year period



Figure 4.9: Percentage of single stroke flashes. Bipolar flashes are included.



Figure 4.10: Multiplicity distribution of negative flashes over Austria (1992-2001, 10x10km resolution)



Figure 4.11: Interstroke intervals versus year (only intervals greater 0.1ms are included)



Figure 4.12: Median flash peak current versus flash multiplicity for negative flashes



Figure 4.13: Median flash peak current versus flash multiplicity for positive flashes



Figure 4.14: Geometric mean of interstroke interval versus multiplicity



Figure 4.15: Geometric mean of preceding interstroke interval versus stroke order