



Meteorological aspects of the atypical seasonal lightning distribution at the Gaisberg tower

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Abstract The seasonal lightning distribution at the Gaisberg tower in Austria is very different from the distribution observed in a circular ring with a radius of 2 to 10 km around the tower. The distribution in the circular ring shows the typical peak during the convective season. In contrast, we find a bimodal distribution with a peak in early spring and late fall at the tower. By selecting two cases representing these two situations, the differences in the meteorological setting are discussed.

Lightning events observed solely at the Gaisberg tower are characterized by strong horizontal winds in the lower layers of the atmosphere from the northwest sector. This direction represents the open window from the Gaisberg towards the foreland, meaning there are no mountains upstream, and the flow can reach the Gaisberg unhindered. Cases of this type occur mainly during the cold season but are not limited to it.

In contrast, lightning events at the tower and in its vicinity are typical for convective events with low horizontal wind speed in the lower layers and occur mainly during the convective season.

Keywords Gaisberg tower · Lightning · Meteorological setting · Cold season · Convective season

Meteorologische Aspekte der atypischen saisonalen Blitzverteilung am Sendemast auf dem Gaisberg

Zusammenfassung Die saisonale Blitzverteilung am Sendemast auf dem Gaisberg in Österreich unterscheidet sich sehr von der Blitzverteilung in einem Kreisring von 2 bis 10 km Radius um den Mast. Die Verteilung im Kreisring zeigt das typische Maximum während der konvektiven Saison, zum Unterschied zeigt sich am Turm eine bimodale Verteilung mit einem Maximum im Spätwinter und im Spätherbst. Es werden zwei Fälle präsentiert, anhand derer die Unterschiede des meteorologischen Settings diskutiert werden.

Blitzereignisse, die ausschließlich am Gaisberger Sendemast beobachtet werden, sind durch starke Horizontalwinde in den unteren Atmosphärenschichten aus dem Nordwestsektor charakterisiert. Diese Richtung repräsentiert das offene Fenster vom Gaisberg in das Vorland in dem Sinne, dass es in dieser Richtung keine vorgelagerten Berge gibt. Die Strömung trifft ungehindert auf den Gaisberg. Fälle dieser Art treten hauptsächlich während der kalten Saison auf, sind aber nicht ausnahmslos darauf beschränkt.

Im Gegensatz dazu sind Blitzereignisse in der nahen Umgebung des Turms und am Turm selbst charakteristisch für konvektive Ereignisse mit geringen horizontalen Windgeschwindigkeiten in den unteren Schichten und treten überwiegend während der konvektiven Saison auf.

Schlüsselwörter Gaisberg-Sendemast · Blitzschlag · Wetterlage · Kalte Saison · Konvektive Saison

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1 Introduction

Towers especially on mountain tops offer a great opportunity to study lightning parameters of mainly upward initiated flashes. Starting from 1998 the radio tower (100 m height) on the top of the *Gaisberg* (1287 m) mountain east of the city of Salzburg has been instrumented for measuring lightning parameters by the Austrian Lightning Detection and Information System (ALDIS) group. For a detailed description of the instrumentation the reader is referred to Diendorfer et al. [1]. Many studies have been conducted since then on different aspects of lightning parameters of the Gaisberg Tower (GBT) and for comparison to other lightning research towers during the last two decades [1–7].

A first indication for the atypical seasonal lightning distribution at GBT was presented by Pichler et al. [8] for a period of four years (2000–2003). In general, this picture was confirmed by Diendorfer et al. [1] for a period of eight years and Watanabe et al. [7] for a period of 19 years. Diendorfer et al. [1] classified all measured negative upward initiated flashes in three categories: initial continuous current only (ICC_{only}) by 48%, ICC with pulses (ICC_p) by 22% and ICC with return strokes (ICC_{RS}) by 30%. Watanabe et al. [2] analysed 19 years of lightning data for the polarity and detailed waveform of upward initiated lightning flashes at GBT. The large majority of 79% has been classified as negative, 4.3% as positive, 17% as bipolar and only 0.5% as downward directed.

Fig. 1a shows the number of strokes on a monthly basis at GBT and for a circular ring as recorded by the ALDIS Lightning Location System (LLS) within a radius from two to ten kilometre for the period 2000–2015. Variations at GBT are bimodal with two maxima in March and November which are two months of the so-called cold season (September to April). The distinct minimum in June falls into the high season of lightning activity in the vicinity during the so-called convective season (May to August). Fig. 1b represents the annual variations of the stroke

numbers. Even on the annual scale the correlation between the two data sets is very small (correlation coefficient = 0.15). High stroke numbers in the vicinity for a particular year are not necessarily connected with high stroke numbers at GBT and vice versa.

The aim of this paper is to examine possible meteorological reasons on the large scale for these differences in the seasonal and annual variations between GBT and its vicinity. There exist only a few investigations on the role of local meteorological parameters directly at the Gaisberg to investigate the characteristic of tower lightning flashes [9, 10]. A comprehensive overview on the large-scale is missing. To put it into a nutshell: Can we connect seasonal lightning occurrence at GBT and its vicinity to typical features in the large-scale meteorological setting?

2 Meteorological aspects leading to lightning producing clouds

2.1 Electrification of lightning producing clouds

The exact details of the electrification of a cloud are still subject of current research and not fully understood. Reasons for that are the complexity and variability of evolving clouds, difficulties to measure electric fields in such a large volume at the same time and of course the danger when entering these clouds by aeroplanes. Beside this some basic ingredients have been identified [11]:

- Strong updrafts (rapid upward moving air) in the central part of a cloud where temperature ranges from -10°C to -25°C . This is defined as the charging zone.
- Coexistence of supercooled cloud droplets, ice crystals and graupel in the charging zone.
- Differences of the vertical velocity of the lighter ice crystals and cloud droplets and the heavier graupel leads to collision of the particles.
- During the collision process the graupel becomes negatively and the ice crystals positively charged.

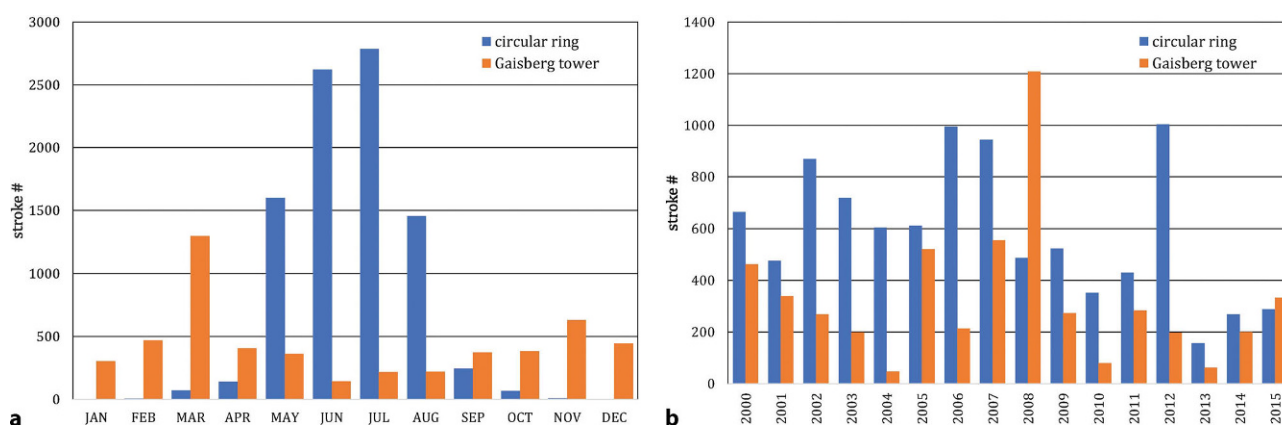


Fig. 1 Stroke numbers for a circular ring around GBT within a radius from two to ten kilometre recorded from the LLS (blue) and for the GBT recorded from direct measurements (orange) for **a** monthly sums for the years 2000–2015 and **b** annual sums

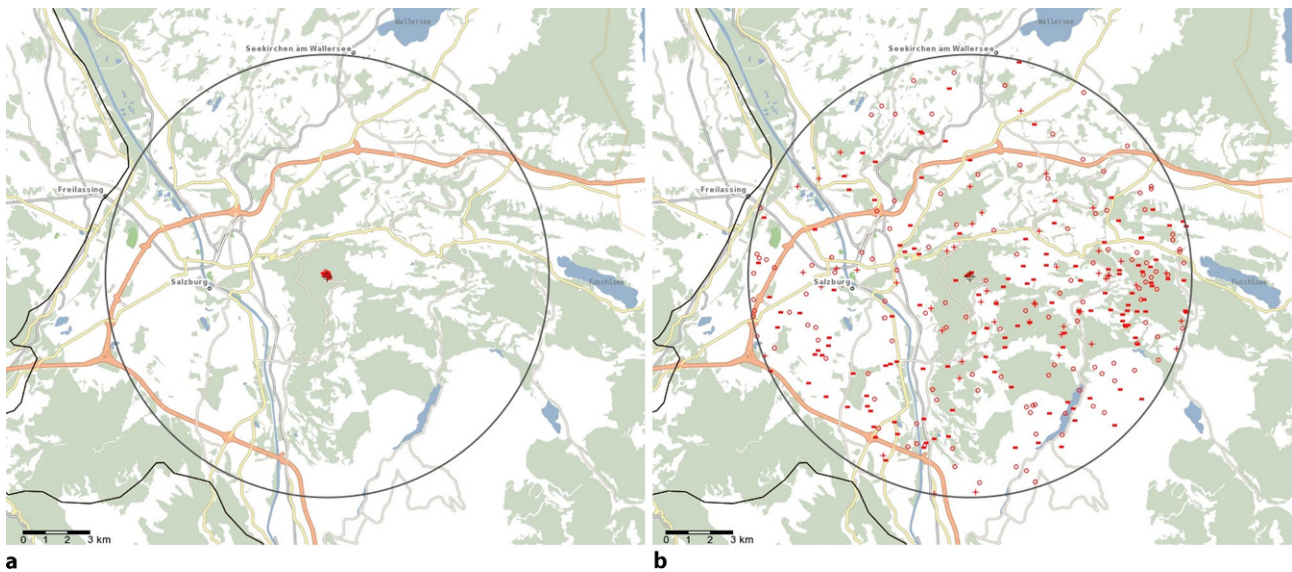


Fig. 2 Stroke distribution at Gaisberg and its vicinity on **a** 31 March 2015 and **b** 4 August 2012 as recorded by the LLS. Only strokes within a circle radius of 10 km around the GBT are plotted. Strokes are marked by red symbols: “+” positive

strokes, “-” negative strokes, “o” intra-cloud strokes. GBT is marked by a *black star*. Note: For 31 March 2015 all strokes are located exactly at the GBT. Courtesy of ALDIS

- e) Ice crystals are carried upward, therefore the upper part of the cloud is positively charged and the middle and lower part of the cloud, where graupel remains becomes negatively charged.
- f) The vertical extension of the cloud must be large enough to allow an effective charge separation. A rule of thumb says, that the cloud must reach the height of the -40°C isotherm to be able to produce lightning.

Strong updrafts and a moist atmosphere in the lower layers are crucial for cloud electrification.

2.2 Mechanisms leading to lifting processes

There exist several processes in the atmosphere to initiate updrafts. The most important ones in the case of the Gaisberg and its vicinity are:

- Convection
- Cross frontal circulation
- Forced ascent on an obstacle

Convection is the answer of the atmosphere to unstable conditions. By re-arranging air parcels vertical the atmosphere reduces the instability till neutral conditions are achieved. A measure for the strength of the expected convection is the convective available potential energy (CAPE). It is given by:

$$CAPE = g \int_{LFC}^{EL} \frac{T_p(z) - T_e(z)}{T_e(z)} dz$$

g is the earth acceleration in m/s^2 . $T_p(z)$ is the temperature of the lifting air parcel at height z in K. $T_e(z)$ is the temperature of the environment as mea-

sured by a radiosonde at height z also in K. As long as $T_p(z) > T_e(z)$ is valid the rising parcel is warmer and therefore less dense as the environment and will further be accelerated upwards. This is true between the level of free convection (LFC) and the equilibrium level (EL). Typical values for CAPE to initiate deep convection are in the range of about 250 up to 2500 J/kg in Europe [12].

A moving cold air mass lifts the warmer air ahead of it. The transition zone defines the cold front. Behind the cold front the air is descending, which results in a cross circulation perpendicular to the front. In case of strong temperature differences between the involved air masses and a fast moving cold front the lifting process is strengthened and may cause lightning (frontal thunderstorm). Winter thunderstorms are usually of this type.

The luv-side of a mountain range is exposed to higher precipitation amounts due to the additional lifting of the air when impinging the mountain range. Natural lightning is rarely observed for this setting without the support by the other two effects but a tower on top of the mountain can increase the electrical field considerably by the peak effect and lightning may occur.

3 Meteorological analysis of two very different case studies

3.1 Classification

Case studies have been selected according to the lightning appearance at GBT recorded by the tower instrumentation and/or in its vicinity recorded by the LLS. It turned out that all lightning events can be grouped

into two different event classes. Note: An event is defined by the *meteorological* event, e.g., passing of a convective cell or crossing of a cold front. This means that different events have in general different time durations.

Class *tower-only*: strokes recorded only at GBT but no strokes recorded in the vicinity by the LLS.

Class *tower and vicinity*: strokes recorded on both locations (GBT and vicinity).

The question arises if these different event types are connected to typical meteorological settings. Fig. 2a represents the stroke distribution for a *tower-only* event. One flash of type ICC_{RS} with 77 strokes hit the tower on 31 March 2015 at 18:48:03 UTC. In contrast Fig. 2b shows the distribution for a *tower and vicinity* event. ALDIS-LLS recorded 317 strokes during the time interval from 16:00 to 20:00 UTC on 4 August 2012. They were composed of 49 positive, 139 negative and 129 intra-cloud strokes. Only one flash of type ICC_{RS} consisting of six strokes has been recorded at the GBT.

3.2 Large-scale setting

The surface weather chart is presented in Fig. 3a for 31 March 2015, 18:00 UTC roughly one hour ahead of the lightning strokes. Main pressure features over Europe are a cyclone complex over Fennoscandia and an anti-cyclone over the eastern Atlantic. Between these two systems a strong pressure gradient can be observed from Iceland over the North Sea southwards to the Alpine Region. The area around GBT has been passed by an accompanying cold-front and is under the influence of this strong pressure gradient resulting in strong winds.

A rather different situation shows up for 4 August 2012 at 18:00 UTC (Fig. 3b) during the passage of a large convective system over the investigated area. No remarkable pressure systems can be found in large parts of Europe. Pressure gradients are small or almost vanishing. However, the short blue lines in Fig. 3b marks a convergence line indicating the inflow of low-level air in the area. For continuity reasons the air must rise and depending from the available

CAPE, this can result in the development of severe thunderstorms as was the case on this day.

Cross-frontal circulation has no effect for the selected cases but is responsible for possible widespread winter thunderstorms, even if they occur rarely [9].

3.3 Convection analysis

CAPE can be estimated from radiosonde launches. Munich is the nearest radiosonde station upstream of the Gaisberg for north-westerly flow. Typically, two launches per day at 00:00 and 12:00 UTC are carried out. The temperature profile in Fig. 4a taken from the sounding of Munich on 1 April 2015, 00:00 UTC illustrates the situation about five hours after the strokes have been initiated by the tower. As the general weather situation has not changed it can be assumed that it is representative for the GBT during the lightning strokes. CAPE analysis results in a very low value of $\sim 8\text{J/kg}$. The charging zone defined by the -10°C and the -25°C isotherms can be found approximately between 2.5 to 4.5 km ASL (above sea level). Values which are rather similar to the winter case study by Diendorfer et al. [9]. The vertical wind profile shows strong westerly to west-north-westerly directions reaching almost 50 kts (knots, approx. 25 m/s) at GBT.

The temperature and dew point temperature profiles of the sounding of Munich on 4 August 2012, 12:00 UTC (Fig. 4b) reflect the unstable situation before convection starts, e.g., CAPE amounts to $\sim 785\text{J/kg}$. The charging zone is located much higher than for the previous case and can be identified between 5 to 7.5 km ASL. The equilibrium level which marks the cloud top in absence of possible overshooting reaches roughly 11 km ASL and is much higher than the -40°C isotherm. All ingredients are favourable for the development of lightning producing clouds (cumulonimbus capillatus). Wind speed is very low in the boundary layer of up to 1500 m ASL, which includes the top of the Gaisberg.

Fig. 3 Weather charts (pressure, frontal analysis and satellite image) for **a** 31 March 2015, 1800 UTC and **b** 4 August 2012, 1800 UTC. Isobars: black isolines with an interval of 5 hPa. Courtesy of ZAMG

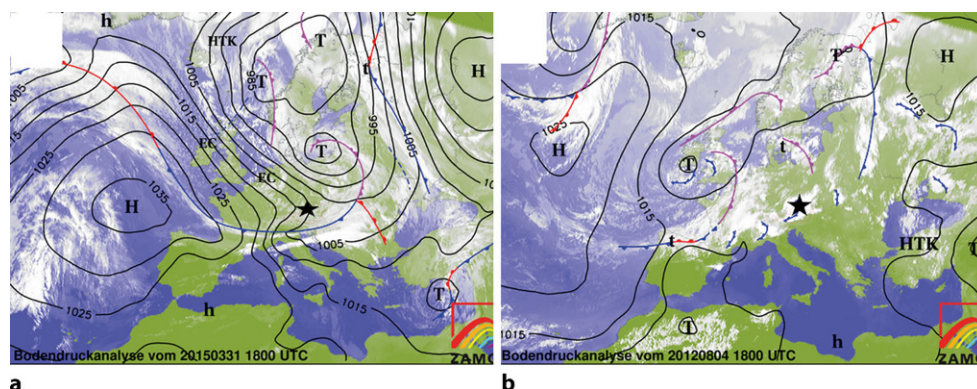


Fig. 4 Radiosoundings of Munich for **a** 1 April 2015, 0000 UTC and **b** 4 August 2012, 1200 UTC. **Bold black lines:** temperature T (right) and dew-point temperature T_d (left), **LFC level of free convection, EL** equilibrium level, **red-shaded area:** CAPE. Source: University of Wyoming (<http://weather.uwyo.edu/upperair/sounding.html>)

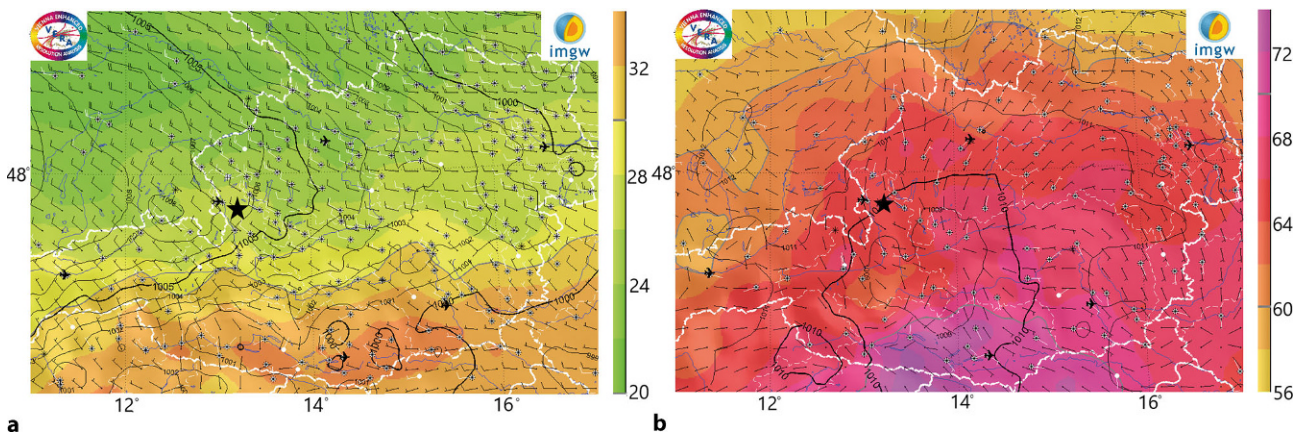
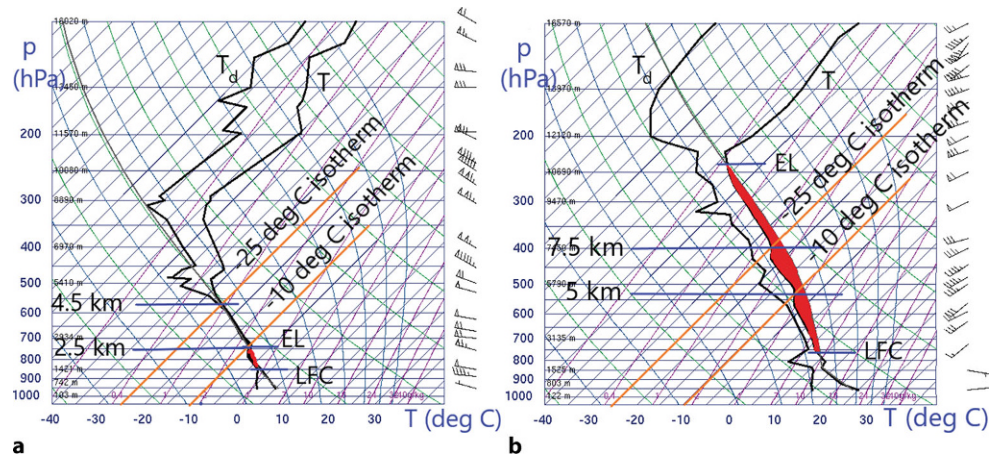


Fig. 5 Mean sea level pressure (contour lines), horizontal winds (barbs) and equivalent potential temperature (shaded) as analysed by VERA for **a** 31 March 2015, 1800 UTC and

b 4 August 2012, 1600 UTC. Position of GBT is marked by black star, legend bar gives temperature values for equivalent potential temperature in

3.4 Forced ascent of air

The geographical location of the Gaisberg is rather specific as it is the first elevation for inflow of air from the north-west sector (westerly to northerly direction). When the air impinges the mountain the entire column of air is forced to ascent generating upward moving air. Physically spoken, kinetic energy is transformed to potential energy. However, this can only be a trigger mechanism. Depending on the stability condition of the air column and moisture distribution the initial impetus for an upward moving air will fizzle out if the air column is stably stratified. But it can further continue and the upward moving air can even accelerate if the air column is conditionally stably stratified for moist air below and dry air above. This situation is also called potential instability.

Fig. 5a from 31 March 2015, 18:00 UTC and Fig. 5b from 4 August 2012, 16:00 UTC show VERA (Vienna Enhanced Resolution Analysis) [13] surface charts of equivalent potential temperature Θ_e [14], pressure and horizontal winds in the larger vicinity of the Gaisberg area. Fig. 5a highlights the strong west to north-westerly flow in the area with wind speeds of up to 15 kts

(7–8 m/s) in the 10 min mean roughly 50 min ahead of the lightning strokes initiated by the GBT. The colder air (lower values of Θ_e) has flooded the entire area north of the main alpine crest. This confirms that the front has already passed the region and the lightning stroke can not be associated with cross frontal circulation. In contrast Fig. 5b does not show any frontal structures over Austria. An almost uniform air mass of very high values of Θ_e covers the area. A small meso-scale cyclone southeast of the Gaisberg causes the air to flow in from all directions but at very low wind speeds of 1–2 kts (0.5–1 m/s).

4 Frequency of event class appearance

Following the event class definition in chap. 3.1 an eight year period from 2008 to 2015 has been analysed. In total 150 meteorological events have been identified producing lightning at the GBT or in its vicinity. The *tower-only* class appears in 42 of all cases (28%). This can be regarded as an estimation of the effectiveness of the tower to initiate lightning strokes. The monthly distribution (not shown) of the different classes highlights some differences. *Tower-only* cases

can appear throughout the year but with a distinct maximum during the cold season. Strong cold fronts may also occur during the convective season creating a *tower-only* case. *Tower and vicinity* cases can also be observed throughout the year but with a distinct maximum during the convective season. One has to note that the number of events braking down on a monthly basis is still very low to draw some final conclusions.

5 Conclusions

The initiation of negative upward lightnings at the GBT is determined by a different meteorological setting if compared to the lightning producing clouds during the convective season. From a large-scale perspective strong horizontal winds mainly directed from the north-west sector provide the trigger mechanism to create updrafts and initiate charge separation leading to lightnings at the GBT. During the convective season the release of CAPE is the main driver for updrafts and lightning producing clouds. The role of local parameters, e.g., the height of the -10°C isotherm or the vertical wind shear has been discussed by e.g., Weber [9] and was not part of the discussion here.

All in all, 28% of all cases during an eight year period are of the type *tower-only*. This can be regarded as a measure of the tower efficiency in initiating lightning.

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