# Review of seasonal variations in occurrence and some current parameters of lightning measured at the Gaisberg Tower

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Abstract: Upward lightning initiated from tall objects has gained considerable interest in the past years. Modern wind turbines are reaching total heights of 200 m and more and these structures are often exposed to this type of discharge. The data set collected by directly measured lightning current waveforms at the Gaisberg Tower (GBT) in Austria is used to evaluate the seasonal variations in the occurrence of upward lighting and variations in their current parameters. Initial continuing currents with superimposed pulses ($ICC_P$) transfer the highest amounts of charge and occur mostly during non-convective season. All flashes with transferred charge exceeding 300 As occurred during non-convective season and were mostly of negative polarity. All days, where more than 10 flashes were recorded at the GBT within 24 hours, belong to the non-convective season.

**Keywords**: Lightning occurrence, upward initiated, lightning current, winter lightning, charge transfer

## 1. INTRODUCTION

Gaisberg Tower (GBT) is located at a height of 1287 m above sea level at 13.1122°E / 47.8053°N close to the city of Salzburg and about 115 km east of Munich. GBT is a radio tower of a height of 100 m and is located at the top of the mountain. Lightning current measurement instrumentation was first installed in 1998 and is described in detail in [1]. In this paper the main focus is on observed seasonal variations of occurrence of different lightning types and their current parameters. At the GBT fast majority of flashes is upward initiated and triggered by the presence of the 100 m tall structure. Upward lightning is initiated by an initial continuing current (ICC) that may or may not be followed by one or more downward leader/upward return stroke sequences. The upward leader bridges the gap between the grounded tower and cloud, and establishes an ICC with a duration of some hundreds of milliseconds and an amplitude of some tens to some thousands of amperes. In many cases the initial stage (IS) contains current pulses superimposed on the slowly varying continuous current referred to as ICC pulses and the type of overall current waveform is named $ICC_P$. Some of these pulses have peaks in the kilo-amperes range and ICC pulses were studied in detail by Miki et al. [2]. It is generally assumed that longer risetimes are indicative of the M-component mode of charge transfer to ground, while shorter risetimes are associated with the leader/return stroke (RS) mode. Downward leader/upward RS sequences following the IS phase after a period of no current flow in the lightning channel are similar to subsequent leader/RSs in natural downward lightning and to downward leader/upward RS sequences in rocket-triggered lightning. Fig. 1 shows a schematic of an overall current waveform of upward-initiated lightning with three pulses superimposed on the ICC and two RSs following the IS after a period of no current flow.

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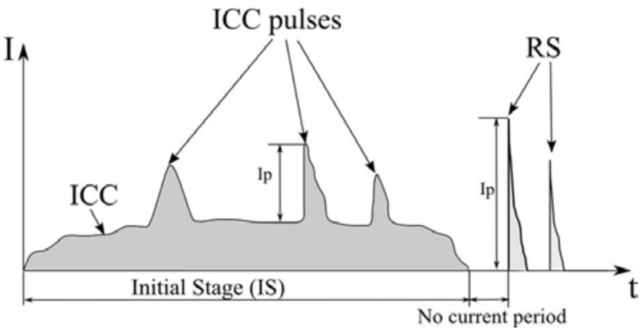



Fig. 1. Schematic current record for an upward-initiated flash. The initial stage (IS) is characterized by ICC with superimposed ICC pulses. The IS is followed by two RS after a period of no current flow.

Depending on the presence of ICC pulses and return strokes following the IS we can distinguish three types of upward lightning current waveforms:

(1) $ICC_{RS}$: This consists of ICC followed by one or more RS;
(2) $ICC_P$: This contains ICC not followed by any RS but with one or more ICC pulses >2 kA;
(3) $ICC_{Only}$: This contains ICC not followed by any RS and no ICC pulse >2 kA occurred.

## 2. DATA

### 2.1. CLIMATE DATA IN THE GBT AREA

Upward initiated lightning is often observed during so called winter thunderstorms in cold season and in literature the term winter lightning is often used for upward lightning initiated from elevated objects during cold season in Japan. In order to describe the long term temperature situation (period 1971 – 2000) at the GBT area the number of days where temperature is not exceeding 0° C is shown in Fig. 2. Data are obtained from two nearby meteorological stations in Radstadt and at Salzburg airport, respectively. Although both meteorological stations are located some hundreds of meters lower in altitude than the GBT we can see in Fig. 2 that it is not unusual to have a few days of cold temperature (below 0° C) even during the warm season, especially at higher altitudes like in Radstadt at 860 m ASL.

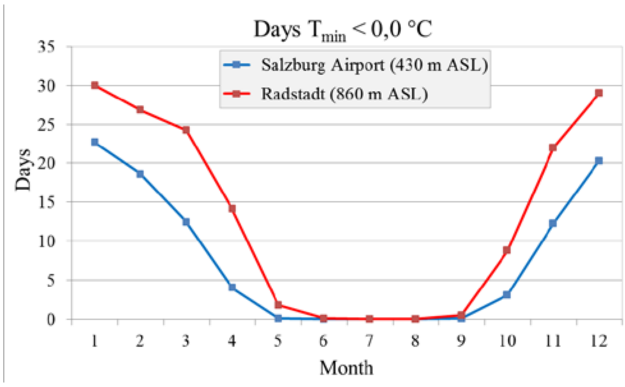
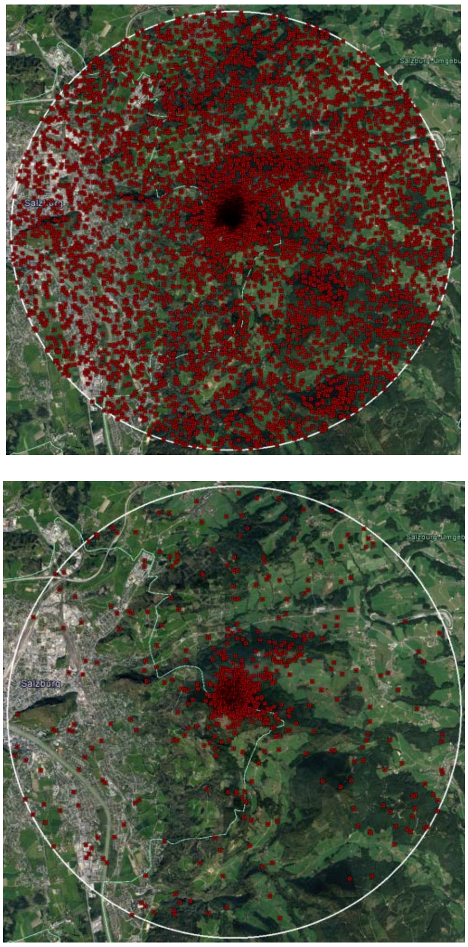



Fig. 2. Number of ice days (WMO definition: days on which the maximum temperature is less than 0˚C) reported by tow meteorological stations in the area around GBT. Met Station Airport Salzburg is located 8.5 km west of the GBT and Radstadt is located about 50 km south of GBT (adopted from [3])

Lightning location system (LLS) located strokes in a circular area of 5 km around the GBT are plotted in Fig. 3, where Fig. 3a shows all strokes located during the period from 2000 – 2015 (16 years), and Fig. 3b shows only the strokes that were detected in the area during the cold period (September, 1st to February, 28th) in the same years.



a)

b)

Fig. 3. LLS located strokes within a radius of 5 km around the GBT. a) All located strokes from 2000 – 2015 (N = 7331) and b) strokes located only during the months Sept. – Feb. in the years 2000 – 2015 (N = 1214)

Obviously very little lightning activity occurs in the surrounding area during the cold season September – February (Fig. 3b), but there is still a high concentration of strokes at the center of the circular area, where the GBT is located.

## 2.2. SEASONAL OCCURRENCE OF LIGHTNING EVENTS

Fig. 4 shows the annual number of flashes recorded at the GBT with counts ranging from only 10 flashes in 2013 up to 99 in 2007. Therefore a ratio of about 1:10 in the number of flashes is observed. A total of 830 flashes has been recorded at the GBT in the period from 2000 – 2015 corresponding to 52 flashes per year on average.

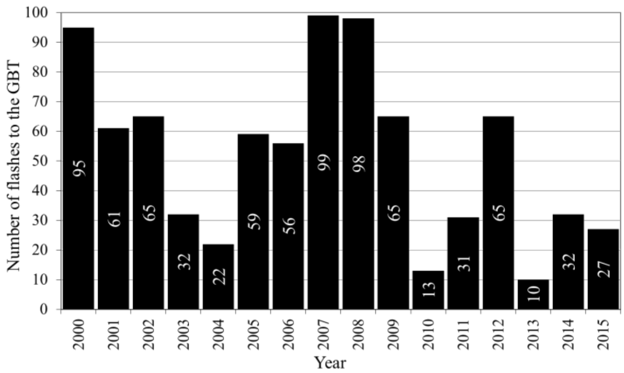



Fig. 4. Annual number of flashes recorded at the GBT (2000 – 2015)

Although the overall thunderstorm season in Austria corresponds to the convective season lasting from April to August, lightning at the GBT is triggered more or less at any time during the year as shown in Fig. 5. Actually the months with the highest numbers of recorded flashes at the GBT are March and November, respectively, which are definitely months outside the convective season and generally with very little thunderstorm activity in the area of Austria.

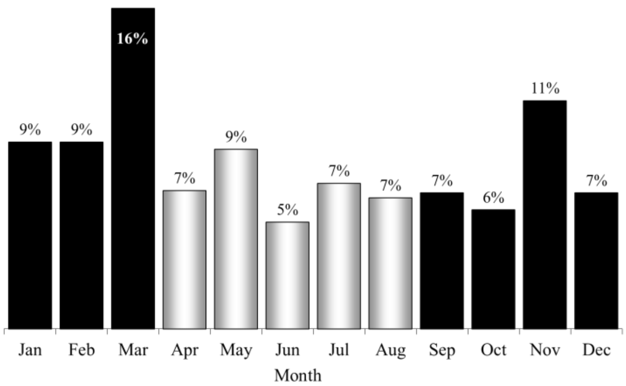



Fig. 5. Number of monthly recorded flashes at the GBT in the period 2000 – 2015. Black bars represent nonconvective season (NCS) and grey bars represent convective season (CS)

As described above, negative lightning current waveforms of three distinct types ($ICC_{Only}$, $ICC_P$, and $ICC_{RS}$) are observed. 93.4 % (N=775) of the GBT recorded flashes had negative polarity, 3.5% (N=29) had positive polarity, and 3.1% (N=26) showed bipolar waveforms. Details of assignment of the negative current waveforms to the three types of current waveforms are given in Fig. 6. A detailed analysis of the positive and bipolar lightning events at the GBT was done by Zhou et al. in [4] and [5], respectively.

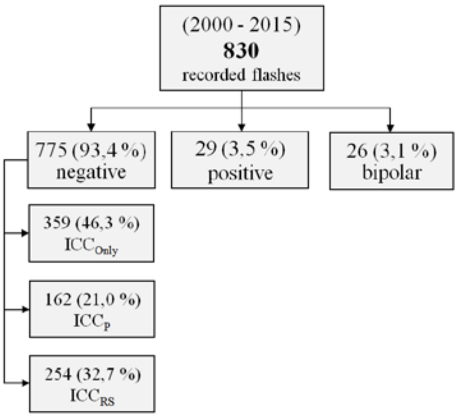



Fig. 6. Occurrences of the various types of upward initiated discharges at the GBT for the period 2000 - 2015

We have to note, that $ICC_{Only}$ type discharges are usually not detected by commercial lightning location systems (LLS). Detection of a lightning discharge with a LLS requires fast rising current pulses in the lightning channel in order to radiate electromagnetic field pulses of amplitudes that are high enough to be detected by a minimum number of sensors (typically 4 or more sensors are required) at distances of up to several hundreds of kilometers. $ICC_{Only}$ type discharges do not show any of these fast rising current pulses and therefore not detected by LLSs operated in the LF frequency range. As a consequence the overall detection efficiency (DE) of a LLS for all flashes to the GBT is as low as 43% [6]. For the $ICC_{RS}$ type flashes, which are assumed to be a good representation of natural CG discharges, a flash DE of 96% was determined. Interestingly the DE for $ICC_{RS}$ type flashes in the same study [6] was higher (99%) during convective season then during non-convective season (95%).

Seasonal occurrence of the three types of negative flash currents is shown in Fig. 7. Obviously in summer time there is the highest percentage of $ICC_{Only}$ discharges and the lowest number of $ICC_P$ discharges. Percentage of $ICC_{RS}$ type discharges remains more or less the same over the seasons with about 30%.

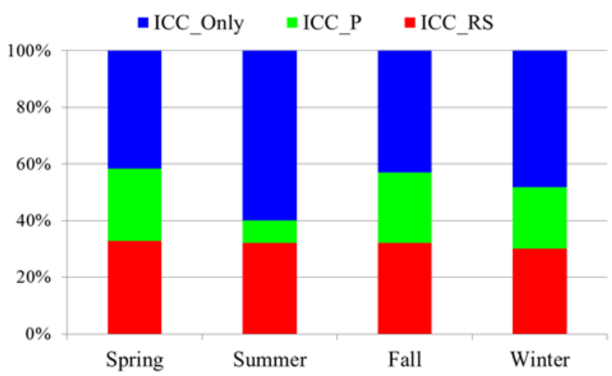



Fig. 7: Seasonal occurrence of the three flash categories

## 2.3. TOTAL FLASH CHARGE

The total transferred flash charge statistics for the different types of negative discharges shows clear differences as depicted in Fig. 8 and Table 1, respectively. $ICC_P$ type discharges transfer much higher amounts of charge than $ICC_{Only}$ type with a median of 74 As versus 22 As and a 90% value of 224 As versus 80 As.

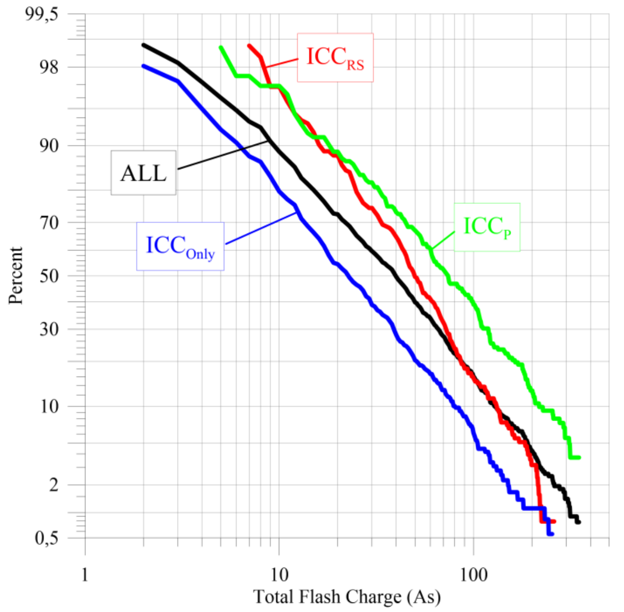



Fig. 8. Log-normal plot of total charge transfer per flash for the three types of flash currents in upward initiated discharges

Table 1: Total charge transfer statistics for the three flash types in negative upward initiated flashes from the GBT (2000 – 2015)

| | N | median (50%-value) | 90%-value |
|---|---|---|---|
| $ICC_{RS}$ | 254 | 49 | 132 |
| $ICC_P$ | 162 | 74 | 224 |
| $ICC_{Only}$ | 359 | 22 | 80 |
| ALL | 775 | 39 | 129 |

Total charge transfer in the four seasons by all negative flash currents is plotted in Fig. 9 and results are summarized in Table 2.

Table 2: Total charge transfer statistics for negative upward initiated flashes from the GBT in the four seasons (2000 – 2015)

| | N | median (50%-value) | 90%-value |
|---|---|---|---|
| Spring | 247 | 45 | 184 |
| Summer | 147 | 33 | 119 |
| Fall | 188 | 46 | 138 |
| Winter | 193 | 38 | 140 |

Details about the median and 90%-value of the total transferred charge are given in Fig. 10a, and Fig. 10b, respectively. Highest 90%-value of 295 As for total charge transfer is obtained for $ICC_P$

type discharges (N= 43) during winter season.

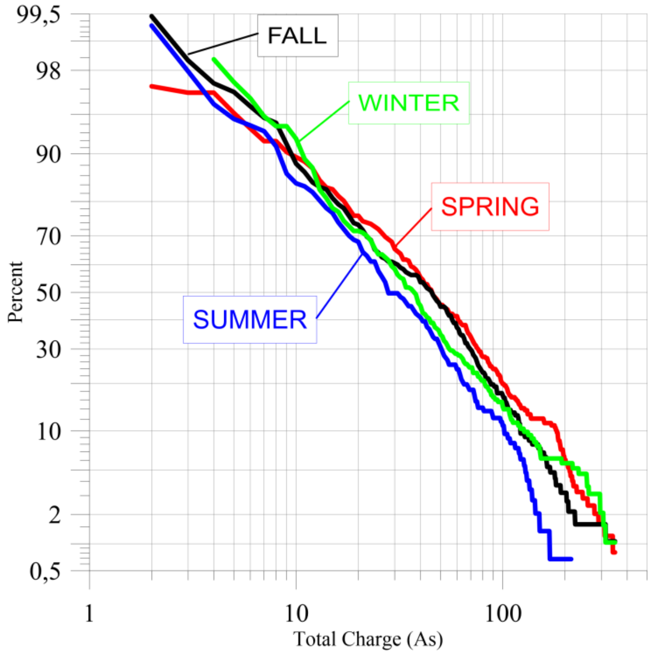
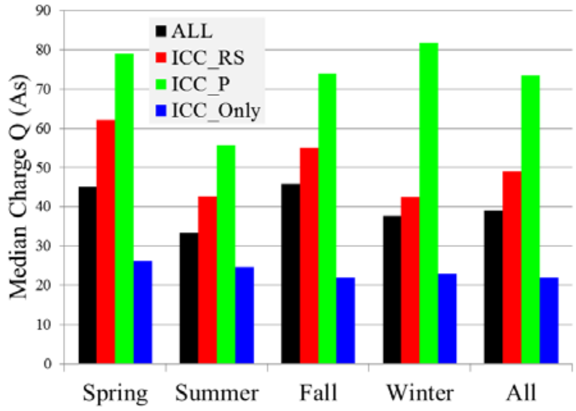
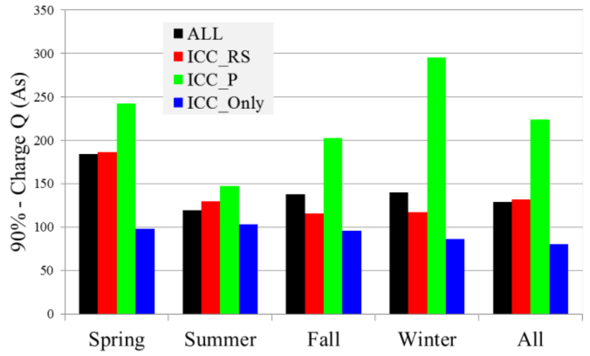



Fig. 9: Total charge transfer per flash in the four seasons




a)




b)

Fig. 10. Total charge transfer of flashes to the GBT
a) median (50%-value) and b) 90%-value (given values are exceeded by 10 % of the flashes)

## 2.4. FLASHES PER DAY

At the GBT it is observed that several upward initiated lightning flashes occur within a short period of time ranging from some minutes to a few hours. In [6] the number of flashes per thunderstorm day at the GBT has been analyzed. A thunderstorm day at GBT was defined as a day where at least one flash was recorded by the tower instrumentation. A histogram of the number of flashes recorded per thunderstorm day at the GBT in the period 2000 – 2013 is shown in Fig. 11. In this figure also the seasonal occurrence of this thunderstorm days is indicated. A maximum of 27 flashes has been recorded on a single day on March 1st, 2008. 17 flashes on a single day were recorded three times during the period 2000 – 2013 and it is worth noting that all of the GBT thunderstorm days with high numbers of flashes per day (>10) occurred during non-convective season (NCS).

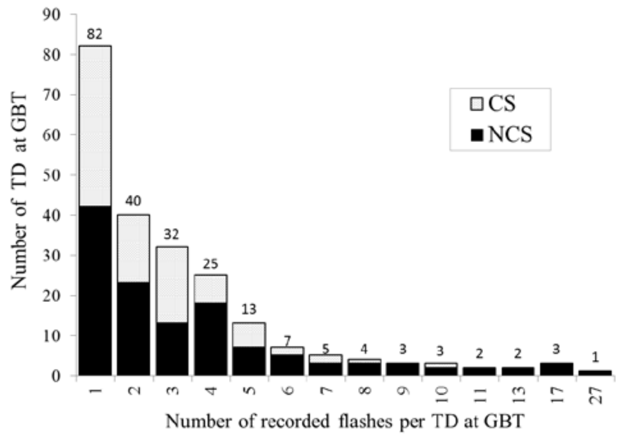



Fig. 11. Flashes per Thunderstorm day (adopted from [5])

During the period from 2000-2015 at the GBT 14 out of the 830 recorded flashes (1.7%) transferred a total charge exceeding 300 As (see Fig. 6). A maximum flash charge of 300 As is specified in the lightning protection standards IEC 62305-1 [7] for lightning protection level I (LPL I).

Table 3: Flashes recorded at the GBT transferring a total charge greater than 300 As (2000-2015)

| # ID | Date | Time | Flash Charge (As) | Comment | LLS located | Neg. Flash Category | Season |
|---|---|---|---|---|---|---|---|
| 112 | 2000-01-21 | 16:25:28 | 356 | Pos. Flash | NO | - | NCS |
| 405 | 2005-02-12 | 22:36:25 | 385 | Neg. flash | YES | $ICC_P$ | NCS |
| 407 | 2005-02-12 | 22:42:16 | > 305 | Neg. flash [1)] | YES | $ICC_{RS}$ | NCS |
| 446 | 2005-12-16 | 16:59:29 | 426 | Pos. Flash | NO | - | NCS |
| 511 | 2007-01-12 | 01:51:51 | 405 | Neg. flash | YES | $ICC_P$ | NCS |
| 520 | 2007-02-09 | 01:24:09 | 320 | Bipolar Flash | NO | - | NCS |
| 614 | 2008-03-01 | 10:21:10 | 546 | Neg. Flash | NO | $ICC_{Only}$ | NCS |
| 631 | 2008-03-01 | 10:41:14 | > 365 | Neg. flash [1)] | YES | $ICC_P$ | NCS |
| 633 | 2008-03-01 | 10:43:17 | 310 | Neg. flash | YES | $ICC_P$ | NCS |
| 693 | 2008-11-21 | 13:52:01 | 314 | Neg. flash | YES | $ICC_P$ | NCS |
| 806 | 2011-12-07 | 23:17:08 | 313 | Neg. flash | YES | $ICC_P$ | NCS |
| 878 | 2012-10-15 | 17:32:12 | 783 | Neg. flash | NO | $ICC_P$ | NCS |
| 879 | 2012-10-15 | 17:38:41 | 430 | Neg. flash | NO | $ICC_P$ | NCS |
| 929 | 2015-03-30 | 15:36:52 | 340 | Neg.flash | NO | $ICC_P$ | NCS |

1) Flash duration exceeded recording time of 800 ms

All of the flashes exceeding the 300 As of charge transfer occurred during non-convective season (NCS). It is also worth noting that 11 of the 14 flashes were of negative polarity whereas in other studies the high charge transfer events are mostly positive (e.g. [8]).

Three flashes in Table 3 (# 614, # 631, and # 633) occurred within about 20 minutes on 2008-03-01. These three flashes transferred a total charge of 1.221 As to ground. During this particular storm on 2008-03-01 a total of 22 flashes were recorded at the GBT within 25 minutes. Charge transfer of these 22 flashes accumulated to 3.735 As.

For the proper and effective scheduling of maintenance cycles of wind turbines the accumulated charge of all flashes to a receptor is a determining parameter. Fig. 12 and Fig. 13 show the accumulated charge transfer per year and per month, respectively. In 2008 a total charge of 8.888 As was transferred in 98 flashes. The months March and November show the highest charge transfer values. In Austria these two months represent the typical transition period from winter to summer and vice versa, but they are definitely outside the convective season.

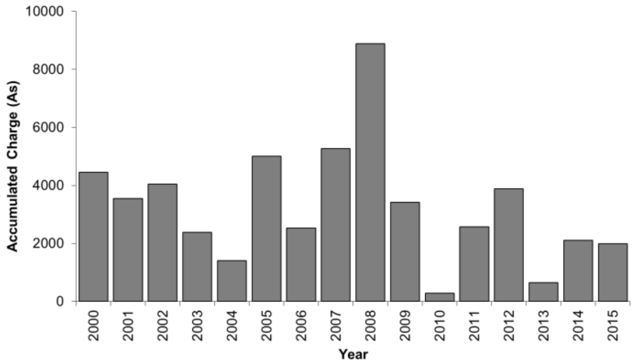



Fig. 12. Accumulated transferred charge per year (2000 – 2015)

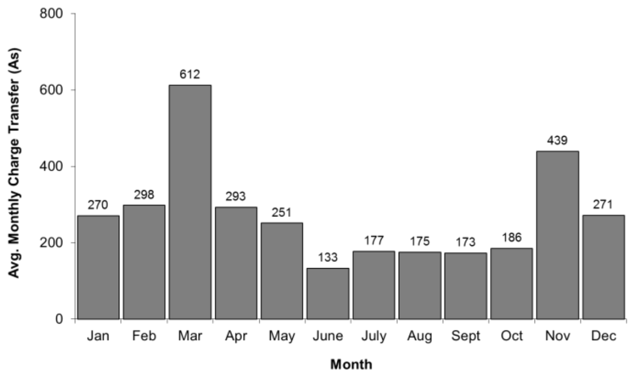



Fig. 13. Monthly average (arithmetic mean) accumulated charge for the period 2000 – 2015

## 2.5. HEIGHT OF -10°C ISOTHERM

The mean height of the -10° C isotherm is typically used as a proxy for the height of the negative charge center in thunderstorms [9], [10]. In Fig. 14 the height of the -10° C isotherm is plotted versus the total transferred charge. The plot indicates no obvious linear relationship between total flash charge and the mean height of the -10° C isotherm. It looks more like there is a kind of optimum height of the isotherm producing the largest values of total charge transfer. These optimum heights of the -10° C isotherm are in the range from about 2000 m to 4000 m where all GBT events with a charge transfer exceeding 300 As occurred.

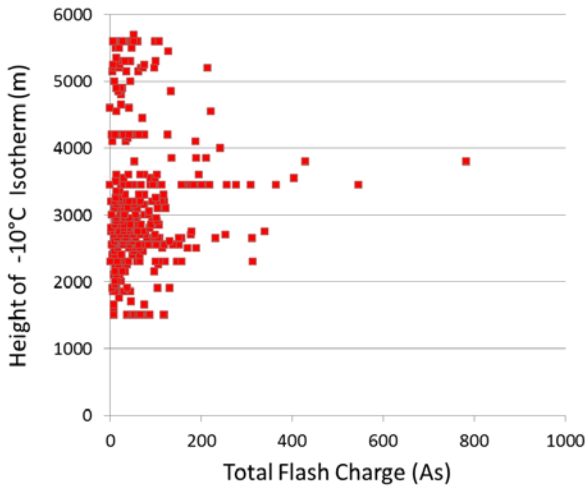



Fig. 14. Height of -10° C Isotherm was determined by the mean height obtained from the last radio sounding prior and after the occurrence time of the recorded flash at the GBT

## 2.6. SELF- VERSUS OTHER-TRIGGERED LIGHTNING OVER SEASON

In [11] Wang et al. suggested to sub-classify upward lightning into two types. The first type being called "self-triggered" is initiated without any nearby preceding lightning activity, while the second type called "other-triggered". In [12] the GBT events have been analyzed regarding this sub-classification with the results shown in Fig. 15.

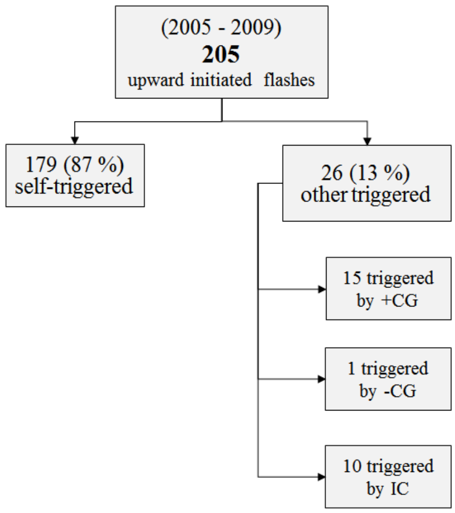



Fig. 15. Classification of self-triggered and other-triggered flashes to the GBT from 2005 to 2009 (adopted from [13]).

At the GBT self-initiated lightning occurred predominantly (79% or 142/179) during non-convective season, whereas most (85% or 22/26) of nearby-lightning-triggered discharges occurred during convective season [12].

## 3. CONCLUSIONS

Lighting currents measured at the GBT during a period of 16 years (2000 – 2015) with a total number of 830 recorded flashes is analyzed with main focus on seasonal variations in the number of flashes triggered by the GBT and variations in some of the lightning current parameters. Although there are considerable year to year variations in the number of flashes to the GBT the total transferred flash charge shows the most pronounced seasonal variations. We have to note that the results presented in this study are strictly valid for the GBT location and may be completely different at other locations on the globe.

## 4. ACKNOWLEGDEMENTS

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