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Initial electric field changes of lightning flashes in tropical thunderstorms and their relationship to the lightning initiation mechanism

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ABSTRACT

In this paper, the key finding is that all the examined first classic Initial Breakdown (IB) pulses in tropical flashes within the reversal distance were found to be initiated by a clearly detectable Initial E-field Change or IEC (45 –CG, 32 normal IC, and 3 IC initiated by +NBE). The durations of IECs for both –CG and IC flashes in tropical storms were longer than in Florida storms. On the other hand, for the magnitudes of the E-change, the values were smaller compared to Florida storms with averages of 0.30 V/m compared to 1.65 V/m for –CG flashes, and −0.81 V/m compared to −6.30 V/m for IC flashes. The IEC process of lightning flashes in tropical regions took longer to increase the local electric field in order to produce the first IB pulse because of the smaller magnitude of E-change. On the other hand, in Florida storms, the IEC process took a shorter time to increase the local electric field to produce the first IB pulse because of the larger magnitude of E-change. We found that very high frequency (VHF) pulses for tropical thunderstorms started sometime prior to the onset of the IECs. They started between 12.69 and 251.60 μs before the initiation of the IEC for two normal IC flashes. The first two VHF pulses were detected alone without narrow IB pulses (fast antenna and slow antenna records) or any pulses from the B-field and dE/dt records. Furthermore, the VHF pulses for three IC flashes initiated by +NBEs were also detected before the onset of the IEC. The IEC started immediately after the detection of the +NBE. It is clear that the IEC is initiated by VHF pulses. It can be suggested that lightning is initiated by Fast Positive Breakdowns or FPBs (which emit strong VHF pulses and large +NBEs) and is followed by several negative breakdowns (weak VHF pulses and/or weak NBE-type pulses) before the IEC started. For the case of normal IC flashes, several weaker VHF pulses (mean values of 41.97 mV and 46.4 mV compared to the amplitudes of the VHF pulses of +NBEs of around 800 mV) were detected before the onset of the IEC. As FPBs can occur with a wide range of VHF strengths and E-change amplitudes, it can be suggested these weak VHF pulses accompanied by narrow IB pulses or weak NBE-type pulses detected before the onset of IEC are actually FPBs followed by negative breakdowns or several attempted FPBs.

1. Introduction

Although lightning significantly influences our daily lives, we are still unclear how lightning is initiated inside thunderclouds. This is one of the biggest unsolved problems in lightning physics. One fact agreed by most lightning researchers is that lightning flashes have been observed to be initiated by a series of electric field (E-field) bipolar pulses known by several names: Initial Breakdown (IB) pulses, Preliminary Breakdown Pulses (PBPs) and characteristic pulses (Appleton and Chapman, 1937; Schonland, 1938; Clarence and Malan, 1957; Kitagawa and Brook, 1960; Weidman and Krider, 1979; Beasley et al., 1982; Bils et al., 1988; Rakov et al., 1996; Gomes and Cooray, 2004; Sharma et al., 2008; Nag and Rakov, 2008, 2009; Nag et al., 2009; Azlinda Ahmad et al., 2010; Sharma et al., 2011; Stolzenburg et al., 2013; Esa et al.,

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2014a,b). Throughout this paper, the term used for the series of E-field bipolar pulses initiating all flashes is IB pulses. The IB pulses can be classified into 2 categories, namely classical and narrow pulses (Nag and Rakov, 2008 and Nag et al., 2009). The classical IB pulses have pulse durations of 10 μs and longer, while for narrow IB pulses the typical pulse durations are below 10 μs (microsecond and sub-microsecond scale pulses; refer to Fig. 7a and b in Nag et al., 2009).

Recent studies conducted by Marshall et al. (2014) and Chapman et al. (2017), based on Florida thunderstorms, as well as Marshall et al. (2019), based on Mississippi thunderstorms, found that lightning flashes did not begin with IB processes. Instead, they found that before IB pulses there was another process occurring, known as Initial Electric Field Changes (IECs). The IECs can be clearly observed for flashes within the reversal distance only. The authors hypothesized that an IEC helps cause the first IB pulse of a flash and therefore is a critical part of flash initiation. So far, these are the only reports regarding IECs and are based on Florida and Mississippi thunderstorms. An IEC is defined as a small amplitude, short duration, slow-developing electric field change that occurs just before the first IB pulse in a lightning flash (Marshall et al., 2014). The IEC duration is determined where there are slow electric field changes, starting at zero moving upwards (for –CG flashes as shown in their Fig. 1) or downwards (for IC flashes as shown in their Fig. 3) and ending at the first IB pulse. Both Marshall et al. (2014) and Chapman et al. (2017) adapted the classical definition of IB pulses. The characteristics of classical IB pulses are they must be a bipolar shape, the pulse durations are from 10 μs up to 200 μs, and they often have two or three narrow, fast-rising sub-pulses superimposed on the main bipolar pulse.

Prior to the work of Marshall et al. (2014), Baharudin et al. (2012) studied the relationship between slow field changes and IB processes for –CG flashes (within the reversal distance) in Malaysia and Sweden. They found that slow field changes occurred after the onset of the IB process, meaning that there were no electric field changes before the first IB pulse. Based on their findings, the durations from the first IB pulse to the onset of the slow field change (defined as the pre-starting time) were in the ranges 1.4–6.47 ms (Malaysia) and 1–3.36 ms (Sweden). This is an obvious contradiction to the finding of Marshall et al. (2014) and Chapman et al. (2017). However, this contradiction is caused mainly by the classification of IB pulses as defined by the authors. Baharudin et al. (2012) have included narrow pulses as part of the IB process. On the other hand, Marshall et al. (2014) and Chapman et al. (2017) have considered only classical IB pulses and the narrow

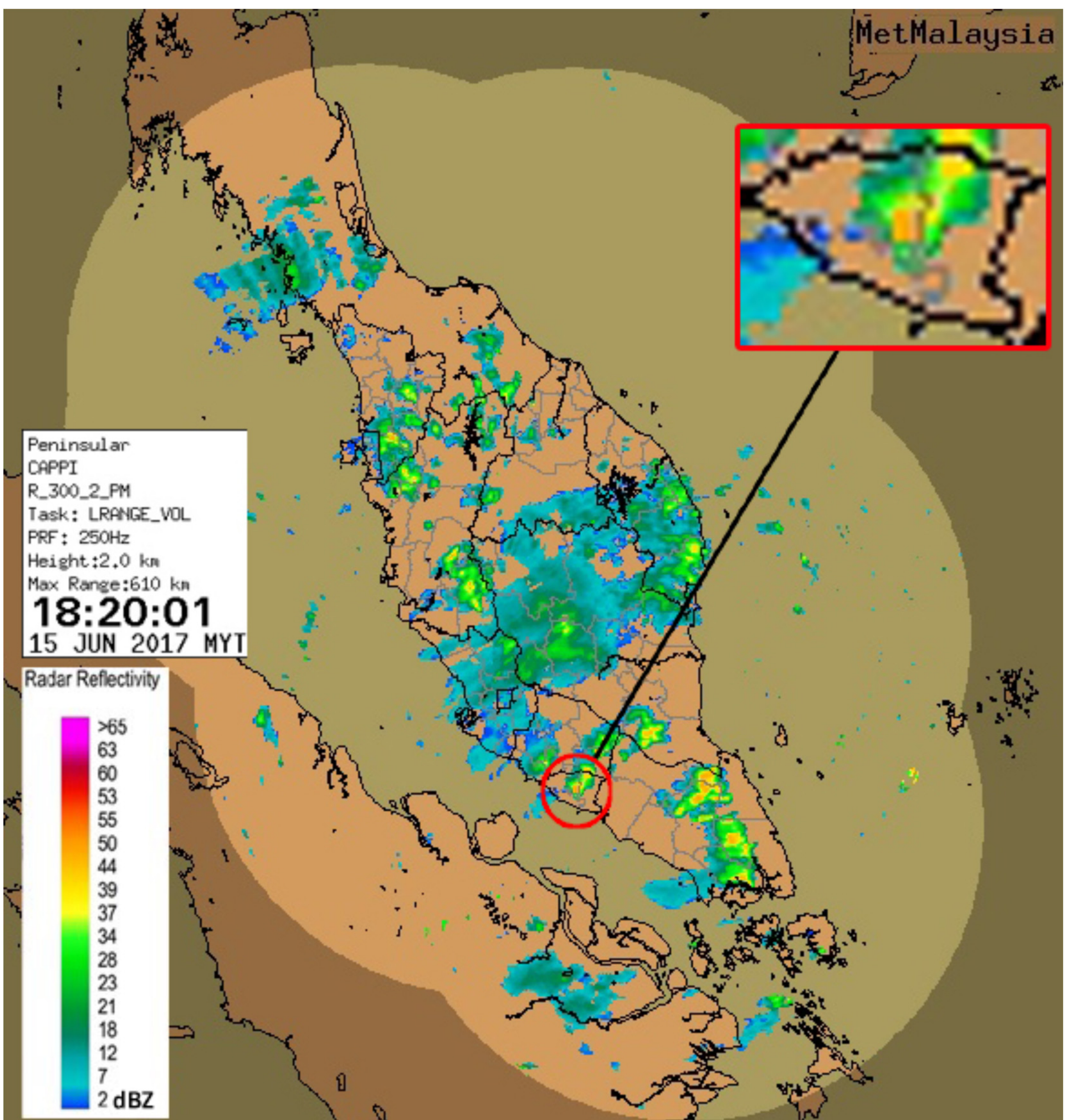

Fig. 1. CAPPI radar format at 2 km altitude for Peninsular Malaysia (the lightning sensor at Malacca is in the centre of the red circle) can be obtained from the Malaysian Meteorology Department. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pulses detected before the classical IB pulses have been classified as enhancing events.

Marshall et al. (2014) hypothesized that lightning initiation begins with an ionizing event that causes the IEC, and the IEC enhances the electric field in the cloud to cause the first IB pulse (following the classical definition). Based on Lightning Mapping Array (LMA) observations, Rison et al. (2016) observed negative breakdowns that happened just after the occurrence of Fast Positive Breakdowns (FPBs) of three NBEs initiating IC flashes, scattered just above the location of the FPBs. These negative breakdowns have been suggested to be the responsible ionizing event that initiates an IEC. In fact, the initial very high frequency (VHF) event that started the negative breakdowns and thus started the IEC is the FPB. By analyzing 76 flashes (only three flashes were initiated by normal NBEs), the FPBs were found to occur within a wide range of VHF strengths and E-change amplitudes. The authors showed that FPBs moved downward before IC flashes (brought down positive charges) and upward before CG flashes (brought up positive charges) and the E-change amplitudes were much smaller when compared to normal NBE pulses (typical normal NBEs have large amplitudes comparable to return strokes and in some cases even larger). These pulses with much smaller E-change amplitudes associated with FPBs and negative breakdowns are known as weak NBE-type pulses (Rison et al., 2016).

In this paper, we extend the study of Marshall et al. (2014), Chapman et al., 2017 and Marshall et al. (2019) by looking for IECs in a total of 80 flashes from ten tropical thunderstorms that were very close (within the reversal distance) to our sensor in Melaka, Malaysia. The key finding is that all the first classic IB pulses were found to be initiated by a clearly detectable IEC (45 –CG, 32 normal IC, and 3 IC initiated by +NBEs). These data provide independent support and validation (totally independent experiments from the tropics) to the hypothesis suggested by Marshall et al. (2014) that IEC is a critical part of flash initiation. A significant number of flashes (14 –CG and two normal IC) were initiated by narrow IB pulses (Chapman et al. (2017) observed only four out of 75 flashes). The IECs of three +NBE-initiated IC flashes were started immediately after the NBE (accompanied by large VHF pulses). These IECs were initiated by normal NBEs rather than by narrow IB pulses. This result is clear evidence that FPBs and negative breakdowns (detected VHF pulses with +NBEs) are responsible for the initiation of the IEC (as Marshall et al. (2014) and Chapman et al. (2017) did not find flashes initiated by NBEs). A small number of flashes (five –CG and three IC flashes) were initiated by IECs alone and were followed by the first classic IB pulse. Interestingly, we found two normal IC flashes with VHF records to be initiated by VHF pulses and then followed by narrow IB pulses before the first classic IB pulse was detected.

2. Instrumentation and methods

The data of 80 flashes from ten tropical storms between June 2017 and May 2018 were recorded from a single observation station located in Melaka, Malaysia (2.314077°N, 102.318282°E) hosting wideband fast electric field change antenna (Fast Antenna or FA) and slow electric field change antenna (Slow Antenna or SA) systems (decay time constants of 13 ms and 1 s, respectively), a wideband magnetic field change (B-field) antenna system operating between 400 Hz and 400 kHz (Zhang et al., 2016), three VHF sensors (40–80 MHz, 3 dB bandwidth) with centre frequency of 60 MHz and an electric field derivative (dE/dt) antenna system. The VHF sensors are positioned at locations away from the other sensors. All other sensors (FA, SA, dE/dt, and B-field) together with a VHF sensor (we called this sensor the central VHF sensor) are placed in close proximity to each other. The other two VHF sensors are located 15 m (3λ) away from other sensors. Even though in the analysis only data from the central VHF sensor were used, data from other VHF sensors were used as additional data to the primary data from the central VHF sensor.

Three digitizers have been used to record the data. The outputs of the antennas were digitized at rates of 10 MS/s or 20 MS/s with a vertical resolution of 12-bit for Digitizer 1 (FA, SA and B-field), 250 MS/s or 500 MS/s with a vertical resolution of 8-bit for Digitizer 2 (FA and VHF sensors), and 10 MS/s with a vertical resolution of 12-bit for Digitizer C (FA, dE/dt). Data records were event-triggered and 500 ms long for all digitizers. The pre-trigger delay was 250 ms (50%) with a trigger level of 500 mV. For the IC flashes with the VHF record, the largest pulses in the FA record were triggered. The quiet period between the starting of the record and the first VHF pulse is almost 250 ms (the first VHF pulse is detected several milliseconds before the largest pulse of the normal IC flashes). The quiet period is a duration when no fast E-field change pulses are observed before the detection of the first narrow IB pulse. This quiet period criterion is important to ensure no multiple lightning flash activity is recorded before the beginning of the IEC. The timing for each event was provided by a Global Positioning System (GPS). All digitizers were run using a single computer to display all the results and to make sure all data had the same timestamp. Additional details for the E-field and B-field instrumentations are given in Esa et al. (2014a), Ahmad et al. (2015) and Zhang et al. (2016).

In this paper, only five lightning flashes with VHF records are presented (two VHF records for normal IC flashes and three VHF records for IC flashes initiated by +NBEs). For all cases, a VHF pulse was observed to initiate the IEC and was found before IEC, in agreement with the findings in Marshall et al. (2019). There were no VHF records for all –CG flashes. Initially, the VHF sensor was up for a short time before breaking down on June 15th 2017. Only a single VHF pulse for an IC flash initiated by a +NBE was recorded on June 15th. Later, the operation of the VHF sensor was resumed starting November 23rd 2017. All recorded flashes within the reversal distance after November 23rd were IC flashes.

Location data were available only for the first return strokes of –CG flashes and the largest pulses of IC flashes. Both of these locations will provide only approximate values of the distances of interest in this study. For –CG flashes, the return stroke location can be many kilometres from the IEC and the first classic IB pulse. For IC flashes, the largest IB pulse might be as much as 1–3 km from the IEC and the first classic IB pulse (unless the first classic IB pulse is the largest IB pulse). These distances are important because the farther the sensors are from the IEC, the more difficult it is to detect the beginning of the IEC and detecting the beginning of the IEC will be important later in these analyses.

The locations were obtained from the Lightning Detection Network (LDN) managed by the Lightning Detection System Laboratory, Tenaga Nasional Berhad Research Sdn Bhd (TNBR). The LDN is installed and calibrated by Vaisala and deploys a combination of LF/VLF magnetic direction finder (MDF) and time-of-arrival (ToA) techniques to estimate the locations of lightning strikes. All the first return strokes, the largest IB pulse of IC flashes and +NBE pulses were located less than 10 km from the observation station as plotted in Fig. 2. The SA record has been used to identify the 80 flashes with IECs within the reversal distance by determining the correct polarity in Slow E-Field versus time (positive slope for –CG flashes as shown in Fig. 3, negative slope for normal IC flashes as shown in Fig. 5). A detailed explanation of the concept of reversal distance is given by Chapman et al. (2017, p. 3720). In addition to the location data, Constant Altitude Plan Position Indicator (CAPPI) radar data at 2 km altitude with a sampling rate of 10 min have been used to identify isolated storms that happened over the observation station. Fig. 1 shows an example of an isolated storm (within the red circle) that occurred on June 15th 2017 sampled at 17:50:01 local time. The observation station is located at the centre of the red circle. The CAPPI radar data have been obtained from Malaysia Meteorological Department (Met Malaysia).

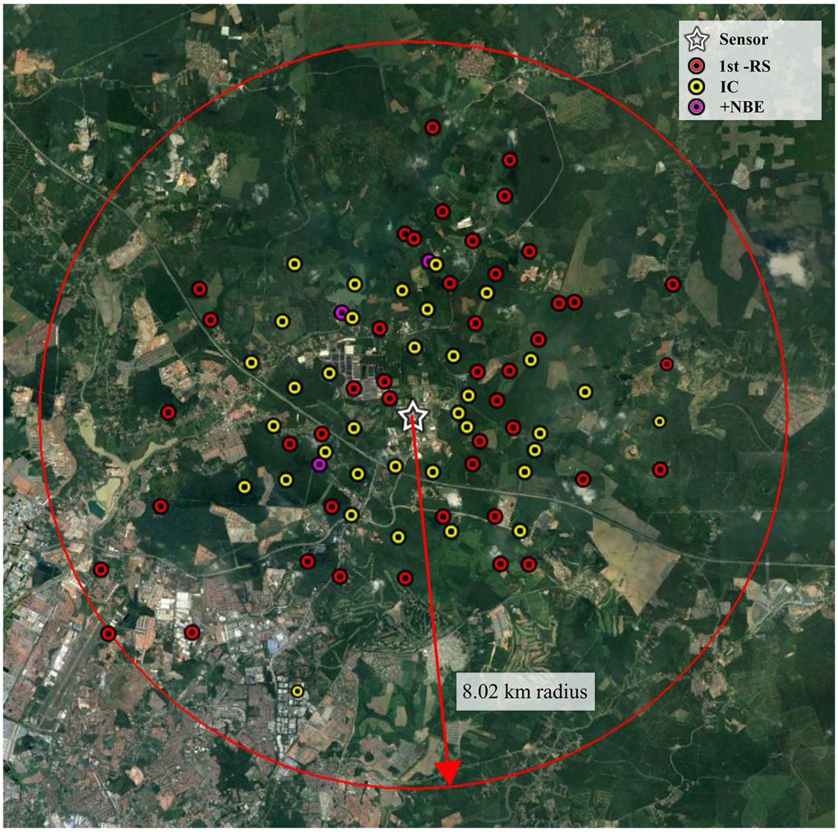

Fig. 2. The locations of lightning strikes for IC flashes (largest pulse, yellow), –CG flashes (first return stroke, red) and +NBEs (pink). The sensor station (star) is located at the centre of the circle with radius 8.02 km indicating the farthest location of a –CG flash. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results and analysis

3.1. Duration and magnitude of tropical IECs

A total of 80 tropical flashes (45 –CG, 32 normal IC and three IC initiated by +NBE) within the reversal distance from ten tropical thunderstorms that happened close to our lightning sensor were chosen. All the results are based on lightning flashes captured for thunderstorms that happened on June 15th, June 21st, June 25th, June 26th, July 2nd, July 7th, July 11th, November 16th, November 23rd, 2017 and May 23rd, 2018. According to Marshall et al. (2014) and Chapman et al. (2017), the IECs are detectable when the lightning strikes very close to the electric field changes sensors – within the reversal distance which is typically less than 10 km from the sensors. Based on our measurements for tropical thunderstorms, we found that all 80 lightning flashes within the reversal distance (less than 8.02 km) are accompanied by IECs.

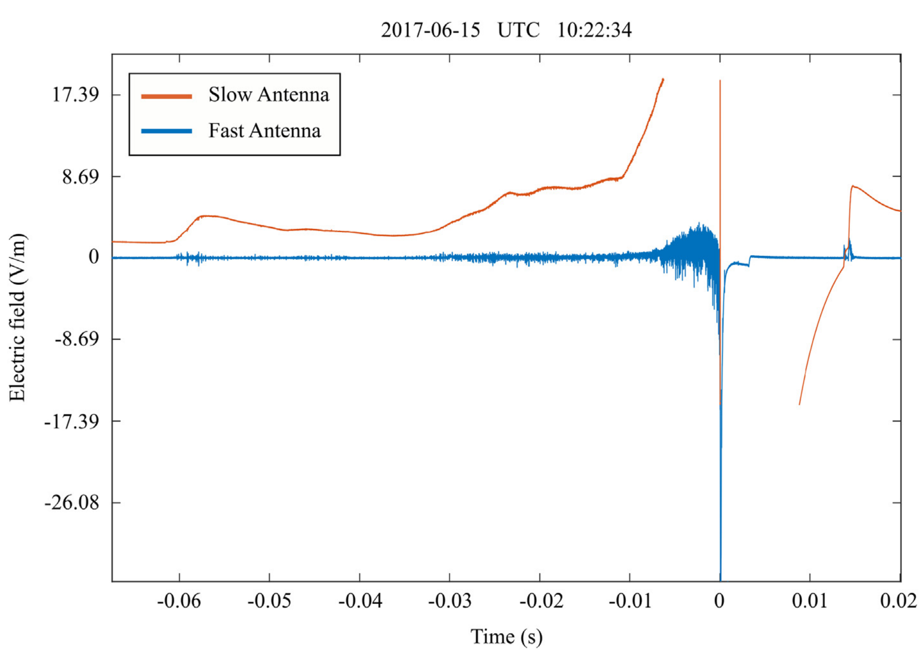

Fig. 3. Negative cloud-to-ground (–CG) flash (within reversal distance) captured by wideband fast and slow antenna systems in Malacca at 10:22:34 UTC on June 15th, 2017.

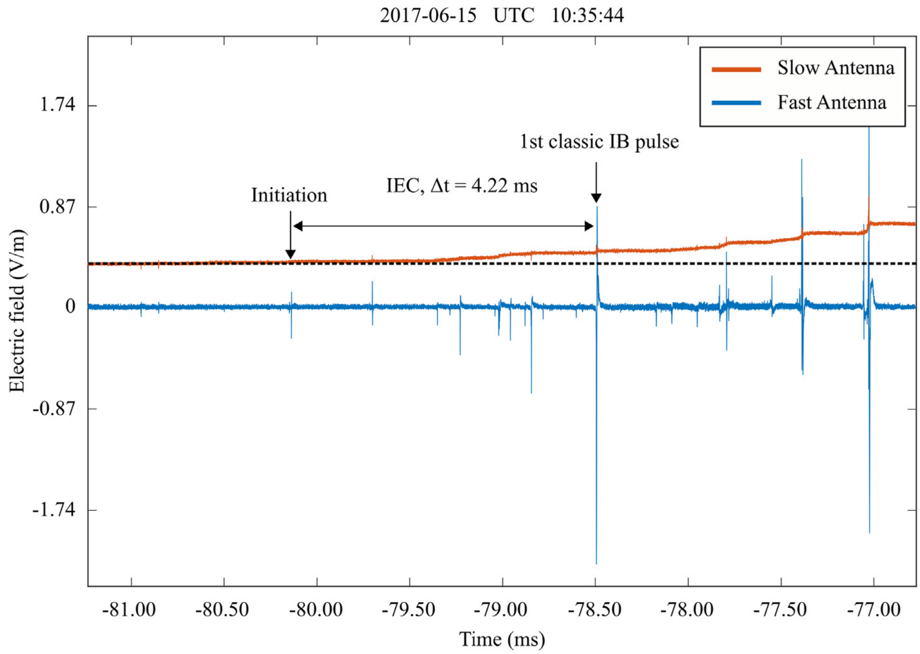

Fig. 4. Example of an IEC (physics sign convention) and the first classical IB pulse for a –CG flash (within reversal distance) captured by wideband fast and slow antenna systems in Malacca at 10:35:44 UTC on June 15th 2017.

The durations of IECs for 45 –CG flashes in the tropical storms averaged 4.32 ms and ranged from 0.22 to 13.47 ms. An example of an IEC followed by the first classical IB pulse for a –CG flash is shown in Fig. 4. In comparison, for –CG flashes, Marshall et al. (2014) found the average duration of IECs was 0.18 ms ranging from 0.08 to 0.33 ms, while Chapman et al. (2017) found the average duration of IECs was 0.23 ms and ranging from 0.08 to 0.54 ms.

For the tropical IC flashes, the average duration of the IECs was 6.83 ms and ranged from 0.08 to 64.71 ms. An example of an IEC preceding the first classical IB pulse for an IC flash is shown in Fig. 5. On the other hand, Marshall et al. (2014) and Chapman et al. (2017) reported much shorter average durations of IECs at 1.53 ms and 2.70 ms, respectively, ranging from 0.18 to 5.70 ms and ranging from 0.04 to 9.80 ms, respectively. In addition to normal IC flashes, the average duration of the IECs for three IC flashes initiated by +NBE was 5.54 ms. An example of an IC flash initiated by a +NBE and followed immediately by an IEC is shown in Fig. 6.

Table 1 provides a comparison of durations of IECs and magnitudes of E-changes between tropical thunderstorms and Florida thunderstorms (Marshall et al., 2014, Chapman et al., 2017) for –CG and normal IC flashes. The magnitudes of the E-changes are based on slow antenna records which started from zero to the maximum amplitude just before the onset of the first classical IB pulse. Fig. 7 shows an example where the initiation point of IEC and the peak amplitude point

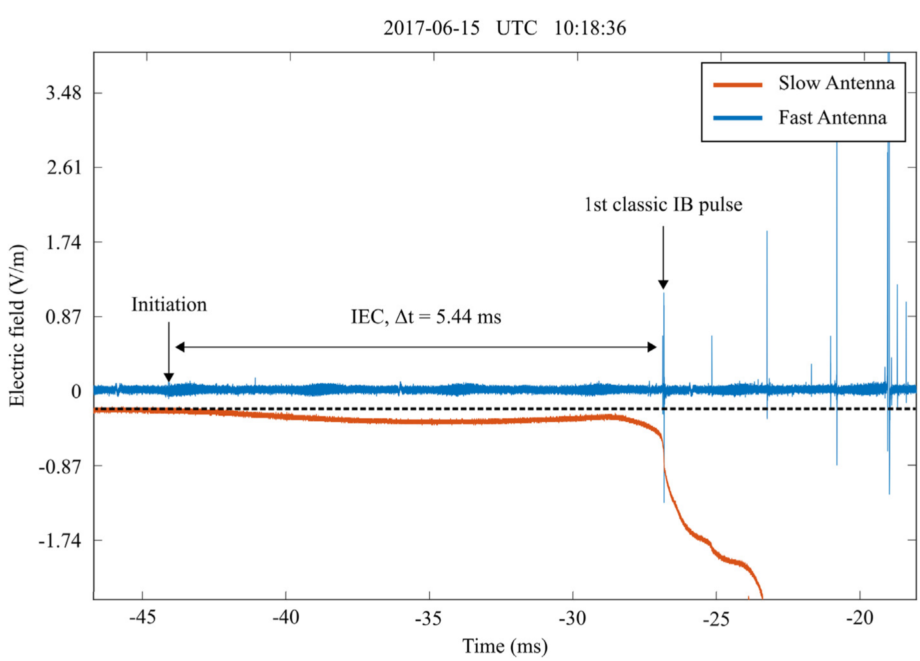

Fig. 5. Example of an IEC (physics sign convention) preceding the first classical IB pulse for an IC flash (within reversal distance) captured by wideband fast and slow antenna systems in Malacca at 10:18:36 UTC on June 15th 2017.

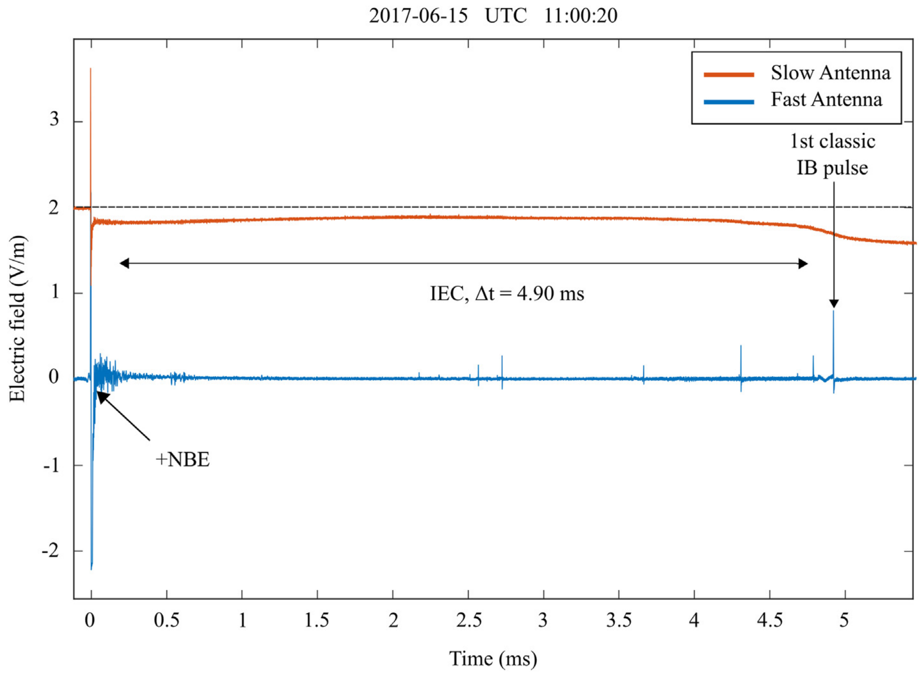

Fig. 6. Example of an IEC initiated by a +NBE (physics sign convention) and the IEC is followed by the first classical IB pulse (within reversal distance) captured by wideband fast and slow antenna systems in Malacca at 11:00:20 UTC on June 15th 2017.

just before the onset of the first classical IB pulse are estimated and calculated.

The average E-change magnitudes for –CG and normal IC flashes were 0.30 V/m, ranging from 0.01 to 1.52 V/m, and −0.81 V/m ranging from −0.03 to −0.674 V/m, respectively. For the IC flashes initiated by +NBEs, the average E-change magnitude was 0.13 V/m and ranged between 0.017 and 0.27 V/m. Marshall et al. (2014) reported much higher E-change magnitudes with average E-change magnitudes for –CG and normal IC flashes in Florida storms of 1.65 V/m, ranging from 0.10 to 6.60 V/m, and −6.30 V/m, ranging from −0.70 to −23.40 V/m, respectively. Moreover, Chapman et al. (2017) also reported much higher E-change magnitudes for –CG flashes, ranging between 0.20 and 15.20 V/m.

3.2. IECs and VHF pulses

We have chosen two normal IC flashes accompanied by VHF E-field emissions records (record numbers Nov_67 and Nov_68) on November 23rd 2017. The records of VHF pulses are shown in Fig. 8 (Nov_67) and Fig. 9 (Nov_68). The first VHF pulses were detected before the onset of the IECs by 12.69 and 251.60 μs, respectively. The total number of VHF pulses for the first IC flash (Nov_67) was 89 events and for the second IC flash (Nov_68) was 67 events. The amplitudes of VHF pulses ranged from 7.89 to 307.9 mV (the mean was 46.4 mV) and from 7.80 to 122.3 mV (the mean was 41.97 mV) for the first and second IC flashes, respectively.

Fig. 10 shows the temporal development of VHF pulses before and after the onset of the IEC. For the first IC flash (Nov_67), 16 of the VHF pulses were detected before the onset of IEC followed by 73 VHF pulses during the period of IEC but before the detection of the first IB pulse. Similarly, the same pattern can be seen for the second IC flash (Nov_68) where there were two VHF pulses detected before the onset of IEC and followed by 65 VHF pulses detected within the period of IEC. From this result, it is clear that VHF pulses were detected earlier than IECs. In comparison, for Florida thunderstorms (Marshall et al., 2014, Chapman et al., 2017), the authors found that the first VHF pulse was detected at the onset of the IEC and not before that.

3.3. IECs and narrow IB pulses

The small or narrow IB pulses are the pulses detected before the first IB pulse that have pulse durations shorter than 10 μs. We found that these narrow IB pulses (based on the FA record) were detected within the period of the IEC and also before the onset of the IECs. First, we are focusing our analysis on two normal IC flashes accompanied by VHF pulses and narrow IB pulses, and then analyzing the remaining thunderstorms with narrow IB pulses records without VHF pulses.

For the first normal IC flash accompanied by VHF pulses (Nov_67), five small pulses were detected before the onset of the IEC and the remaining 25 narrow IB pulses were detected during the IEC process as

Table 1
Comparison of durations of IECs and magnitudes of E-changes of IECs between Florida thunderstorms (Marshall et al., 2014 and Chapman et al., 2017) and tropical thunderstorms for –CG and normal IC flashes.

`Flash	Researcher	Duration of IECs (ms)			Magnitude of E-change (V/m)		
		Mean	Min	Max	Mean	Min	Max
	This paper	**4.32**	**0.22**	**13.47**	**0.30**	**0.01**	**1.52**
–CG	Marshall et al. (2014)	0.18	0.08	0.33	1.65	0.10	6.60
	Chapman et al. (2017)	0.23	0.08	0.54	–	0.20	15.20
	This paper	**6.83**	**0.08**	**64.71**	**−0.81**	**−0.03**	**−6.74**
Normal IC	Marshall et al. (2014)	1.53	0.18	5.70	−6.30	−0.70	−23.40
	Chapman et al. (2017)	2.70	0.04	9.80	–	–	–

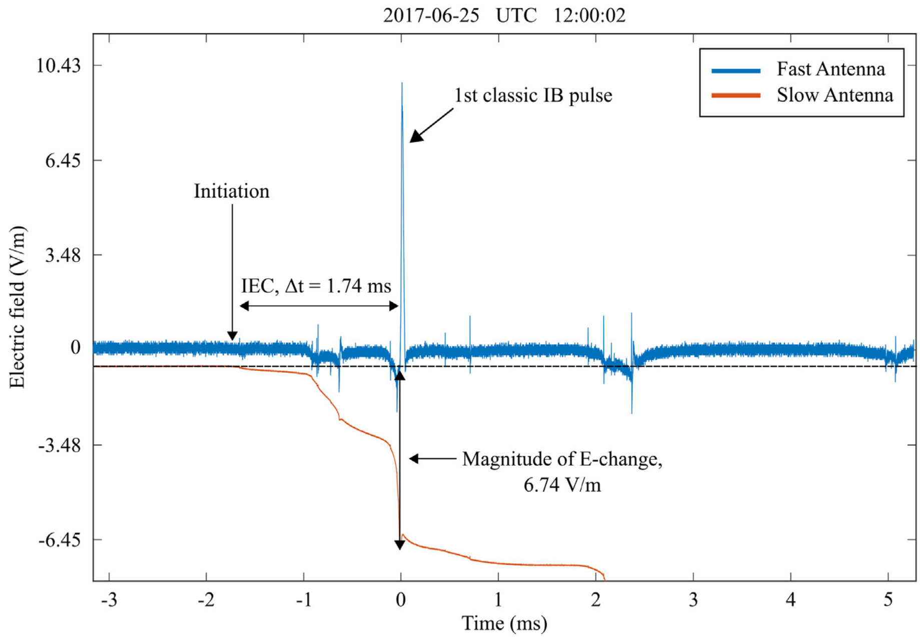

Fig. 7. Example of an IEC for IC (physics sign convention) flash (within reversal distance) captured by wideband fast and slow antenna systems in Malacca at 12:00:02 UTC on June 25th 2017.

shown in Fig. 11. It is important to notice that 16 VHF pulses were detected before the onset of the IEC and some of the VHF pulses were detected coincidently with five narrow IB pulses as shown in Fig. 11. For the second normal IC flash accompanied by VHF pulses (Nov_68), no single narrow IB pulses were detected before the onset of the IEC and all 29 narrow IB pulses were detected during the IEC process as shown in Fig. 12. On the other hand, two VHF pulses were detected before the onset of the IEC.

From both VHF sensor records of the normal IC flashes, the first narrow IB pulse was detected coincidently with the third VHF pulse (refer to Figs. 11 and 12). In other words, narrow IB pulses were absent when the first two VHF pulses were detected. For the first normal IC flash (Nov_67), the first five narrow IB pulses were detected before the onset of the IEC and all with positive polarity (polarity of initial cycle). Out of five pulses, only one pulse was detected in phase (detected at the same time) with a VHF pulse (VHF 16 just before the onset of the IEC). Note that the other four VHF pulses were found to coincide with other narrow IB pulses starting a bit earlier than the narrow IB pulses with average lead time of 55.70 ns.

For the second normal IC flash (Nov_68), ten narrow IB pulses were detected coincidently with VHF pulses (in phase) within the period of IECs and the remaining narrow IB pulses were detected shortly after the VHF pulses with an average lead of 368.89 ns. Contrary to the finding from the first normal IC flash, the polarity of the narrow IB pulses was not always the same. It is important to notice that the first nine narrow IB pulses were detected with positive polarity (refer Fig. 14). A similar pattern can be observed for the first normal IC flash (Nov_67) where the first 16 narrow IB pulses were all detected with positive polarity (refer to Fig. 13).

For the first normal IC flash (Nov_67), the average values of pulse

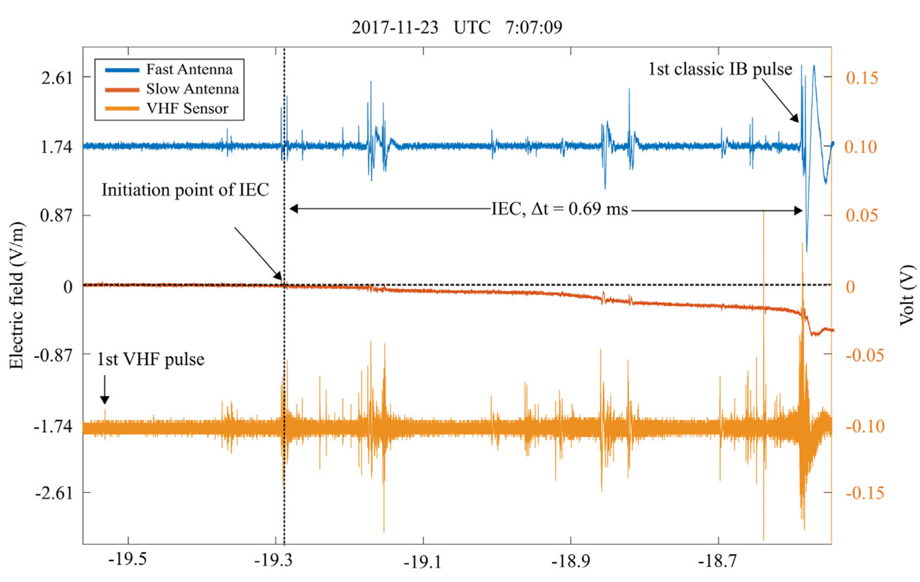

Fig. 8. The IEC in normal IC flash (Nov_67) accompanied by VHF pulses (physics sign convention; within reversal distance) captured by our lightning sensor in Malacca at 7:07:09 UTC on November 23rd 2017.

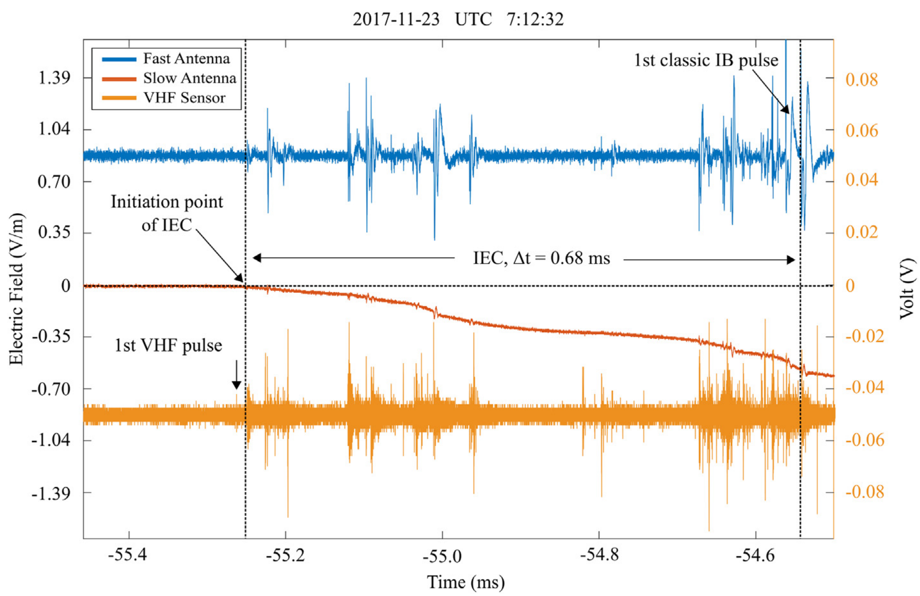

Fig. 9. The IEC in normal IC flash (Nov_68) accompanied by VHF pulses (physics sign convention; within reversal distance) captured by our lightning sensor in Malacca at 7:12:32 UTC on November 23rd 2017.

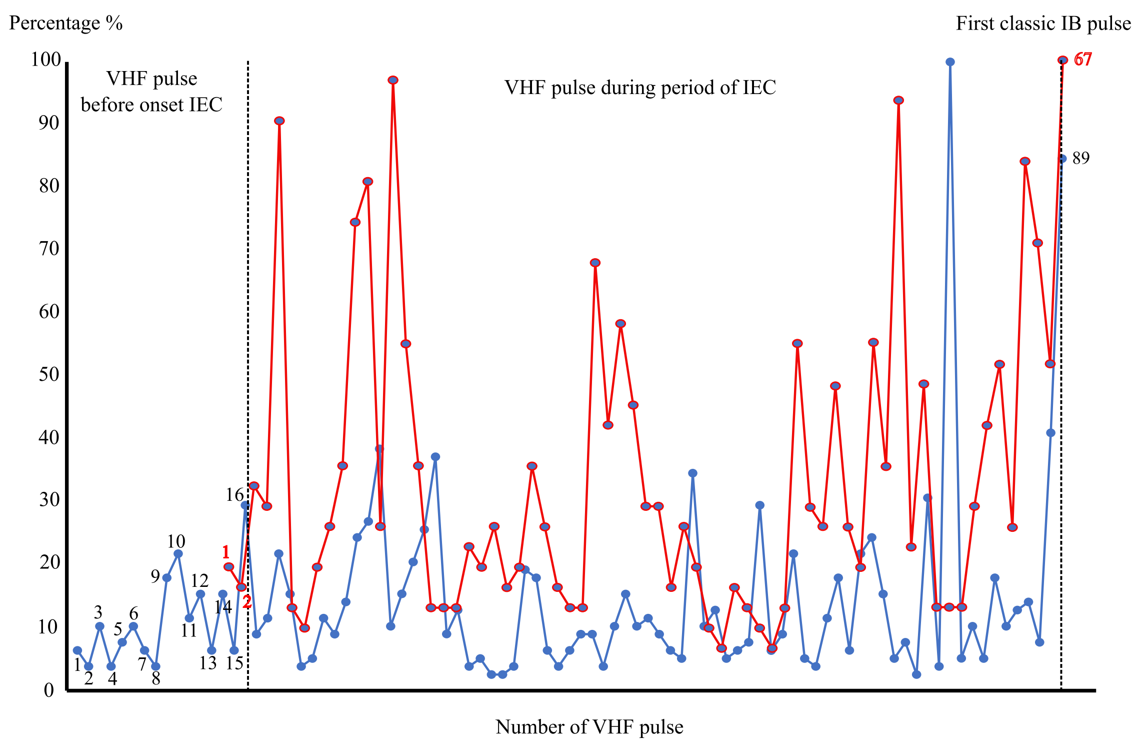

Fig. 10. The temporal development of VHF pulses for two normal IC flashes. The blue plot is for the first IC flash (Nov_67) captured on November 23rd, 2017 at UTC 7:07:09 and the red plot is for the second IC flash (Nov_68) captured on November 23rd, 2017 at UTC 7:12:32. The amplitudes of the VHF pulses have been normalized to the highest amplitude and shown in percentage values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

duration, zero crossing time and the peak amplitude for positive pulses were 1.77 µs, 0.80 µs and 1.62 V/m, respectively, and for negative polarity with only one narrow IB pulse, the values of pulse duration, zero crossing time and peak amplitude were 0.28 µs, 0.12 µs and −0.28 V/m, respectively.

For the second normal IC flash (Nov_68), 16 narrow IB pulses with positive polarity and 13 narrow IB pulses with negative polarity were detected as shown in Fig. 14. There were no narrow IB pulses detected before the onset of the IEC. The average values of pulse duration, zero crossing time and the peak amplitude for positive pulses were 1.80 µs, 0.62 µs and 1.41 V/m, respectively. For the negative polarity pulses, the mean values of pulse duration, zero crossing time and peak amplitude were 1.22 µs, 0.57 µs and −2.88 V/m, respectively.

Besides that, most flashes without detectable VHF pulses were also accompanied by narrow IB pulses. These narrow IB pulses were detected before the onset of the IECs and during the period of the IECs. Table 2 gives the temporal characteristics (pulse duration, zero crossing time, amplitude and the polarity of the pulses) of the narrow IB pulses

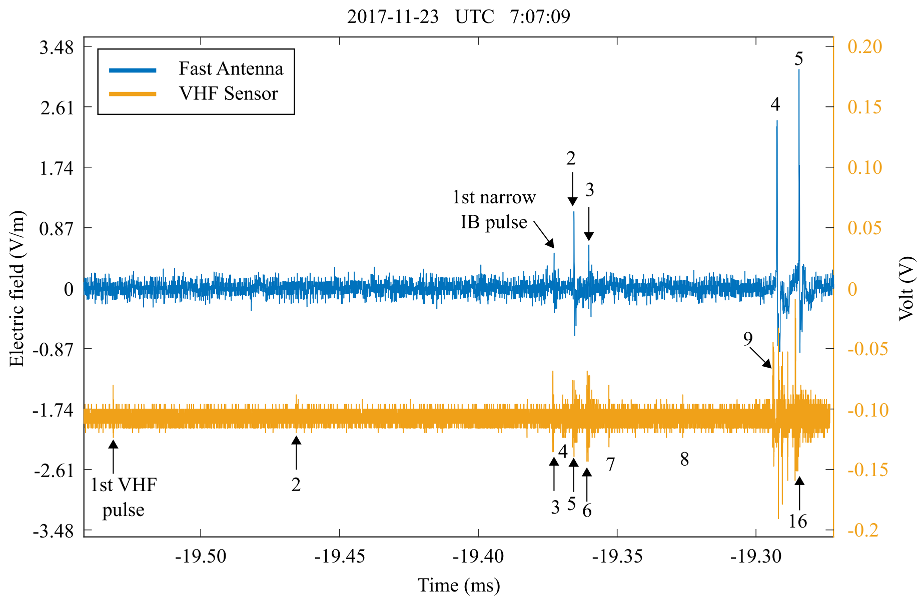

Fig. 11. Plot of VHF pulses and narrow IB pulses for the first normal IC flash (Nov_67). Note that the first two VHF pulses were detected before the first narrow IB pulse and five VHF pulses were coincident with all five narrow IB pulses.

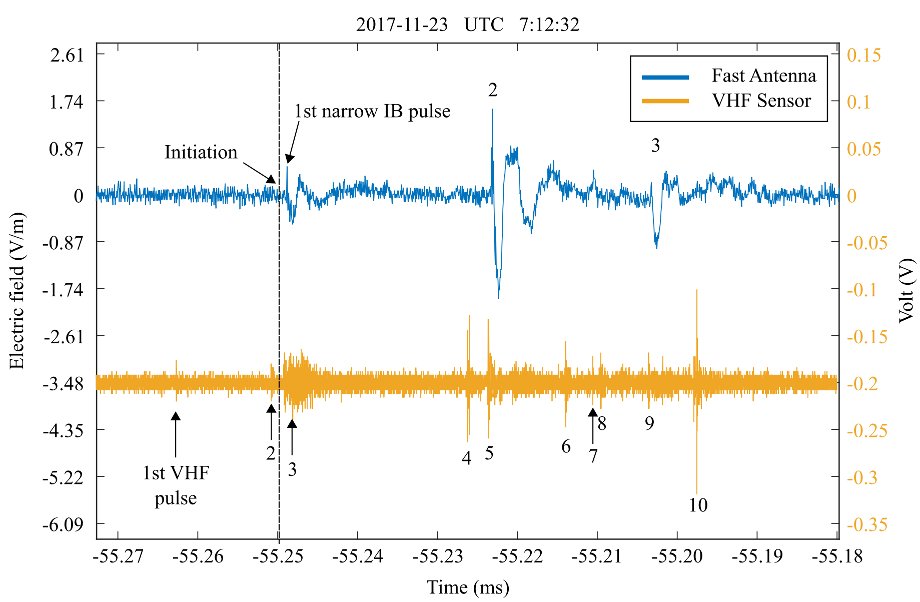

Fig. 12. Plot of VHF pulses and narrow IB pulses for the second normal IC flash (Nov_68). Note that the first two VHF pulses were detected before the first narrow IB pulse. The first narrow IB pulse was detected just after the initiation of IEC.

for 34 –CG flashes (out of 45 flashes) and 29 normal IC flashes (out of 32 flashes) recorded from nine tropical thunderstorms. Note also that a small number of flashes (both –CG and IC flashes) did not have accompanying (detectable) narrow IB pulses.

3.4. IECs and IC flashes initiated by positive NBEs

We found three IC flashes initiated by +NBEs and accompanied by VHF pulses on June 15th, 2017 and on May 23rd, 2018 as shown in Fig. 15. The IECs were observed to start immediately after the +NBEs and end before the first IB pulses. The first VHF event for all three IC flashes was at the onset of the +NBE. There were no VHF pulses detected before the onset of the +NBEs. Also, there were no VHF pulses detected during the IEC before the first IB pulse except for the IC flash on 23rd May at time 03:54:03. For this particular IC flash, four VHF pulses were detected within the IEC period after the first VHF pulse at the onset of +NBE. The amplitudes for all detected VHF pulses before the first IB pulse were calculated and are tabulated in Table 3.

On the other hand, narrow IB pulses were detected during the IEC processes for the other two IC flashes (no VHF during the IEC process) and were absent for the IC flash on 23rd May at time 03:54:03 (with detected VHF during the IEC process). All the narrow IB pulses were detected with positive polarity. Table 3 provides the temporal characteristics of the narrow IB pulses (average pulse duration, average zero crossing time and average peak amplitude).

4. Discussion

We extend the study of Marshall et al. (2014) and Chapman et al. (2017) by looking for IECs in a total of 80 flashes from ten tropical thunderstorms that were very close (within the reversal distance) to our sensor in Melaka, Malaysia. The key finding is that all the first classic IB

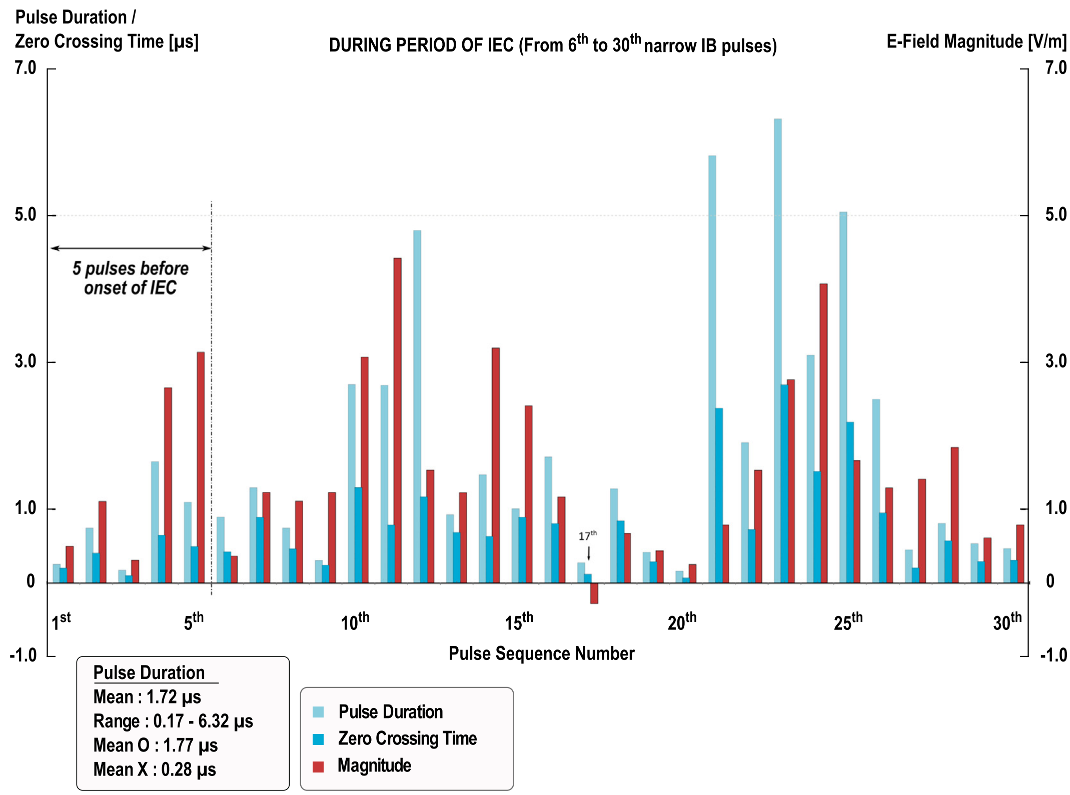

Fig. 13. The narrow IB pulses detected before the onset of IEC and during the period of IEC for the first normal IC flash (Nov_67) captured by lightning sensor in Malacca. The label 'O' refers to positive polarity pulses while 'X' refers to negative polarity pulses. The light blue bars represent pulse duration, blue bars represent the zero crossing time and red bars represent the magnitude of E-field change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

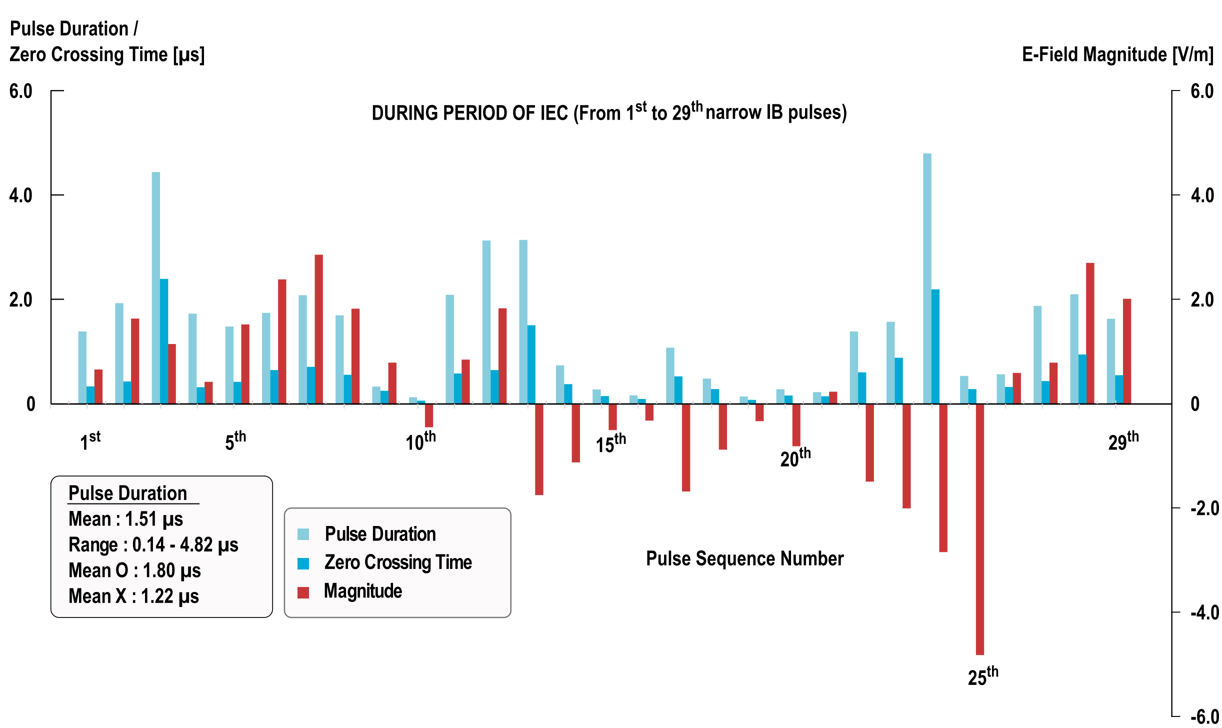

Fig. 14. The narrow IB pulses that were detected during the period of IEC for the second normal IC flash (Nov_68) captured by lightning sensor in Malacca. The label 'O' refers to positive polarity while 'X' refers to negative polarity. The light blue bars represent pulse duration, blue bars represent zero crossing time and red bars represent magnitude of E-field change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Average temporal characteristics of narrow IB pulses for –CG and normal IC flashes. The first row for each storm date is for the average values of negative polarity narrow IB pulses while the second row is for the positive polarity of narrow IB pulses respectively.

Flash	Storm	Polarity	Pulse duration (μs)	Zero crossing time (μs)	Amplitude (V/m)
–CG	15 June	N	3.66	1.04	−2.71
	2017	P	11.2	4.09	5.88
	21 June	N	1.24	0.72	−0.95
	2017	P	0.45	0.30	0.88
	16 Nov	N	1.49	0.81	−2.49
	2017	P	0.61	0.33	2.59
Normal IC	15 June 2017	P	5.31	2.24	0.83
	21 June	N	1.12	0.73	−0.44
	2017	P	3.83	1.69	2.73
	26 June 2017	P	4.98	2.54	2.19
	2 July	P	4.05	0.56	1.34
	7 July	N	3.56	1.49	−0.82
		P	5.11	2.51	1.93
	11 July	P	4.38	2.05	3.51
	16 Nov	N	1.40	0.56	−1.73
		P	4.72	2.24	5.96

pulses of tropical flashes were found to begin with a clearly detectable IEC (45 –CG, 32 normal IC, and three IC initiated by +NBE). These data provide independent support and validation (totally independent experiments from the tropics) to the hypothesis suggested by Marshall et al. (2014) that the IEC is a critical part of flash initiation. In other words, the IEC is critical before the first IB pulse and can be detected in all flashes. It is important to note here that the identification of the first IB pulse was made based on the criteria set by Marshall et al. (2014) which follows classical IB pulse definition.

Marshall et al. (2014) have issued several relevant hypotheses regarding IECs as stated below:

1. The IEC helps cause the first IB pulse
2. The beginning of the IEC is coincident with the VHF event
3. Lightning initiation is an impulsive event that causes the VHF event
4. This impulsive event produces ions
5. The IEC increased the local electric field near the initiation location, thereby causing the first IB pulse

The first hypothesis emphasizes that IEC is a critical event before the first IB pulse can happen. Further study by Chapman et al. (2017) based on Florida thunderstorms verified this hypothesis. It is important to notice that the work of Chapman et al. (2017) is part of Marshall's research group. Thus, the results are not independent enough to verify the earlier finding. Experiments conducted by our group in a tropical region are totally independent and we can verify the claim made by Marshall's group – that the IEC helps the cause of the first IB pulse of a flash. This statement is true for both –CG and IC flashes. See Figs. 4, 5, 6, and 7 for the examples of an IEC preceding the first IB pulse for both tropical –CG and IC flashes.

Table 1 in Section 3.1 summarizes the differences in IEC durations and the magnitude of E-changes recorded between tropical storms (our data) and Florida storms (Marshall et al., 2014 and Chapman et al., 2017). It can be seen that the durations of IECs for both –CG and IC flashes in tropical storms are longer than in Florida storms. For tropical –CG flashes, the average IEC E-change value is 0.30 V/m compared to the much higher average value of 1.65 V/m in Florida. A similar pattern is observed for tropical IC flashes with an average IEC E-change value of −0.81 V/m compared to −6.30 V/m for IC flashes in Florida. For lightning flashes in the tropical region, the IEC process took a longer time to increase the local electric field (related to hypotheses 4 and 5) to produce the first IB pulse because of the smaller magnitude of E-change. On the other hand, in Florida storms, the IEC process took a shorter time to increase the local electric field to produce the first IB pulse because of the larger magnitude of E-change.

It can be suggested that smaller magnitudes of E-change for tropical flashes, particularly –CGs, are closely related to a weaker Lower Positive Charge Region (LPCR) in tropical thunderstorms as suggested by Gomes and Cooray (2004), Cooray and Jayaratne (2008) and Ahmad et al. (2015). Stronger background electric fields between the main negative charge and the LPCRs in Florida storms compared to tropical storms shortened the time taken by the IEC process to reach the stage where the first IB pulse could be emitted. This is easy to understand because a stronger local electric field facilitates a much faster ionization process (the IEC) and thus shortens the time to reach the level where accumulated charges are enough to allow drastic changes of conductivity inside the cloud, leading to the production of the first leader

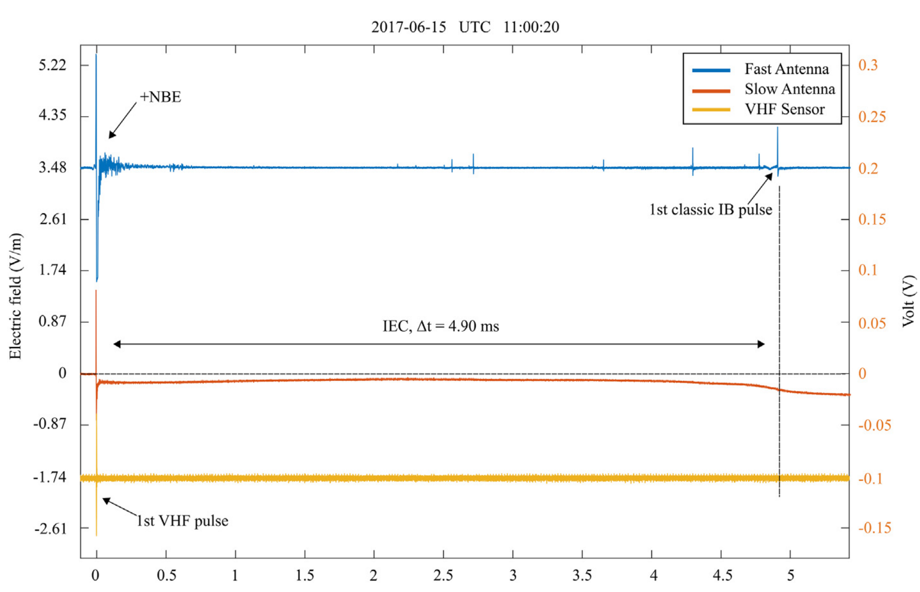

Fig. 15. The first sample of IC flash initiated by +NBE (within reversal distance based on slow field record; physics sign convention) captured by wideband lightning sensor in Malacca at 11:00:19 UTC on June 15th, 2017.

Table 3
Temporal characteristics of narrow IB pulses detected during IEC process for 2 IC flashes initiated by +NBE and the amplitude of the first VHF pulse at the onset of +NBE and the average and range values for the 4 VHF pulses detected within IEC process for sample on 23rd May 2018 at 3:54:03 UTC.

Sample	Pulse duration (µs)	Zero crossing time (µs)	Amplitude (mV)	Peak amplitude of first VHF impulse (mV)	Average and range of VHF impulse during IEC (mV)
	Mean (range)	Mean (range)	Mean (range)		
15 June 2017 (9 narrow IB pulses, all positive)	3.01 (1.31–5.94)	1.61 (0.65–3.43)	85.92 (19.78–210.47)	482.9	–
23 May 2018 (3:54:03) (no narrow IB pulses detected)	–	–	–	821.4	220.63 (96.11–428.2)
23 May 2018 (4:01:23) (4 narrow IB pulses, all positive)	2.04 (0.70–4.09)	0.86 (0.40–1.85)	58.65 (43.67–103.6)	795.1	–

that emits the first IB E-field pulse.

The second hypothesis explores the relationship between the IEC and a VHF event. Marshall et al. (2014), Chapman et al. (2017) and Marshall et al. (2019) found that the first VHF pulse for most of flashes in Florida and Mississippi storms was detected coincident with the initiation of the IEC. In contrast, we found that the VHF pulses for two normal IC flashes started sometime before the onset of the IEC (see Figs. 8, 9, 10, 11, and 12). They preceded the initiation of an IEC by between 12.69 and 251.60 µs. The first two VHF pulses for both IC flashes were detected alone without narrow IB pulses or any pulses from the B-field and dE/dt records. More importantly, these two VHF pulses were detected before the onset of the IECs. In addition, the VHF pulses for three IC flashes initiated by +NBE were also detected before the onset of the IEC and the IEC started immediately after the NBE. Furthermore, our observations, similar to those made in Marshall et al. (2019), showed that some of the VHF pulses were coincident with narrow IB pulses and some VHF pulses occurred before narrow IB pulses by average leads of 55.70 ns and 368.89 ns for the normal IC flash (Nov_67) and for the normal IC flash (Nov_68), respectively. Moreover, the pulse durations of the narrow IB pulses of tropical flashes (0.14–6.32 µs) were similar to the pulse durations of the narrow IB pulses examined by Marshall et al. (2019) in Mississippi storms (1–7 µs).

The analysis of Rison et al. (2016) included some IC flashes initiated by +NBEs but without the IEC record. Marshall et al. (2014) and Chapman et al. (2017) did not find a single flash initiated by an NBE in order to analyze the relationship between the NBE and the IEC. Luckily, we managed to capture three IC flashes initiated by +NBEs together with the IEC and VHF records. The analysis of these three flashes gives us a significant idea how +NBE, VHF events and IECs are related. One obvious observation is that the IEC is initiated by a VHF pulse (see Fig. 15) and this observation is in full agreement with the findings in Marshall et al. (2014), Chapman et al. (2017) and Marshall et al. (2019). This is true for the case of IC flashes initiated by +NBEs. We can suggest that the impulsive events (FPB and negative breakdowns) responsible for emitting VHF pulses and +NBEs occurred before the onset of the IECs. In other words, lightning is initiated by FPBs (emitting strong VHF pulses and large +NBEs) and followed by several negative breakdowns (weak VHF pulses and/or narrow IB pulses) before the IEC starts.

For the case of normal IC flashes (see Figs. 8 and 9 and Table 3), several weaker VHF pulses (mean values of 41.97 mV and 46.4 mV compared to the amplitudes of the VHF pulse of the +NBE at around 800 mV) were detected before the onset of the IEC. The first two VHF pulses were detected alone without narrow IB pulses (fast and slow antenna records) or any pulses from B-field and dE/dt records. As Rison et al. (2016) found that the FPBs can occur with a wide range of VHF strengths and E-change amplitudes, we believe these weak VHF impulses accompanied by narrow IB pulses detected before the onset of the IEC are actually FPBs followed by negative breakdowns or FPBs occurring several times.

The first two VHF impulses without narrow IB pulses are believed to be FPBs that came as a pair. The following VHF pulses accompanied by narrow IB pulses are negative breakdowns or other FPBs. All narrow IB pulses detected before and around the onset time of the IEC were positive polarity (see Figs. 13 and 14). As a matter of fact, 90.6% of the narrow IB pulses for IC flashes were positive polarity while for –CG flashes 75.6% of the narrow IB pulses were observed to be negative polarity. This is well understood because the FPB propagates downward (above main negative charge) and upward (below main negative charge) and therefore the detected E-field change at the ground must have a positive initial cycle for IC flashes and a negative initial cycle for –CG flashes.

For the normal IC flash with record numbers of pulses (Nov_67; see Fig. 11), the first two VHF pulses were followed by another 14 VHF pulses before the onset of the IEC. There were five narrow IB pulses coincident with five of the VHF pulses. These VHF pulses and narrow IB pulses are believed to be either a series of negative breakdowns before the IEC started or several attempted FPBs and negative breakdowns before the onset of the IEC. We prefer the second explanation based on the fact that Rison et al. (2016) observed attempted FPBs for several flashes through LMA observation. For the normal IC flash with record numbers of pulses (Nov_68; see Fig. 12), the first two VHF pulses were immediately followed by the IEC. The second VHF pulse was detected just before the onset of the IEC. The first narrow IB pulse was detected coincident with the third VHF pulse just after the onset of the IEC. In this case, it seems that a pair of FPBs was enough to initiate the IEC unlike in the case of the previous IC flash (Nov_67). In comparison to the normal flashes of Florida storms, a single VHF pulse (similar to IC flashes initiated by +NBEs) is sufficient to initiate an IEC, perhaps because the stronger local E-field provides enough accumulated charge to initiate the IEC process.

So far, our analyses were based on the classical IB definition that has been used by both Marshall et al. (2014) and Chapman et al. (2017). The reason we followed this criterion is to make sure the analysis between tropical and Florida thunderstorms is valid. On the other hand, following the narrow IB classification, Baharudin et al. (2012) observed that the slow electric field changes began sometime after the first IB pulse for all analyzed flashes in Malaysia. Clearly, their observation is in contradiction with our finding and also with the results presented by Marshall et al. (2014) and Chapman et al. (2017).

In order to resolve this, further analysis was carried out to consider all pulses including the narrow pulses as IB pulses and whether the first IB pulse is detected before the onset of the IEC or after. Fig. 16 shows the total number of flashes (both –CG and IC flashes) with the first IB pulse detected before IEC onset (column 1), the first IB pulse detected after IEC onset (column 2) and flashes without narrow IB pulses (column 3). Clearly, 14 –CG and two IC flashes had a first IB pulse that was detected before the IEC onset. Another 26 –CG and 30 IC flashes were found to have first IB pulses detected after the onset of the IEC. Also, there were five –CG and three IC flashes with no detectable narrow IB pulses. For this case, all first IB pulses were detected after the onset of IEC.

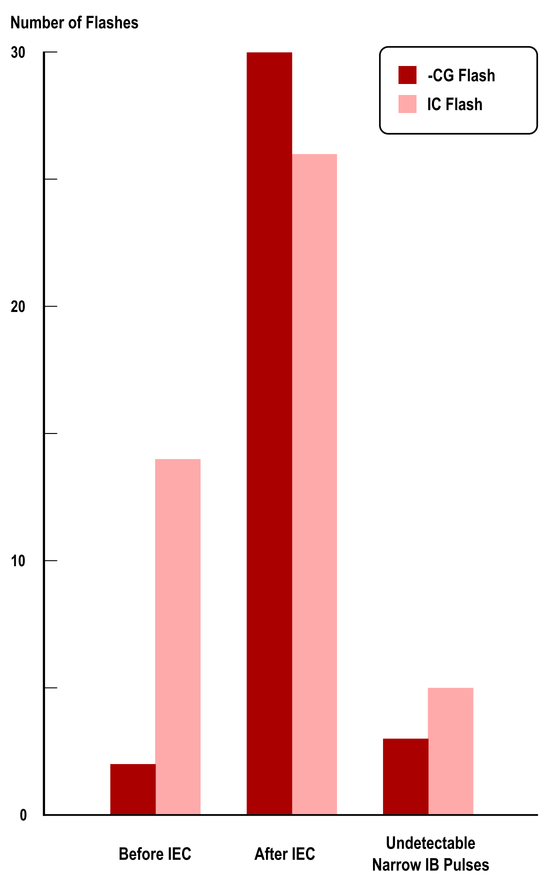

Fig. 16. The narrow IB pulses detected before and after the onset of IEC in Column 1 and Column 2, respectively. There are also flashes with undetectable of narrow IB pulses in Column 3.

Obviously, most of the flashes (31 –CG flashes and 33 IC flashes) were initiated by the IEC rather than the first IB pulse even when we have considered all the narrow IB pulses as part of the IB process. However, we cannot neglect the fact that a small portion of flashes (14 –CG and two IC) had been initiated by narrow IB pulses instead of an IEC. This might be due to the 16 flashes that appear to have narrow IB pulses before the beginning of the IEC not being close enough to the SA sensor to correctly determine the real (earlier) beginning of the IEC.

Marshall et al. (2014) discussed the distance problem in determining the beginning of IECs for IC flashes (refer to Fig. 4a and c) and Marshall et al. (2019) discussed the same problem for –CG flashes (see Figs. 7b and 8). This is because the initiations of –CG flashes typically occur at low altitudes (5–6 km) compared to the initiations of IC flashes which occur at higher altitudes (typically 7–9 km). Thus, the reversal distance for –CG flashes is shorter compared to IC flashes. It is important to note that 14 of the 16 flashes with narrow IB pulses before the apparent beginning of the IEC were –CG flashes, so they were more likely to have incorrect beginning times for their IECs. The 16 flashes that appear to have narrow IB pulses before the beginning of the IEC may not be close enough to the SA sensor to correctly determine the real (earlier) beginning of the IEC. Further studies will be needed to decide which explanation is correct.

5. Conclusion

In this paper, we extend the study of Marshall et al. (2014), Chapman et al. (2017) and Marshall et al. (2019) by looking for IECs in a total of 80 flashes from ten tropical thunderstorms that were very close (within the reversal distance, less than 8.02 km) to our sensor in Melaka, Malaysia. The key finding is that all the first classic IB pulses of tropical flashes were found to begin with a clearly detectable IEC (45 –CG, 32 normal IC, and 3 IC initiated by +NBE). These data provide independent support and validation (totally independent experiments from the tropics) to the hypothesis suggested by Marshall et al. (2014) that the IEC is a critical part of flash initiation.

We found that the IEC process of lightning flashes in the tropical region took a longer time to increase the local electric field in order to produce the first IB pulse because of the smaller magnitude of the E-change. On the other hand, in Florida storms, the IEC process took a shorter time to increase the local electric field to produce the first IB pulse because of the larger magnitude of the E-change.

Marshall et al. (2014), Chapman et al. (2017) and Marshall et al. (2019) found that the first VHF pulse for most flashes in Florida and Mississippi storms were detected coincident with the initiation of IECs. In contrast, we found that the VHF pulses for two normal IC flashes started sometime before the onset of IECs between 12.69 and 251.60 μs. The VHF pulses for three IC flashes initiated by +NBEs were also detected before the onset of the IEC. For these IC flashes, the IEC started immediately after the detection of the +NBE. It was obvious that the IECs were initiated by VHF pulses. It can be suggested that the impulsive events (FPB and negative breakdowns) responsible for emitting VHF pulses and + NBEs occurred before the onset of the IEC. In other words, lightning was initiated by FPBs (which emit strong VHF pulses and large +NBEs) and followed by several negative breakdowns (weak VHF pulses and/or narrow IB pulses) before the IEC started.

For the case of normal IC flashes, several weaker VHF pulses (mean values of 41.97 mV and 46.4 mV compared to the amplitudes of the VHF pulse of +NBE of around 800 mV) were detected before the onset of the IEC. The first two VHF pulses were detected alone without narrow IB pulses (fast and slow antenna records) or any pulses from B-field and dE/dt records. As Rison et al. (2016) found that the FPBs can occur with a wide range of VHF strengths and E-change amplitudes, we believe these weak VHF pulses accompanied by narrow IB pulses or weak NBE-type pulses detected before the onset of IEC are actually FPBs followed by negative breakdowns or several attempted FPBs.

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