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Key Points:
- The vast majority of halos observed by ISUAL are produced by negative cloud-to-ground strokes predominantly over oceans
- The production of halo and sprite observed by ISUAL is dominated by negative and positive cloud-to-ground strokes, respectively
- Threshold of lightning in terms of impulse charge moment change for halo production does not exhibit a dependence on lightning polarity

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On the Causative Strokes of Halos Observed by ISUAL in the Vicinity of North America

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Abstract The analysis of impulse charge moment change (iCMC) for the parent lightning strokes of 497 halos observed by the Imager of Sprites and Upper Atmospheric Lightning near North America in 2004–2015 indicates that the majority were produced by negative cloud-to-ground strokes predominantly produced in oceanic and coastal thunderstorms. Positive halos are almost always accompanied by sprites, and negative sprites are usually associated with halos. There are limited observations of positive pure halos with supercritical iCMCs ($>+320$ C km), but there are many negative pure halos with supercritical iCMCs (>-500 C km), suggesting a critical role of impulse charge transfer duration in the formation of streamers. The halo-producing threshold of lightning strength does not considerably depend on the polarity. Due to the dependence on the timescale of impulse charge transfer for streamer development, many negative cloud-to-ground strokes with iCMCs exceeding the threshold for sprite production actually produce halos instead.

Plain Language Summary Our previous analysis has shown some features for the parent lightning strokes of red sprites observed by the Imager of Sprites and Upper Atmospheric Lightning in the vicinity of North America during a 12-year period from 2004 to 2015. In this paper, we extend the analysis to 497 halos observed by Imager of Sprites and Upper Atmospheric Lightning in the same region and during the same time period. The results show that the majority (75%) of halos were produced by negative cloud-to-ground strokes, which are predominantly produced in oceanic thunderstorms. The duration of impulse charge transfer plays a critical role in the formation of sprite streamers. There are only very limited observations of positive pure halos with supercritical iCMCs ($>+320$ C km) for positive sprites, whereas there are many negative pure halos with supercritical iCMCs (>-500 C km) for negative sprites. Due to the dependence on the timescale of impulse charge transfer for the streamer development, many negative cloud-to-ground strokes with impulse charge transfer exceeding the threshold for sprite production actually produce halos instead.

1. Introduction

As short-lived (~2-ms) optical emissions that are less structured than sprites, halos appear as spatially diffuse glows attached to the bottom of nighttime ionosphere, usually centered at ~80-km altitude and expanding over a lateral scale typically less than 100 km (Frey et al., 2007; Wescott et al., 2001). The electron density in the halo region is enhanced by 1–2 orders of magnitude compared to the ambient electron density (Kuo et al., 2013). Previous observations indicate that halos typically occur within 1 ms in the lower ionosphere after the causative cloud-to-ground (CG) stroke and are usually laterally offset within 10 km from the stroke location (Miyasato et al., 2002; Newsome & Inan, 2010), indicating a formation mechanism that is most likely connected to the very initial charge transfer of parent strokes. In the ground observations using regular speed (25/30 frames per second) image-enhanced video cameras, halos are often observed in association with sprites that usually endure sufficiently long to trigger the imaging system (Li et al., 2012; Taylor et al., 2008);

pure halos generally enduring <2 ms are more readily captured with high-speed photometric instrumentation, which is capable of revealing more dynamic features of halo formation (Frey et al., 2007; Marshall et al., 2008; Williams et al., 2012).

Although the occurrence of halos might be more frequent than red sprites even over continental thunderstorms (Newsome & Inan, 2010), there is a lack of statistical analysis on the impulse charge transfer of halo-producing CG strokes, which causes an inadequate understanding on the lightning characteristics (e.g., strength and duration of charge transfer) responsible for the halo occurrence. Moreover, it has been shown that the oceanic and coastal thunderstorms are more efficient in producing CG strokes with high peak currents and large charge moment changes, especially that of negative polarity (Chronis et al., 2016; Said et al., 2013; Sato & Fukunishi, 2003). Therefore, halos might be more frequently produced over the oceans, and the results acquired from the ground-based observations in the land areas may not be typical. Nevertheless, an investigation of halo-producing CG strokes based on a sufficiently large data set is desired to obtain additional insights into parent thunderstorms in different geographic regions.

The Imager of Sprites and Upper Atmospheric Lightning (ISUAL) aboard the Taiwanese FORMOSAT-2 satellite provides the opportunity to investigate the occurrence of halos on a global scale (Chen et al., 2008; Chern et al., 2015). Our previous work has examined the ISUAL observation of sprites near North America during 2004–2015 (Lu et al., 2017), which have a highly structured feature due to the development of streamers driven by the quasi-electrostatic field of parent strokes (Pasko et al., 1997; Qin et al., 2013). In this writing, we examine the parent lightning strokes of 497 halos observed by ISUAL in the vicinity of North America during a 12-year time period from 2004 to 2015. Frey et al. (2007) and Williams et al. (2012) analyzed the halos observed by ISUAL in the similar region prior to March of 2007. With broadband lightning sferics measured typically within range of 5,000 km near Duke University, our analysis with a much larger data set yields an estimate of threshold for halo-producing lightning strength (in terms of impulse charge moment change [iCMC]) on a statistical basis and also provides an opportunity to investigate the difference between halo-generating strokes spawned by continental and oceanic storms.

2. Observations and Data Analysis

The radio frequency lightning signals (sferics) that are used to analyze the halo-producing lightning strokes are recorded in Duke Forest (35.971°N, −79.094°E), where two pairs of magnetic sensors are deployed to record the ultralow frequency (ULF, <1 to 400 Hz) and very low frequency (VLF, 50 Hz to 30 kHz) magnetic fields that are sampled at 2.5 and 100 kHz, respectively (Lu et al., 2013). The iCMC (defined as the product of charge transferred to ground within 2 ms after the return stroke and its original height above the ground) of halo-producing strokes are estimated from the ULF data with the method that has been applied in our previous work (Cummer & Lyons, 2005; Lu et al., 2012, 2017). For the events without qualified ULF data recorded, the low-pass-filtered VLF data are used alternatively to estimate iCMC. The polarity of lightning strokes is defined as that a positive stroke transfers positive charge from cloud to ground, resulting in a positive iCMC. For some halo events accompanied by bright sprites that are related to especially large iCMCs (e.g., > +500 C km), the estimated iCMCs partially contain the contribution from the sprite current (Cummer et al., 1998; Pasko et al., 1998).

Figure 1a shows the measurement of a pure halo produced by a negative CG stroke with iCMC of −644 C km. The VLF sferic waveform indicates that the source current of halo-producing stroke might have a relatively short timescale (about 0.5 ms). Figure 1b shows a halo with barely visible sprite feature caused by a negative CG stroke (with longer timescale about 1.5 ms, comparable to the typical positive CG strokes) with iCMC of −856 C km. The sprite streamers in halo-sprite (HS) events produced by negative CG strokes as observed by ISUAL are typically dim (e.g., Frey et al., 2007), which is consistent with ground observations (Li et al., 2012; Taylor et al., 2008). According to Qin et al. (2013), a longer duration (>1 ms) of charge transfer in the causative stroke is favorable for the development of streamers, namely, the formation of sprites.

Figure 1c shows a pure halo associated with a positive CG stroke that was registered by the U.S. National Lightning Detection Network as having a high peak current of +228 kA (Cummins et al., 1998), and the estimated iCMC for the halo-producing CG stroke is about +797 C km. The ISUAL-reported location of this event was about 820 km to the west of the stroke location (used for calculating the distance and iCMC) as the positioning procedure (as described by Chen et al., 2008) treated the event behind the horizon as a case in sight

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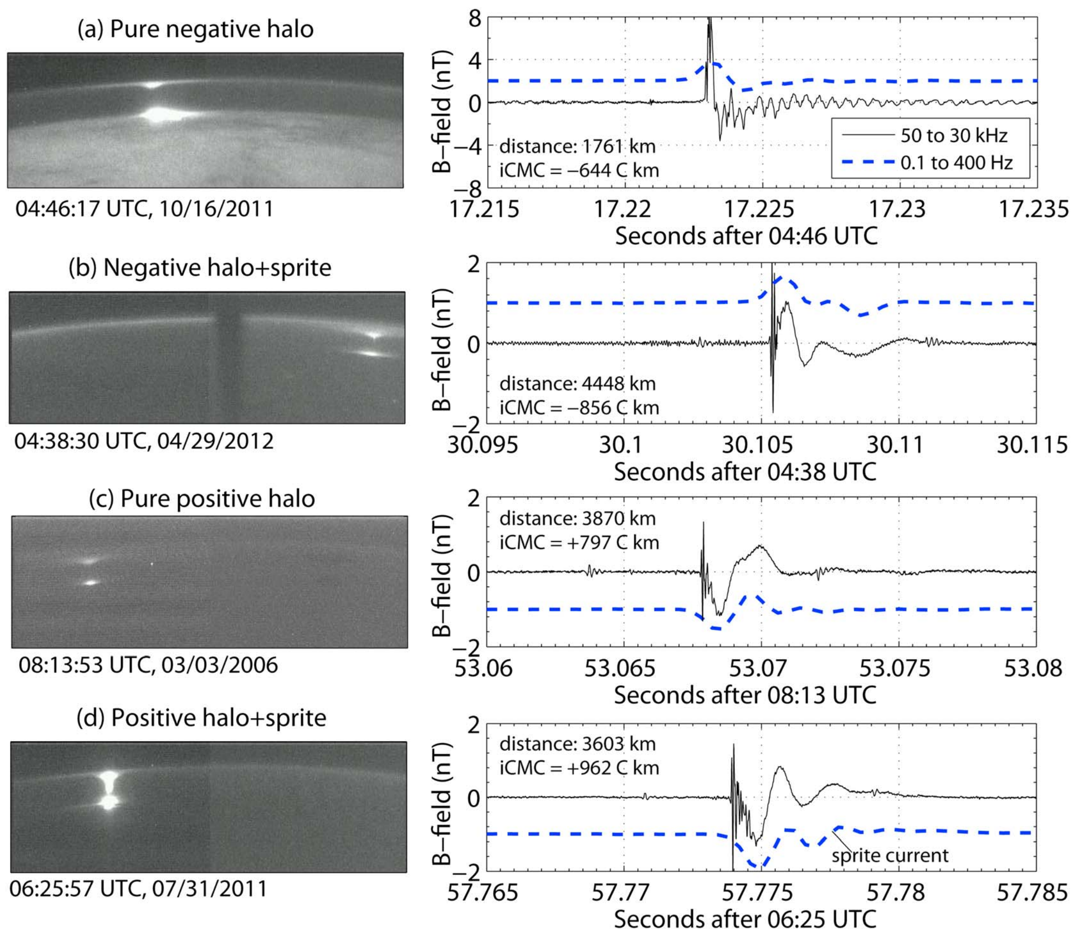

Figure 1. Examples of halos observed by Imager of Sprites and Upper Atmospheric Lightning and the associated sferics recorded (at the distance given in the panel) in Duke Forest, showing (a) a pure halo produced by a negative CG stroke, (b) a negative halo accompanied by sprite, (c) a pure halo produced by a positive CG stroke, and (d) a positive halo accompanied by sprite. The magnetic field recorded by the ultralow frequency sensor (with bandwidth of 0.1 to 400 Hz) is appropriately offset for the comparison. iCMC = impulse charge moment change; CG = cloud-to-ground.

(e.g., Lu et al., 2017). (If we examine this event as a halo centered at 80 km behind the horizon, e.g., Wescott et al., 2001, the estimated halo location is at about 192-km range from the stroke location.) There is no signature of sprite current, which is not typical for sprite-associated iCMCs in excess of +500 C km, and thus further confirms the absence of sprite streamers in this event. Figure 1d shows a typical bright ISUAL halo+sprite event (also with elves feature according to the analysis of ISUAL team) produced by a +CG stroke, and the sferic signal clearly shows the presence of a sprite current (i.e., the second millisecond-scale pulse without association with fast VLF signal; e.g., Cummer et al., 1998, 2006; Pasko et al., 1998), in addition to the long impulse current contributing to a large iCMC of +962 C km.

To ensure the analysis on a sufficient number of events with reliable iCMC estimate, we focus on ISUAL halos in the same geographic domain as Lu et al. (2017). Almost all of these events were located within 5,000 km of the site (marked by a black pentagram in the figure) where the sferic signals are recorded. As the distance is a critical parameter in the iCMC estimate, we performed a validation on the ISUAL location of halo events as the location of parent strokes. The parent lightning strokes of 71 halos observed by the IUSAL are also detected by National Lightning Detection Network, which provides the lightning detection with location uncertainty generally $<$1 km (Nag et al., 2011). For about half of these halo events, the ISUAL-reported location is within 100 km of the National Lightning Detection Network location, and the comparison also shows a 30-km systematic offset to south in the ISUAL location, which is also shown in Figure 4 of Lu et al. (2017). Presuming that the location given by ISUAL for other halos can confine the parent strokes with similar accuracy, the uncertainty in iCMCs estimated for the halo events examined in this paper is typically within 10%.

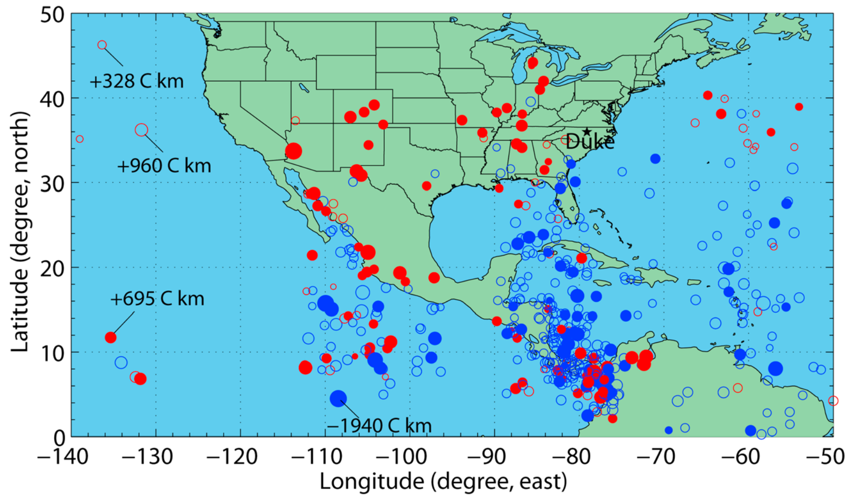

Figure 2. Distribution of halos observed by Imager of Sprites and Upper Atmospheric Lightning near North America during 2004–2012. The area of circles (red for positive and blue for negative) is proportional to the magnitude of impulse charge moment changes estimated on the basis of broadband magnetic sferics measured near Duke University. Pure halos and halo+sprite events are marked as open and solid circles, respectively.

The geographic locations for 497 ISUAL halos examined in this paper along with the estimated iCMCs are shown in Figure 2. Positive and negative strokes are shown with red and blue symbols, respectively, and the area of symbols is proportional to the magnitude of estimated iCMC (given for several selected examples). Also, pure halos (353, or ~71%) and HS events (144, or ~29%) are distinguished with solid and open circles, respectively. As discussed by Williams et al. (2012, Figure 1), the timescale of impulse charge transfer producing halos, without distinguishing between two polarities, is typically $<$2 ms. A relatively short timescale of the impulse charge transfer might not be sufficient to sustain the downward development of negative streamers (Li et al., 2012; Qin et al., 2013). According to Hiraki (2010) and Qin et al. (2013), a continuing current that endures at least 5 ms after the return stroke is favorable for the development of downward streamers.

As shown in Figure 2, the vast majority of pure halos observed by ISUAL, mainly driven by negative strokes, are produced above oceanic thunderstorms; similarly, all the pure halo events examined by Frey et al. (2007) also occurred over oceanic areas. The energetics of oceanic lightning in comparison with their continental counterpart has been addressed by Füllekrug et al. (2002) based on the measurement of extremely low frequency electromagnetic lightning radiation on a planetary scale; in particular, negative CG strokes occurring over oceans tend to produce larger charge moment change than those over continents.

Data from both the ground-based worldwide lightning detection network and the space-borne lightning imaging sensor indicate that the lightning frequency on the continent is about 10 times that in the ocean (Christian et al., 2003; Pan et al., 2013). However, it has been shown that oceanic negative CG strokes generally have larger peak current than their continent counterparts (Chronis et al., 2016; Said et al., 2013). It is noticed that most of the so-called *superbolts* (i.e., unusually intense lightning strokes with optical power in excess of 10^{11} W) listed by Turman (1977) are located in coastal/oceanic areas (Füllekrug et al., 2002); the characteristic timescale ($\leq$1 ms) of these extraordinary lightning events actually implies a physical connection to negative strokes that are usually more impulsive than their positive counterpart. Therefore, it is very likely that the lightning source of these extremely powerful lightning bolts is of negative polarity. Unfortunately, although Turman (1977) noticed the radio frequency signals associated with superbolts, these signals were not examined with a purpose to determine the polarity of lightning source.

It has been shown that on a global scale, there are comparable quantities of positive and negative CG strokes with the equivalent charge moment change (e.g., 600 C km) sufficient to producing sprites (Sato & Fukunishi, 2003), which is also shown by the survey of Williams et al. (2007) based on the measurement of transient Schuman resonance. However, due to the dependence of streamer development on the duration of charge transfer, many negative strokes with sprite-producible iCMC might eventually lead to the occurrence of halos. Hence, negative strokes produced by oceanic thunderstorms appear to be more capable of producing halos.

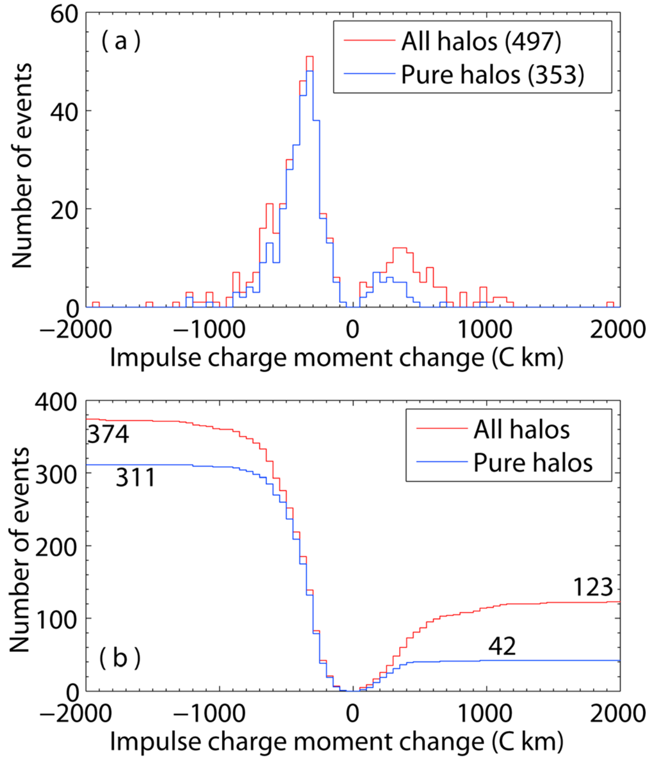

Figure 3. (a) Histogram (in 50 C km bin) and (b) cumulative distribution of impulse charge moment changes associated with halos observed by Imager of Sprites and Upper Atmospheric Lightning near North America during 2004–2015. The blue and red lines show the results for pure halos and all halos, respectively.

It is also possible that the distribution pattern shown in Figure 2 actually reflects a dependence on latitude, rather than a difference between continental and oceanic thunderstorms. Indeed, the proportion of halos produced by negative strokes is as high as 90% for the ISUAL events located at latitudes between 0° and 30°N, while this ratio is only 24% for the events observed to the north of 30°N.

3. Dominance of Negative Strokes in Pure Halo Production

Figure 3a shows the histogram of iCMCs estimated for 497 ISUAL halos. Most (374, or 75%) of these halos were produced by negative CG strokes, and the vast majority (311 out of 374, or 83%) of negative halos are pure events without discernible sprite streamers, implying a more stringent condition for the streamer development as seen in sprites than the halo production. This is reflected at least partly by the typically higher iCMCs associated with the HS events. The mean and median iCMC of negative strokes producing pure halos are −461 C km and −402 C km, respectively, which are significantly lower than that (−715 and −650 C km, respectively) for negative strokes producing HS events; the mean and median iCMC of positive strokes producing pure halos are +474 and +400 C km, respectively, which are considerably lower than that (+571 and +497 C km, respectively) for the HS-producing positive strokes. Note that for both positive and negative halos, there are a small amount of cases associated with relatively small iCMCs (e.g., below 100 C km) below the claimed threshold in the theoretical analyses, for example, +200 C km for positive sprites and −300 C km for negative sprites (Qin et al., 2012). These observations of atypical events imply that the actual situation leading to the occurrence of sprites could be complicated due to the variation in the mesospheric condition and detailed charge transfer in causative lightning strokes.

It is noticed that pure halos are rarely (only in two cases out of 41) produced by +CG strokes with iCMC greater than +500 C km, whereas a significant proportion (71 out of 119, ~60%) of halos produced by negative strokes with iCMC greater than −500 C km are pure events. Nevertheless, pure halos observed in association with large iCMCs that substantially exceed the threshold of sprite production by lightning strokes of either polarity imply that in addition to the charge moment change, the timescale of charge transfer is also critical for the formation of streamers (Qin et al., 2013). This is especially distinct for negative halo-producing strokes, including one case examined by Kuo et al. (2013) to study the halo-related ionization emissions and estimate the reduced electric field in the halo region.

Based on the iCMC estimates (for both pure halos and HS events), the mean and median iCMC of negative halo-producing strokes are −461 and −402 C km, respectively, which are not considerably different from the results (+474 and +400 C km, respectively) for the halo-producing positive strokes. Therefore, it seems that the threshold of lightning strength for the halo production does not considerably depend on the polarity of parent strokes, which is consistent with the fact that the formation of both halos and sprites is a consequence of conventional dielectric breakdown driven by lightning-induced transient electric field perturbation (Hiraki, 2010; Pasko et al., 1997; Qin et al., 2011, 2013). The survey of charge moments produced by intense lightning strokes on a global scale shows that there are roughly equal amounts of positive and negative lightning strokes with iCMC $>$ ±400 C km (e.g., Sato & Fukunishi, 2003; Yamashita et al., 2011). Based on our results and previous studies indicating that positive iCMCs greater than +400 C km are $>$80% likely to produce sprites (e.g., Cummer & Lyons, 2005; Lu et al., 2013), it is likely that the occurrence rate on the global scale is similar for the halos/sprites produced by positive and negative CG strokes, respectively.

The dominance of negative strokes is particularly distinct for pure halos. Among 353 ISUAL halos without discernible streamers extending below the diffuse glow, about 88% events were produced by negative strokes.

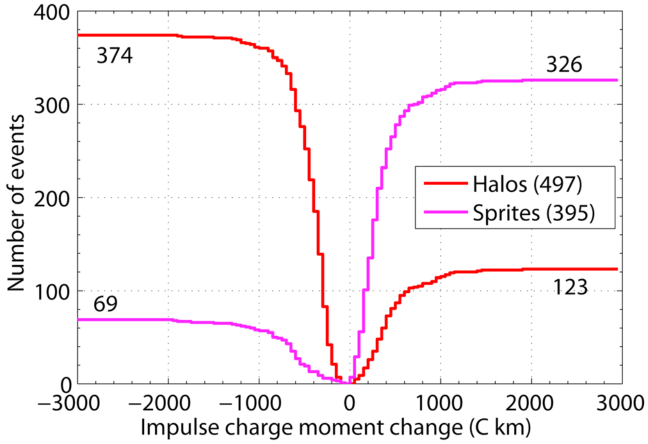

Figure 4. Cumulative distribution of impulse charge moment changes produced by the causative lightning strokes of 497 halos (red) and 395 sprites (pink) observed by Imager of Sprites and Upper Atmospheric Lightning near North America during 2004–2015.

The dominance of negative strokes in the halo production has been revealed by Frey et al. (2007) and Williams et al. (2012) with a smaller data set in ISUAL observations prior to 2007. In contrast, the ground-based observations with Photometric Imager of Precipitated Electron Radiation in central New Mexico indicate that slightly more than half (55.4%) of halos are produced by negative CGs (Newsome & Inan, 2010). This disparity also suggests that the dominance of negative strokes in halo production is particularly distinct in noncontinental areas.

Figure 3b shows the cumulative distribution of iCMCs by further distinguishing between pure halos and HS events. The vast majority (~83%) of halos produced by negative strokes are not associated with discernible sprite streamers; in contrast, most (65%) halos produced by +CGs were accompanied by sprites (this ratio is $>$90% for iCMCs$>$ + 400 C km). For halo-producing strokes of both polarities, the median and mean iCMC for pure halos are smaller than that for HS events, which implies that the critical iCMC for sprite occurrence is usually higher than that for halos with less ionization, consistent with the analysis of Hiraki and Fukunishi (2006).

It has been suggested that the timescale of charge transfer following the return stroke plays a significant role in the formation of streamers (Li et al., 2012; Qin et al., 2013). For comparable impulse iCMCs, negative strokes have shorter timescale than positive strokes. For instance, Williams et al. (2012) show that the duration of negative halos is typically $<$1 ms, while that of positive halos is longer than 1 ms in most cases; also, the duration of halos varies inversely with the peak current of positive CG strokes. Based on the sferic measurements for a large number of sprites with distinct signal of sprite currents (Cummer et al., 1998), the time lapse after return stroke that is sufficient for the development of streamers is 2–3 ms (Cummer et al., 2006; Hu et al., 2002), which is substantially shorter than the critical timescale (about 5.5 ms) concluded by Hiraki (2010).

With the discussions above, it is apparent that the iCMC is not the exclusive criterion to determine the occurrence (and brightness) of sprites, and the exact timescale of impulse charge transfer and the local ionospheric conditions should also be taken into account (Qin et al., 2012, 2013). Moreover, the sferic waveform recorded in the measurement should at least reflect the exact timescale of intense lightning charge transfer. The ideal upper cutoff frequency for the magnetic sensor should be at least 2 kHz, and meanwhile other novel techniques for determining the timescale of impulse charge transfer in CG strokes based on radio frequency sferics remain to be developed.

4. Comparison With ISUAL Sprites

Red sprites and halos are both manifestations of conventional breakdown in the upper mesosphere driven by intense lightning strokes. Figure 4 compares the cumulative distribution of iCMCs for 497 halos and 395 sprites observed in the vicinity of North America during the same 12-year period from 2004 to 2015 (Lu et al., 2017). The contrast is very obvious in that positive and negative CG strokes dominate the production of sprites and halos, respectively. For the positive causative strokes, the mean and median iCMC (+474 and + 400 C km, respectively) associated with halo production are larger than those (+346 and + 280 C km, respectively) associated with sprite production, which implies that a considerable proportion of ISUAL sprites examined by Lu et al. (2017) are long delayed events (e.g., Li et al., 2008). Therefore, halos observed by ISUAL, which are usually produced with very short delay after the return stroke (Frey et al., 2007), appear to be related to more energetic lightning strokes.

Except for that ISUAL observed slightly more halos than sprites in the region of interest (on a global scale, ISUAL observed nearly equivalent amount of sprites and halos; Chen et al., 2008; Chern et al., 2015), there is an apparent symmetry in the distribution of iCMCs associated with halos and sprites, which reminds us of the polarity asymmetry for the parent lightning strokes of sprites discussed by Williams et al. (2012). The asymmetry could be mainly attributed to the timescale of impulse charge transfer in the CG strokes of opposite polarity. Our results generally support the resolution proposed by Williams et al. (2012) to explain the so-called *sprite polarity paradox* raised by Williams et al. (2007), namely, the ratio of negative sprite ($<$1%)

reported in ground-based observations is much lower than that (>10%) inferred from the global survey with Schumann resonance. The ISUAL observations actually indicate that ~18% sprites were produced by negative CGs, with the vast majority (>80%) located in the oceanic and coastal areas (Lu et al., 2017). A significant fraction of the missing sprites associated with negative iCMCs larger than the threshold actually occur as pure halos due to the relatively short timescale of causative strokes, which are difficult to capture in most previous ground-based observations using the low-light-level video cameras (e.g., Boccippio et al., 1995; Li et al., 2012; Lyons, 1996).

It is noticed that the distribution pattern of halos/sprites inferred from ISUAL observations is considerably different from that revealed by sferic measurements (e.g., Sato & Fukunishi, 2003), which is partially caused by that the observation schedule of ISUAL yields varying temporal coverage in different regions on a circular Sun-synchronous orbit (Chen et al., 2008; Frey et al., 2016). Therefore, the ground-based observation remains to supplement the space observation to reveal the dominance of oceanic thunderstorms in spawning negative halo-producing CG strokes. The global survey of Williams et al. (2012, Figure 2) also indicates a dominance of negative halo-producing strokes in South China Sea, in addition to the Caribbean Sea shown in Figure 2. Both regions with dominance of negative strokes in halo production were located at relatively low latitudes (<20°). Hence, the case studies of parent thunderstorms of halo-producing negative strokes might provide further information on the meteorology of such thunderstorms.

5. Summary

In this paper, following our previous analyses with respect to sprites (Lu et al., 2017), we examined 497 halos observed by ISUAL in 2004–2015 in the vicinity of North America based on the coordinated measurements of broadband sferics near Duke University. The results indicate that the majority (353, or 71%) of ISUAL-observed halos are pure events without discernible streamer development. Negative strokes generated by oceanic and coastal thunderstorms appear to dominate the production of pure halos near North America. Most halos produced by positive strokes are accompanied by visible streamer development (namely, HS event), which is mainly attributed to the relatively long timescale of charge transfer in the causative strokes.

Our results indicate that there is no considerable dependence for the threshold of lightning strength for producing halos on the polarity of causative strokes, which is consistent with the previous modeling studies indicating the polarity symmetry of positive and negative strokes in producing halos based on the conventional breakdown theory (e.g., Pasko et al., 1997; Qin et al., 2011). However, the relatively short timescale of halo-producing negative strokes leads to more rapid relaxation of *E* field perturbation in the lower ionosphere, thus preventing the development of sprite streamers (e.g., Qin et al., 2013). By combining with our previous analyses on 395 sprites observed by ISUAL in the same geographic region and during the same time period, we can see that the negative CG strokes with impulse charge transfer exceeding the threshold for sprite production often produce pure halos instead. Therefore, the comparable occurrence rate of intense negative and positive strokes on the global scale is likely translated to the observation of almost equal amount of sprites and halos.

The results presented in this writing regards the observations of ISUAL with a limited coverage in both space and time. Due to the limited duration of space-borne observations over a specific region of interest (e.g., Sato et al., 2015; Yair et al., 2004), it remains necessary to conduct the routine observation of transient luminous events from ground-based stations located in coastal areas, especially those at relatively low latitudes, in order to get more insights into the oceanic thunderstorms that appear to be more capable of producing negative sprites and halos. Along with the global detection of intense lightning strokes with considerable charge transfer to ground (Füllekrug & Constable, 2000; Price et al., 2002; Sato & Fukunishi, 2003; Yamashita et al., 2011), this information might provide the basis for estimating the global occurrence rate of halos.

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