Long recovery VLF perturbations associated with lightning discharges

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[1] Long D-region ionospheric recovery perturbations are a recently discovered and poorly understood subcategory of early VLF events, distinguished by exceptionally long ionospheric recovery times of up to 20 min (compared to more typical ∼1 min recovery times). Characteristics and occurrence rates of long ionospheric recovery events on the NWC transmitter signal recorded at Malaysia are presented. 48 long recovery events were observed. The location of the causative lightning discharge for each event is determined from GLD360 and WWLLN data, and each discharge is categorized as being over land or sea. Results provide strong evidence that long recovery events are attributed predominately to lightning discharges occurring over the sea, despite the fact that lightning activity in the region is more prevalent over land. Of the 48 long recovery events, 42 were attributed to lightning activity over water. Analysis of the causative lightning of long recovery events in comparison to all early VLF events reveals that these long recovery events are detectable for lighting discharges at larger distances from the signal path, indicating a different scattering pattern for long recovery events.

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1. Introduction

[2] The intense electromagnetic pulse (EMP) radiated from powerful cloud-to-ground (CG) lightning discharges can couple directly into the lower ionosphere, producing transient localized *D*-region conductivity changes. This conductivity change perturbs the subionospheric propagation of Very Low Frequency (VLF, 3–30 kHz) transmitter signals through the region, producing detectable early/fast events on the VLF signal. These events are triggered within <20 ms ('early') after the causative lightning impulse with a <20 ms onset duration ('fast') [*Inan et al.*, 1988] followed by a slower relaxation of ionization to undisturbed levels in 60–180 s [*Sampath et al.*, 2000]. *Haldoupis et al.* [2006] demonstrated a new category of early events with comparatively longer onset duration (∼1–2 s; 'slow') with similar recovery signatures. The gradual risetime of these events implied cumulative ionization generated by consecutive intracloud lightning discharges. These consecutive discharges appeared as clustered sferics in their broadband measurements. These events were labeled as 'early/slow' events. The term 'Early VLF events' applies to both early/fast and early/slow VLF events, to emphasize the small onset delay associated with direct coupling of the lightning electromagnetic energy to the lower ionosphere. Also, it has been shown that sprites are very often, if not always, associated with early VLF events [*Haldoupis et al.*, 2004, 2010].

[3] Recently, *Cotts and Inan* [2007] catalogued a new category of early VLF events with unusually long enduring recoveries of up to ∼20 min, and suggested these long recovery events may be consistent with gigantic jets. *Lehtinen and Inan* [2007] proposed a new chemistry model for the stratosphere/lower ionosphere, and attributed the observation of early VLF events with long lasting recoveries (∼10^3–10^4 s) to the persistent ionization of positive and negative ions at altitudes below 50 km induced by a gigantic jet. *van der Velde et al.* [2010] were the first to report a pellucid correlation between a gigantic jet event initiation and an early VLF event, although the recovery time was obscured by a subsequent sprite.

[4] *Cotts and Inan* [2007] classified three distinct types of long recovery events based on the recovery rates in amplitude and phase back to their ambient levels. Type 1 events display long amplitude recovery while the phase recovery resembles that of a typical early event (<200 s). Type 2 events exhibit long recovery signatures on both amplitude and phase. In type 3, or 'step-change', events the perturbed

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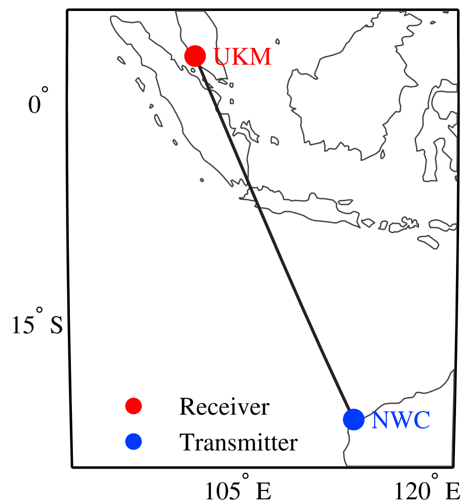

Figure 1. Geographic map showing the locations of the NWC transmitter, VLF receiver and the GCP.

signal fails to recover to its ambient conditions. A typical step-change early VLF event endures for 200 s [*Kumar et al.*, 2008; *Inan et al.*, 1996]. One suggested cause of the long recovery times is substantial ionization of heavy ions at lower altitudes (<50 km) [*Glukhov et al.*, 1992; *Pasko and Inan*, 1994] induced by gigantic jet events [*Lehtinen and Inan*, 2007].

[5] In this paper, we present a large new catalog of long recovery early VLF events observed at Universiti Kebangsaan Malaysia (UKM), on the VLF NWC signal. Long recovery events were studied previously by *Cotts and Inan* [2007] by monitoring multiple all-sea-based and all-land-based signal paths. The authors found that these events occur more often over the water-based signal paths. However, due to the lack of lightning location information, *Cotts and Inan* [2007] were unable to determine the scattering pattern of long recovery events, and were unable to distinguish the effect of the lightning location along the path, which is known to significantly affect the perturbed ionospheric signature [*NaitAmor et al.*, 2010]. The NWC to UKM path traverses over both ocean and land regions, providing further insight into the geographical distribution of long recovery events, and for the first time correlates the events with lightning discharge locations to investigate their VLF scattering patterns.

2. Instrumentation and Observations

[6] The VLF data presented here consist of the amplitude and phase of the NWC transmitter signal (21.8°S, 114.1°E; 19.8 kHz), as recorded by the Stanford-AWESOME receiver installed at UKM, Malaysia (2.55°N, 101.46°E) in 2009 and 2010. The Stanford-AWESOME receiver at UKM, described by *Cohen et al.* [2010], consists of two orthogonal crossed loop antennas to collect wideband magnetic fields as weak as a few fT/rt-Hz in both the North–South and East–West directions. The detected signal is bandpass filtered between 0.3–47 kHz and sampled at 100 kHz using GPS timing (<100 ns error). The amplitude and phase of narrowband signals at specific frequencies are demodulated and recorded at 50 Hz time resolution. The VLF receiver was distributed as part of the International Heliophysical Year (IHY) and United States Basic Space Science Initiative (UNBSS) [*Scherrer et al.*, 2008]. Data from the GLD360 network [*Said et al.*, 2010] and World Wide Lightning Location Network (WWLLN) [*Dowden et al.*, 2002] provide the time and location of each lightning strike along the transmitter-receiver great circle path (GCP). Comparing the timing of observed VLF events with lightning strikes recorded in the GLD360 and WWLLN data determines the location of the lightning discharge associated with each long recovery event. Neither GLD360 (~40–60% detection efficiency, 1–4 km accuracy) nor WWLLN (few % detection efficiency, 15–20 km accuracy) are able to detect all lightning discharges, so a causative discharge location cannot always be determined.

[7] Figure 1 shows the location of the NWC transmitter, VLF receiver and the GCP. NWC to UKM signal path is part-sea-based and part-land-based, providing a single VLF link to explore occurrence characteristics of long recovery events, whereas previous observation [*Cotts and Inan*, 2007] utilized multiple VLF paths with different frequencies (28.5, 40.75 kHz NAU and 24 kHz NAA) to investigate these events. Monitoring multiple VLF transmitters for studying the recovery signatures of the lightning-associated perturbations may create ambiguities due to the different ionospheric reflection height for each of these signals. *Mika et al.* [2006] observed that the recovery durations of the VLF events identified on the 18.3 kHz signal were significantly shorter than those detected in the 24.0 and 37.5 kHz signals. Also, *Kumar et al.* [2008] reported that early/fast VLF events observed on NWC signal exhibit faster recovery rates than those detected in the 21.4 kHz NPM.

[8] Most of the VLF data presented in this study were acquired during 83 active nights in October–December 2009 and April–December 2010. A total of 403 early VLF events were detected on the NWC signal received in UKM, Malaysia, and 48 of these events exhibited a long recovery (defined here as >200 s). The events were detected by visual inspection of the recorded VLF signal. We considered a detection threshold of ~0.2 dB for amplitude and ~2 degree for phase based on typical noise levels.

[9] The characteristics of the identified long recovery events are analogous to those reported by *Cotts and Inan* [2007], possessing three different long recovery signatures. Figure 2 displays examples of each of the three types of observed long recovery events. Figure 2a presents a Long-amplitude/short-phase recovery perturbation (Type 1). The amplitude of Event A displays a negative polarity perturbation of ~2 dB followed by a long recovery signature to undisturbed level in ~22 min, whereas the phase signature recovers in ~3 min like a typical early event. The expanded record of Event A (Figure 2b) shows a high resolution view of the amplitude signal event onset which coincides with a lightning discharge in the vicinity of the GCP. Event B of Figure 2c displays a large amplitude and phase perturbation on the VLF signal followed by a long recovery to pre-event level in both the amplitude and phase (Type 2). The expanded windows in Figure 2d show the high resolution (20 ms) examination of Event B within a ±5 second interval of the event onset, as well as a 12-point median filter (red line). The second immediately following the event onset (marked by the red dashed rectangle in Figure 2d) clearly

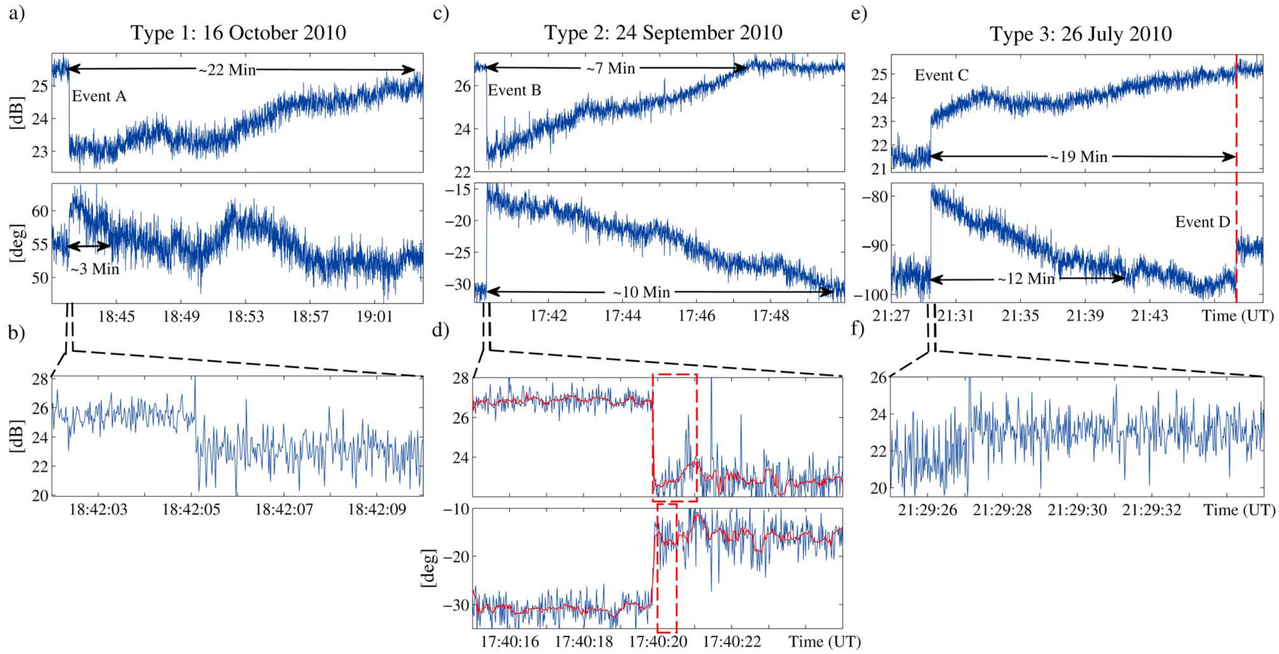

Figure 2. An example of a long recovery event of each type. (a) A type 1 long recovery event observed on 16 October 2010, referred to as Event A. (b) High resolution (20 ms) analysis of Event A. (c) A type 2 long recovery event observed on 24 September 2010, referred to as Event B. (d) An expanded view of the event onset with the initial rapid partial recovery highlighted in each plot. (e) A typical long enduring step-change event observed on 26 July 2010. There are two onset events occurring 19 min apart, these events are labeled C and D. (f) The onset of Event C.

displays an exponential rapid initial partial recovery. GLD360 and WWLLN did not record any lightning flashes precisely coinciding with this event onset, but WWLLN did detect a significant number of CG discharges near this time due to an active oceanic storm overlying the path. This suggests the approximate location of the causative discharge near the GCP. Event C of Figure 2e exhibits a lengthy step-change event (Type 3) whose amplitude perturbation does not recover to ambient levels, while the large perturbed phase signal recovers back to the ambient levels in ∼12 min. The impulsive sferic shown in Figure 2f is time-correlated with a lightning discharge recorded by WWLLN. Furthermore, occurrence of a powerful lightning discharge near the GCP produced the ∼0.2 dB and 6 degree perturbation which is labeled as Event D.

[10] Figure 3 displays histograms of amplitude and phase changes associated with all early VLF events detected on the NWC signal received at UKM. We detect amplitude and phase perturbations as high as ∼−4.4 dB and 23 degree respectively. The majority of the VLF events displayed amplitude perturbations between −1.5 and +1.5 dB and phase perturbations between −10 and +10 degrees. To estimate the size of the region affected by early and long recovery events, we measured the lateral distance of the causative lightning of all VLF events from the signal path. Figure 4a shows the locations of the lightning responsible for all detected early VLF perturbations. Figure 4b shows that the causative lightning discharges of 259 of the 355 early VLF events occur within 100 km of the GCP from the transmitter to receiver, and are thus associated with narrow-angle scattering for our geometry. This 73% rate is consistent with past studies [*Inan et al.*, 1996; *Johnson et al.*, 1999]. In the other 96 events, the causative lightning discharges were situated 100–350 km from the GCP, implying wide-angle scattering. Figure 4c and 4d show the locations and lateral distance of the lightning discharges for the long recovery events. Only 44% of the long recovery events correlate with lightning discharges within 100 km of the GCP; the lightning responsible for the other 27 long recovery events were 100–350 km from the signal path. We should also note that the causative lightning for all our observed VLF events

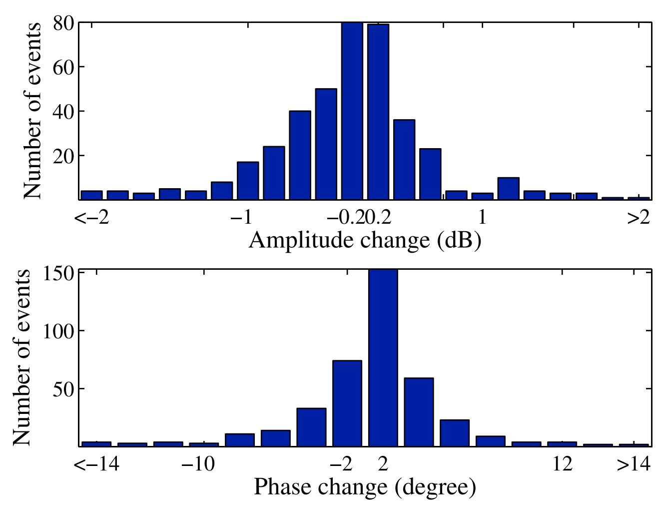

Figure 3. Histograms of the amplitude and phase perturbations associated with all early VLF events.

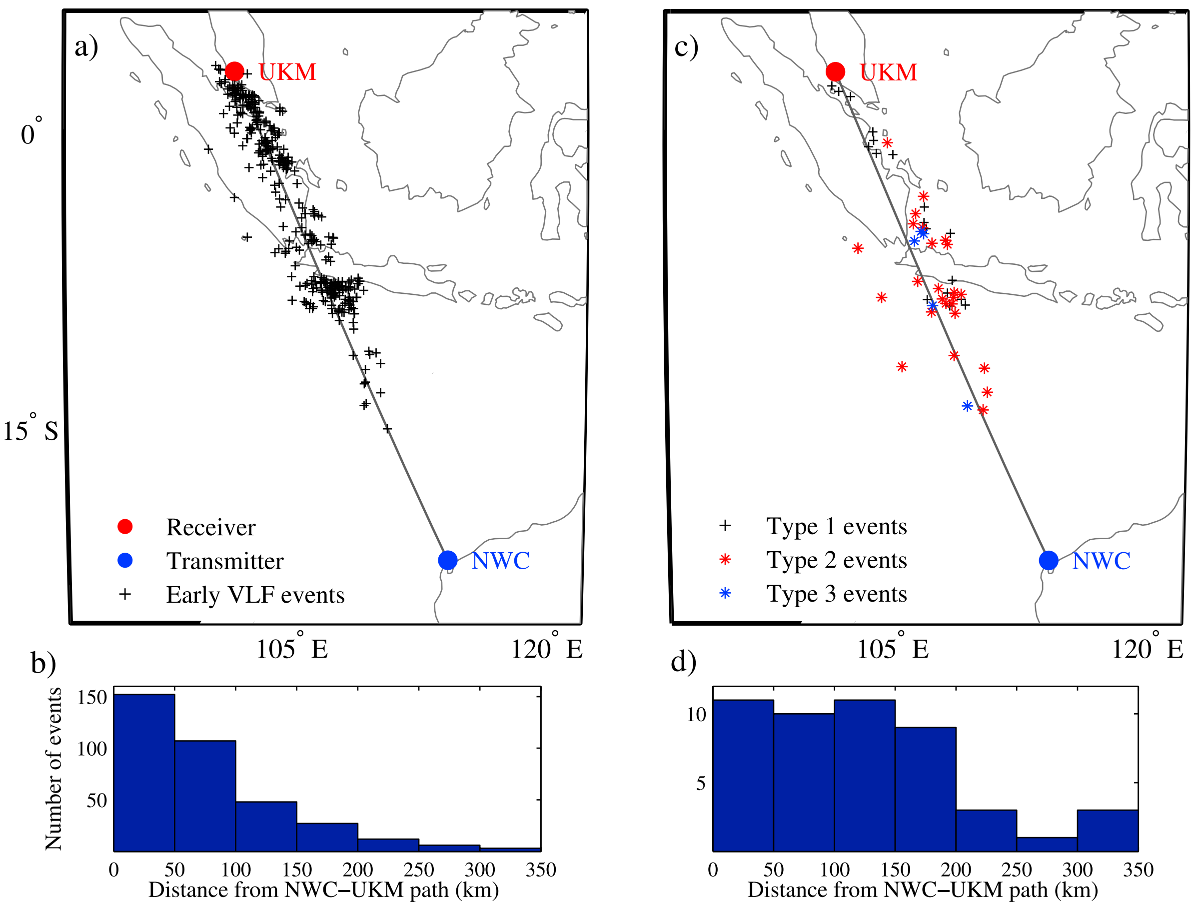

Figure 4. (a) Map shows the locations of the causative lightning discharges associated with early VLF events. (b) Distribution of the lateral distance of the causative lightning of early VLF event from the signal path. (c) Map of the lightning flashes time-correlated with the onset of long recovery events. The black crosses and red and blue asterisks indicate the location of the lightning responsible for Type 1, 2 and 3 long recovery events respectively. (d) Distribution of the lateral distance of the causative lightning of long recovery events from the GCP.

occurred within ~350 km of the GCP, which is consistent with the size of optical emissions observed during elves [*Inan et al.*, 1997].

[11] To investigate the geographic distribution of long recovery events, we divided all observed events into two subsets: land events and sea events. Since thunderstorm cells may be tens of km wide, Land events are classified as those events that occur over land and within 20 km of the coastline, otherwise the event is classified as a sea event. The causative lightning discharges of 8 events (16.7% of the total long recovery observations) were not identified. It is possible that the causative lightning discharges in these cases were simply not detected by the GLD360 and WWLLN, whose CG detection efficiencies are estimated at about 40–60% and a few percent, respectively. Even in these cases, however, the lightning detection networks located active storms overlying the path during the events. All 8 of the unidentified events coincide exclusively with oceanic storms overlying the GCP, so they were each classified as sea events. Table 1 shows the total number of early VLF events over the sea and land areas as well as the percentage of events which exhibit the recovery duration of >200, 540 and 1000 sec. An overwhelming majority (87%) of the observed >200 sec long recovery events correlate with lightning discharges located over the sea. This occurred despite the observation that lightning discharges along the signal path occur mostly over land areas rather than over the sea, with an average ratio of ~4:1. In particular, as the recovery time gets longer, the tendency for the event to be over the sea increases. The distribution of the causative lightning locations for each of these event types is presented in Table 2. Type 1 and Type 2 events were the more prevalent cases, and Type 3 events were much rarer.

3. Discussion

[12] We investigated characteristics and occurrence rates of long recovery events in association with lightning discharges. There is general agreement between our observed long recovery events and those presented by *Cotts and Inan* [2007], including three distinct recovery signatures, and a sporadic rapid (~0.5–1 s) initial partial recovery observed in some cases. The recent chemistry model of stratospheric/lower-ionospheric altitude proposed by *Lehtinen and Inan* [2007] suggests that gigantic jet discharges are able to produce early/fast perturbations on subionospheric VLF signals

Table 1. Distribution of the Lightning Located Within ∼350 km of the GCP and All Early VLF Events Observed on the NWC Signal Received in UKM, Malaysia

Lightning Location	Lightning Flashes	Total Events	Recovery $t_r < 200$ s	Recovery 200 s $\leq t_r <$ 540 s	Recovery 540 s $\leq t_r <$1000 s	Recovery $t_r \geq$ 1000 s
Sea	100144	231	53%	83%	87%	100%
Land	378351	172	47%	17%	13%	0%
Total	478495	403	355	23	15	10

with prolonged recoveries in range of $\sim 10^3$–10^4 s. They classified such long recovery signatures into two stages. The initial stage exhibits a fast recovery which endures for a few seconds due to the attachment detachment of electrons as illustrated in red dashed rectangular in Figure 2d. This initial stage, however, may not be observable in VLF data (e.g., Figure 2b) due to the high electric field induced by gigantic blue jets [*Lehtinen and Inan*, 2007]. This initial rapid recovery is followed by a lengthy recovery stage produced by the process of the mutual neutralization of negative and positive ions at lower altitudes (<50 km) which can persist for tens of minutes.

[13] The causative lightning of long recovery events were located on the average at larger distances from the GCP relative to the distances of typical early VLF events. Results of Figure 4a and 4b indicate that the majority of early VLF event-associated lightning are located near the signal path, whereas Figure 4c and 4d clearly show that long recovery early VLF events do not follow this distribution. We should also note that this larger scattering pattern observed in long recovery events may imply different physical mechanism or origin.

[14] The causative lightning of all VLF events are separated into land and sea subsets, as presented in Tables 1 and 2, due to the strong discrepancy in sea/land lightning occurrence rates and properties. This strong discrepancy is based on a substantial difference in sea/land thermal characteristics. During daytime, land surface temperature becomes higher than oceans, producing stronger updraft intensity, and this lead to dominance of lightning flash rate density over land areas [*Williams and Stanfill*, 2002; *Williams et al.*, 2004]. However, the average peak current of oceanic CG lightning appears to be stronger than their land counterpart due to the higher conductivity of the oceanic salt water relative to land surface [*Seity et al.*, 2000; *Füllekrug et al.*, 2002]. *Chen et al.* [2008] observed that lightning discharges with peak current higher than 80 kA occur 10 times more prevalent over the sea than land; whereas lightning flash rates in average is 10 times lower over the sea than over land areas [*Christian et al.*, 2003]. Also, we should note that lightning activity in general along the GCP from the NWC transmitter to the receiver, was much more prevalent over land areas than over the sea, according to the GLD360 and WWLLN measurements. By analysis of the geographical distributions of the 48 long recovery events, we have determined that 42 events occurred over the sea while only 6 events occurred over land and within ∼20 km of the coastline. However, the collection of 403 early VLF events in general does not exhibit this trend. Since the ground conductivity does not affect the recovery signature of the early VLF event, the connection between the sea/land location and the recovery is likely a function of the type of lightning event that triggers the ionospheric disturbance, one that is more prevalent over water.

[15] Gigantic jets have been classified into three different types based on their morphological evolution and spectral properties [*Chou et al.*, 2010]. *van der Velde et al.* [2010] reported the first correlation between a positive polarity type 3 gigantic jet initiation and a −2 dB amplitude perturbation observed on narrowband VLF signal monitored at Stanford-AWESOME network in Tunisia. Unfortunately, the occurrence of a sprite triggered by a powerful +CG lightning right after the event onset disturbed the recovery signature and produced another −2 dB perturbation. The low occurrence rate of gigantic jets is the main difficulty in establishing the correlation between different types of long recovery events and gigantic jets. Therefore, to investigate the feasible relation between gigantic jets and long recovery events, we compare the statistical results of Table 1 with the occurrence rates of gigantic jets from past works. *Chen et al.* [2008] reported 13 gigantic jets recorded by ISUAL during a three year survey, with 69% observed over sea and 30% over land and coastal areas. Also, *Su et al.* [2002, 2003] reported observations of TLEs around Taiwan using ground campaigns in 2002 and 2003. The authors indicated that all gigantic jets (6 events) were attributed to oceanic storms. Since *Lehtinen and Inan* [2007] postulated recovery durations of $\sim 10^3$–10^4 s for early VLF events associated with gigantic jets, we compare this gigantic jet distribution to the distribution of our observed events with recovery duration ≥1000 s. Long recovery events with duration of ≥1000 s occur exclusively over the sea. This geographic distribution indicates that unusually long recovery events are associated predominantly with oceanic thunderstorm activities which lend support to the suggestion that long recovery VLF events may be consistent with the occurrence of gigantic jets.

4. Conclusion

[16] We presented characteristics and the occurrence properties of long recovery VLF perturbations in association with lightning discharges. The long enduring recoveries observed in certain early VLF events can be attributed to the lengthy process of the mutual neutralization of negative and positive ions at altitudes below 50 km which persist up to

Table 2. Distribution of Each of the Three Long Recovery Event Types Associated With Lightning Flashes Over the Sea, Coast, and Land[a]

Lightning Location	Type 1	Type 2	Type 3
Sea	12	25	5
Land	6	0	0
Total	18	25	5

[a]Type 1 exhibits long recovery in amplitude only, type 2 exhibits long recovery in amplitude and phase, and type 3 exhibits indefinitely long recovery.

20 min, consistent with theoretical prediction of *Lehtinen and Inan* [2007]. The recovery signatures of 12 events exhibit a rapid initial partial recovery lasting for ~0.5 to a few seconds, which is the behavior to be expected due to attachment of electrons generated by gigantic jet discharges as postulated by *Lehtinen and Inan* [2007]. The vast majority of the long recovery events are attributed to lightning discharges located over the water, similar to the occurrence of gigantic jets observed by *Su et al.* [2003] and *Chen et al.* [2008]. However, more experimental research needs to be conducted to certify the possible correlation between different types of long recovery events and gigantic jets.

[17] Analysis of the causative lightning of long recovery and early VLF events indicates that lightning associated specifically with long recovery events is more likely to be located at larger distances from the signal path. This suggests a larger and/or denser ionospheric modification which speculates a distinct physical nature involved in this subset of events. We also note that, as the recovery time gets longer, the tendency for the event to be over the sea increases, and early VLF events with unusually prolonged recoveries (≥1000 s) are exclusively observed in association with oceanic thunderstorm activity.

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