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**Paper**

# Deducing Locations and Charge Moment Changes of Lightning Discharges by ELF Network Observations in Japan

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The electromagnetic radiations from lightning discharges have been intensively studied for a long time in different frequency ranges. Recent observations of electromagnetic radiations from lightning in the ELF (extremely low frequency) frequency range so-called ELF transients are recognized as a powerful tool to obtain one of the most important properties of lightning discharges; the charge moment changes ($Qds$). In this paper we demonstrate the spatio-temporal distributions of lightning discharges together with their charge moment change (CMC) around Japan by using our newly developed domestic ELF observation network. This is the first time to obtain such type of distribution by using only ELF observations in the spatial scale of Japan (a few thousands km). We found that the obtained lightning source distributions both over the Pacific Ocean and the Sea of Japan are originated from the thunderstorm active regions confirmed by other measurements such as WWLLN. Statistical properties of the charge moment changes indicate that both number and CMC of positive CGs are superior to those of negative CGs. Moreover considerably large CMC with both polarities are identified for the CGs over the Pacific Ocean as well as those with positive polarity over the Sea of Japan.

**Keywords:** ELF transient, charge moment change, red sprite, thunderstorm activity

## 1. Introduction

Wide-band electromagnetic waves are generated in association with cloud to ground flashes (CGFs) in the troposphere. Among them, powerful transient radiations from intensive CGFs in the Extremely Low Frequency (ELF) range can propagate over significantly long distances (~ up to 10 Mm) in the Earth-ionosphere waveguide (EIWG) due to rather small attenuation and are observed globally as ELF transients [(1)].

One of the most important electrical properties of lightning flashes obtained from the ELF transient is a vertical charge moment change (CMC) in contrast to the peak current ($I$p), the property obtained from the conventional lightning detection network.

Recent applications of ELF transient observations include the global distribution of energetic lightning exciting the so-called ELF transient or Q-burst [(2)(3)] by a single locating technique using the multi-component measurement [(4)–(7)]. Since lightning discharges with large CMC are recognized as a proxy of transient luminous events (TLEs) such as red sprites [(5)(8)(9)], red sprites have been observed frequently in the Hokuriku area where many lightning flashes with a large amount of charge are expected during the winter thunderstorm activity [(10)–(12)]. Moreover the strong perturbation at the bottom of ionosphere (D/E regions) are observed by receiving VLF/LF transmitter singals over sprite producing thunderstorms indicative of the electro-dynamic coupling between the tropospheric lightning and overlaying ionosphere [(11)].

Despite the usefulness of ELF measurement in the sense of CMC estimation from a remote site, due to relatively large locating error expected from the single locating method (typically ~ few hundreds km), no detailed spatial distribution of CGFs with CMC around Japan has been obtained. Moreover, meteorological conditions for winter and summer thunderstorm activities in relation with TLEs have not been understood well [(13)].

We have set up a new ELF observation station in Kagoshima Japan in addition to the existing station in Moshiri Hokkaido, Japan to establish the network observations of ELF transients and to deduce the detailed spatio-temporal lightning distribution with CMC around Japan and Asian region. This is the first attempt to use an ELF network observation with separation distance of few thousands km scale applied to a rather small area to deduce more precise determination both of location and $Qds$ of lightning discharges in comparison to the previous works for world-wide detection of very energetic lightning but rather large locating error (~500 km) [(5)–(7)].

In this paper we demonstrate the capability of the energetic lightning properties around Japan such as temporal and

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regional dependences (over Pacific Ocean and the Sea of Japan) from our initial results. In future we are going to use lightning information with CMC for natural disaster monitoring and mitigation due to severe weather, and also provide useful information promoting renewable energy power plant such as wind farm and solar power because serious damage of the facilities is expected from the lightning with rather large CMC [14]. Furthermore providing the intensive lightning locations with CMC information is very useful for the several new spacecraft missions to monitor TLE with intensive lightning discharges from the space by Japanese ISS (International Space Station) GLIMS [15] and French micro-satellite TARANIS [16].

## 2. Charge Moment Change Estimation (CMC)

Electromagnetic emissions in the ELF range from a CGF propagates in the EIWG as a QTEM mode consisting of the vertical electric field and horizontal magnetic field components are well described by the following equations [1][17].

$$E_z = i\frac{I(f)ds\,\nu(\nu+1)P_\nu^0(-\cos\theta)}{4a^2c_o 2\pi f h\sin(\pi\nu)} \quad [\mathrm{Vm^{-1}Hz^{-1}}]$$

$$H_\varphi = -\frac{I(f)ds\,P_\nu^1(-\cos\theta)}{4ah\sin(\pi\nu)} \quad [\mathrm{Am^{-1}Hz^{-1}}]$$

$I(f)ds$ is the current moment, $P_\nu^{0,1}$ are associated Legendre functions with complex subscripts $\nu$ representing propagation constant, $h$ is the thickness of the waveguide, $\varepsilon_0$ is the dielectric constant of free space, and $a$ is the Earth radius. The angle $\theta$ is the great circle angular distance between the lightning source and receiving field site.

Given the calibrated frequency spectra for either the vertical electric field component or horizontal magnetic field component, one can derive the source current moment $I(f)ds$ by using one of above-mentioned equations. Since the characteristic duration of most lightning discharges is smaller than the propagation time of the round the world, $I(f)ds$ is simplified to the vertical charge moment change $Qds$ (C·km).

## 3. ELF Transient Observation

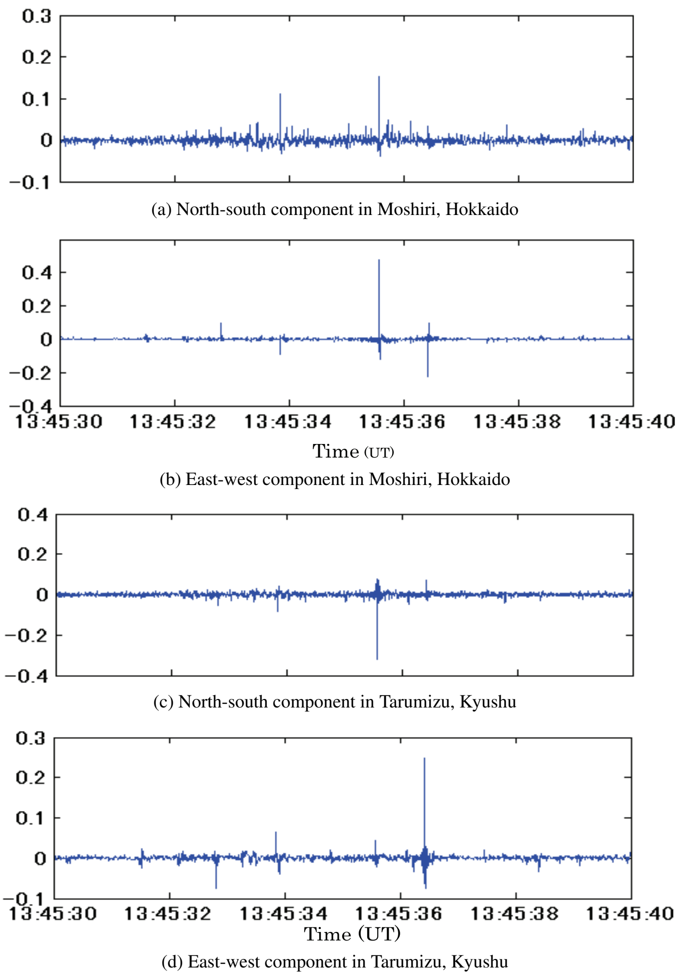
A new ELF field site was installed by the University of Electro-Communications (UEC) and is located in Tarumizu (TRU), Kagoshima (geographic coordinates: 44.37°N, 142.26°E) in the territory of Solar Terrestrial Environment Laboratory (STE) of Nagoya University. The two horizontal magnetic waveforms are continuously recorded by a pair of induction coils with a sampling rate of 4 kHz and upper cutoff frequency of 1 kHz.

The similar system with the same sampling frequency and bandwidth was installed in Moshiri (MSR), Hokkaido and has been operated by UEC since 1996 [9][18]. This existing system was located in the STE Laboratory, Moshiri observatory. In MSR, the vertical electric field observed in addition to the two horizontal magnetic field components enables us to determine the unique arrival direction of transient waves. Above-mentioned waveforms are GPS time stamped and are able to be compared with each other in the absolute time coordinate system.

## 4. Observational Results

**4.1 Case Study** ELF transient waveforms observed in the distant field site were processed as follows. First, the power line radiation and its harmonics were removed by a digital filtering technique. Second, transient signals are identified by imposing the threshold value such as 10 times of the standard deviation of the total field intensity. Third, the transient events from the same lightning source are identified both by occurrence time and arrival direction calculated by a goniometric method by using 2 magnetic field components. Fourth, the lightning source locations are obtained by a conventional triangulation technique, and corresponding CMCs and discharge polarities are calculated.

Figures 1(a)–(d) demonstrate an example of typical ELF time series originated from lightning discharges around Japan. Figures 1(a) and (b) indicate the magnetic waveforms for two horizontal components at MSR, while Figures 1(c) and (d) indicate the same format as Figures 1(a) and (b) but for TRU. As is seen from the figures, an ELF transient from the same lightning discharge is clearly identifiable at two stations around the time of 13:45:35.5 (UT) on March 9, 2011. The difference in amplitude between the two orthogonal magnetic components at each station suggests the arrival direction of the ELF radiation (i.e. lightning source direction).



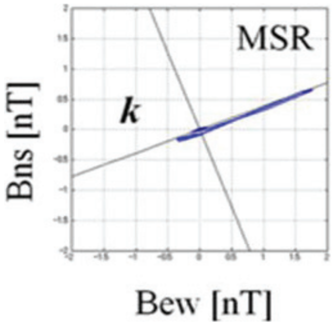

(a) North-south component in Moshiri, Hokkaido

(b) East-west component in Moshiri, Hokkaido

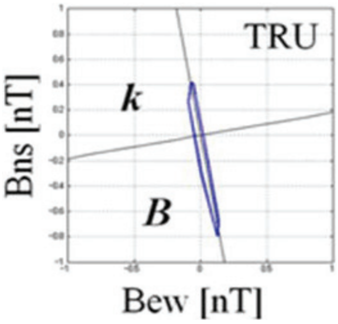
(c) North-south component in Tarumizu, Kyushu

(d) East-west component in Tarumizu, Kyushu

Fig. 1. Horizontal magnetic waveforms in ELF range observed at two separated field sites




(a) MSR




(b) TRU

Fig. 2. Magnetic hodograms of ELF transients originated from the same lightning source

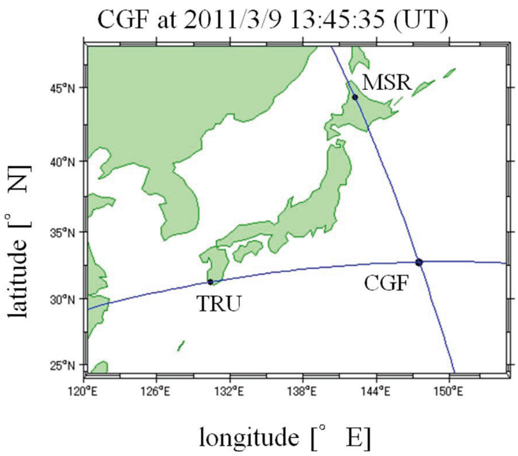



Fig. 3. Locating CGF source by using an ELF transient simultaneously observed at MSR and TRU

Figures 2(a) and (b) show the magnetic hodograms of ELF transients simultaneously observed in the two field sites, MSR and TRU. As is seen from Fig. 2, both of the hodograms indicate almost linear polarization, so that the conventional goniometric technique is applicable to obtain the wave normal direction $\boldsymbol{k}$ (i.e. direction of the wave propagation). It is found that the ELF transient arrives from the South-East at MSR, whilst the transient from the same lightning arrives from the East at TRU.

Figure 3 demonstrates the location of the CGF obtained from the triangulation technique based on two arrival directions in Fig. 2. The determined CGF position is found to be over the Pacific Ocean in the geographical coordinate system of 32.5°N and 147.7°E. Corresponding calculated CMC is −396 C·km (negative CGF).

Figure 4 illustrates the image from the meteorological satellite around the occurrence time of the observed ELF transient in Fig. 3 (14 UT on March 9, 2011). Since the developed cloud system corresponding to the low pressure is identified over the Pacific Ocean around the calculated onset location of the ELF transient source, the identified ELF source is from the lightning discharge from the thunderstorm activity.

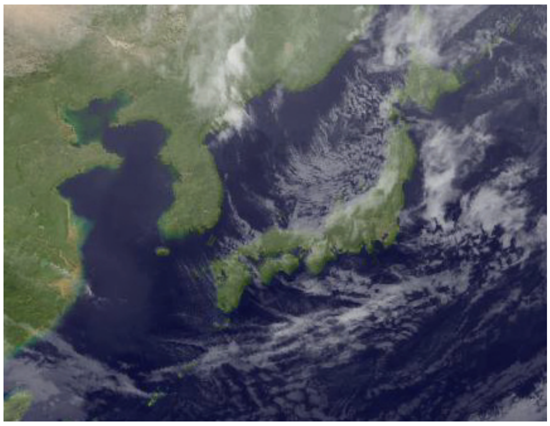
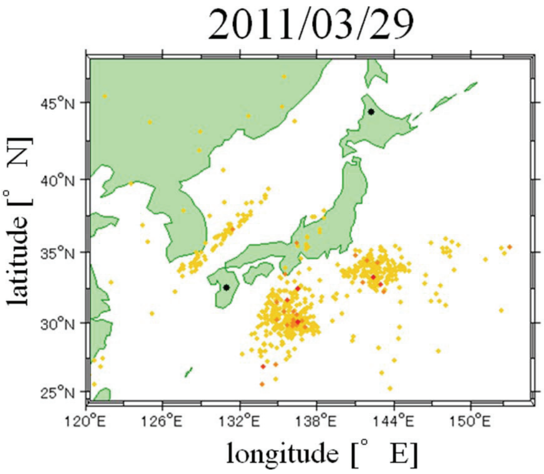
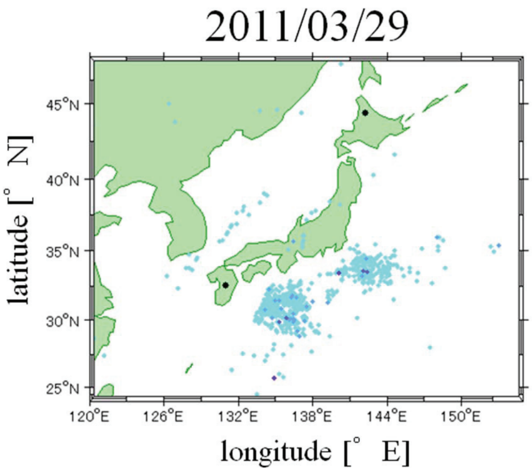


Fig. 4. Weather satellite (HIMAWARI) image over Japan at 14 UT on March 9, 2011 around the timing of ELF transient reception at two Japanese field sites




(a) Positive CGF




(b) Negative CG

Fig. 5. CGF distributions with CMC calculated from ELF transients

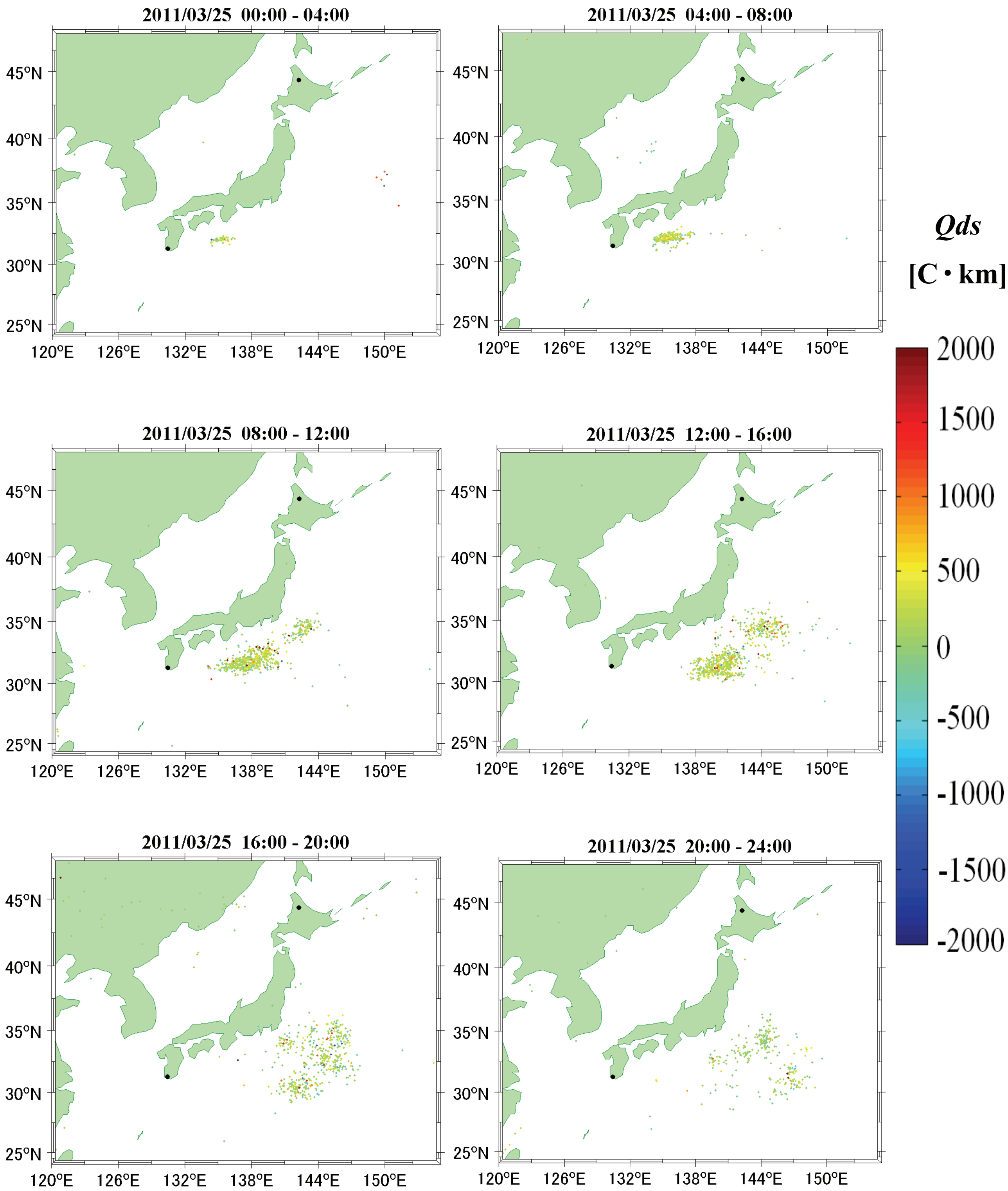
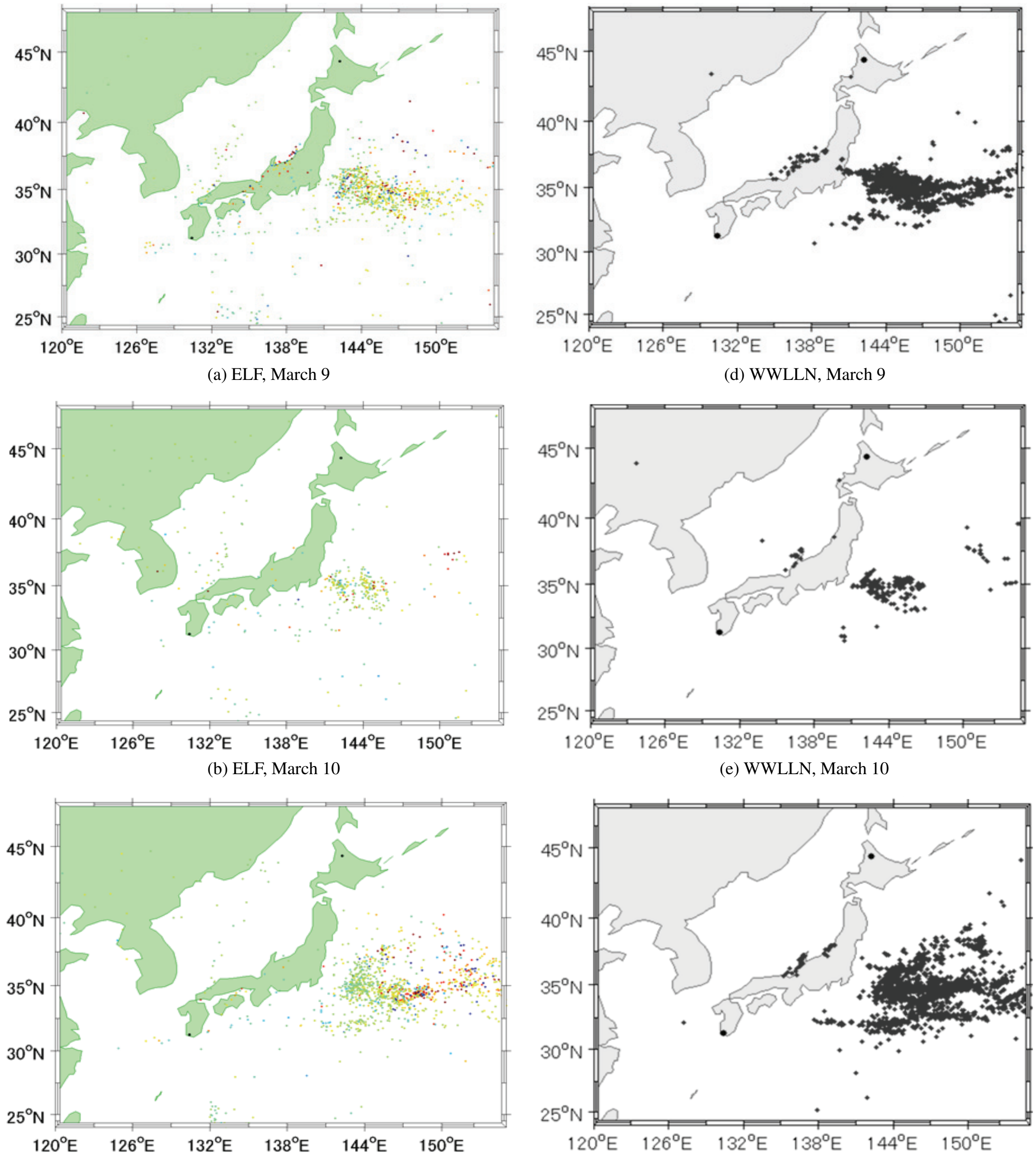



Fig. 6. Temporal dependence of the CG locations estimated by ELF network measurement on March 25, 2011

### 4.2 Spatial Distributions of CGF with Qds

Figures 5(a) and (b) show the spatial distributions of CGFs on March 25, 2011 for the positive and negative CGFs respectively. The color of each dot (individual CGF) stands for the amount of CMC with its polarity. As is seen from the figure, two active thunderstorm centers are clearly identified over the Pacific Ocean by our ELF network observations. Both positive and negative flashes have similar spatial distributions. Another typical thunderstorm center is located over the Sea of Japan in March (not shown).

Temporal migration of the ELF transient sources (i.e. lightning discharges with an intensive energy in ELF range) over the day of March 25, 2011 is shown in Fig. 6. Each picture indicates the lightning locations for a four-hour time interval. The color of each lightning discharge corresponds to the amount of CMC with a polarity indicated in the bar graph




(a) ELF, March 9
(d) WWLLN, March 9
(b) ELF, March 10
(e) WWLLN, March 10
(c) ELF, March 11
(f) WWLLN, March 11

Fig. 7. Comparison of daily spatial CG distribution by ELF network measurements with those from WWLLN on three consecutive days

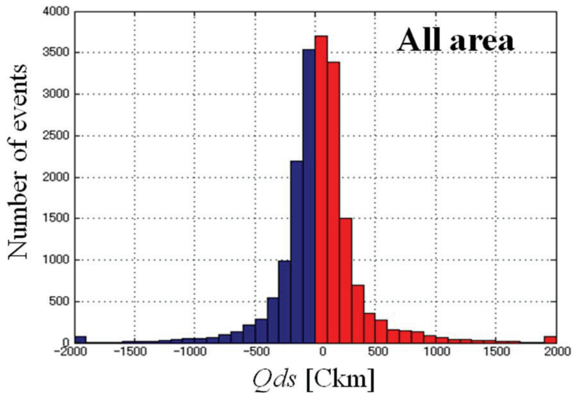
on the right hand side of figures. As seen from the figures, the lightning activity started in the local morning (0–4 UT) off the coast of Shikoku with small amount of CMC values (Qds < 500 C·km). Then the storm developed and reached the mature stage (4–20 UT). The number of lightning flashes reached a maximum and intensive lightning flashes with very large CMC (> 1000 C·km) are identifiable for both polarities (dark red and blue for very energetic positive and negative flashes). These events are energetic enough to excite TLEs such as red sprites. Among these energetic events, positive events tend to surpass in number than negative events, which is described in detail in the next section. During the course of thunderstorm development, the active thunderstorm area migrated toward the east and was separated by several areas (8–20 UT). Finally in the dawn to the morning, the thunderstorm activity decayed.

Figure 7 shows the spatial distributions of estimated CGs by ELF observations and corresponding distributions obtained from VLF network measurement by WWLLN (World Wide Lightning Location Network) for three different storm days. Since WWLLN provides only the information of onset location of VLF sources (CGs) but with rather high spatial pointing accuracy (~ a few km), we can compare the locating accuracy of our ELF measurement.

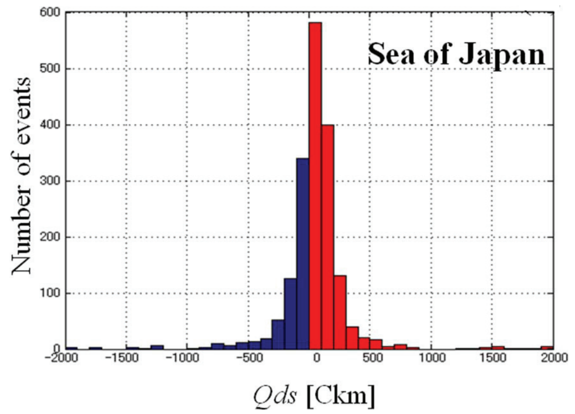
As seen from the figures, active thunderstorms over Pacific areas obtained by WWLLN are in rather good agreement with those from ELF sources from our network measurement, which indicates that our ELF measurement properly tracks the lightning discharges from active thunderstorms in this region. Although lightning activities around the coast of Sea of Japan (Hokuriku) were identified for three days by WWLLN, the ELF network observed lightning only on March 9. This discrepancy between the two measurements can be due to the increase of the local background noise in particular at TRU station during the lightning activity leading to the smaller reception of the triggered events (local time of thunderstorm activities between the Pacific and Sea of Japan is different in general).

## 5. Statistical Properties

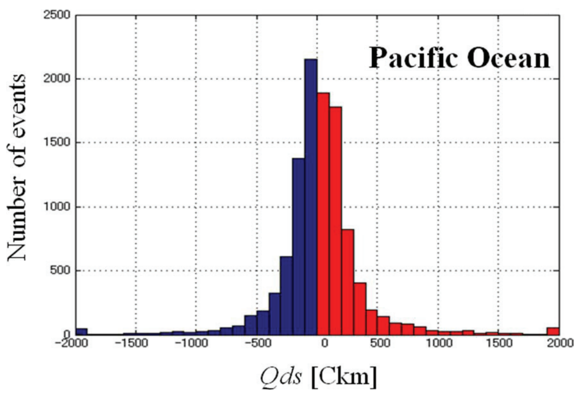
Figures 8(a) to (c) show the histograms indicating the regional dependence of the CMC, and Table 1 summarizes the number of these CMC distributions. As is seen from Fig. 8(a), the number of lightning events monotonically decreases with increasing CMC for both polarities but the total number detected by ELF transients for positive CGFs is larger than that for negatives. One of the most remarkable findings in this paper is that the median value of the CMC from Pacific CGFs is considerably larger than that of the Sea of Japan for both polarities (Table 1) because CMC values over the Pacific Ocean have not been obtained before despite the fact that active thunderstorms are identified both by ground and satellite measurements in this region during winter. The number of positive GCFs is much larger than negatives over the Sea of Japan indicating typical the nature of winter thunderstorm activity in the region of Hokuriku, whilst the number of positives and negatives are comparable for CGFs over the Pacific Ocean (Figs. 8(b) and (c), and Table 1). The difference in CMC between two regions can be due to the different meteorological conditions of thunderstorm activities (Pacific Ocean and Sea of Japan) during the early spring season. Physical mechanisms of these differences will be investigated in detail.



(a) All regions



(b) Over the Sea of Japan



(c) Over the Pacific Ocean

Fig. 8. Histograms indicating the number of CGF events as a function of CMC

Table 1. Summary table of median CMC (C·km) for different polarity and location

| | Negative CGF | Positive CGF | Ratio(Pos./Neg.) | |
|---|---|---|---|---|
| | | | Number | Qds |
| All | 123 | 140 | 1.28 | 1.1 |
| Sea of Japan | 82 | 102 | 2.22 | 1.2 |
| Pacific Ocean | 131 | 156 | 1.15 | 1.2 |

## 6. Summary

Spatio-temporal dependences of lightning locations and associated electric charge moment changes around Japan are successfully derived by using our ELF observation network. Major findings from the initial results obtained in the data during March 2011 are summarized as follows:

(1) Most thunderstorm activities are identified over the Pacific Ocean and the Sea of Japan.

(2) Mean CMC for positive flashes is much greater than that for negatives flashes.

(3) Large numbers of positive flashes are observed over the Sea of Japan

(4) CGFs with larger CMC are predominant over the Pacific Ocean

(5) Spatial distributions of the lightning derived by ELF observations are in rather good agreement with those from VLF network measurement provided by WWLLN.

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## References


( 1 ) A.P. Nickolaenko and M. Hayakawa: Resonances in the Earth-Ionosphere Cavity, p.380, Kluwer Acad. Pub., Dordrecht (2002)

( 2 ) T. Ogawa, T. Miura, Y. Tanaka, and M. Yasuhara: "Observations of natural ELF and VLF electromagnetic noises by using ball antennas", *J. Geomag. Geoelectr.*, Vol.18, p.443 (1966)

( 3 ) A.P. Nickolaenko, M. Hayakawa, and Y. Hobara: "Q-bursts: Natural ELF radio transients", *Survey Geophys.*, Vol.31, pp.409–425, DOI 10.1007/s10712-0010-9096-9 (2010)

( 4 ) K. Yamashita, T. Otsuyama, Y. Hobara, M. Sekiguchi, Y. Matsudo, M. Hayakawa, and V. Korepanov: "Global distribution and characteristics of intense lightning discharges as deduced from ELF transients observed at Moshiri (Japan)", *J. Atmos. Electr.*, Vol.29, pp.71–80 (2009)

( 5 ) E. Huang, E. Williams, R. Boldi, S. Heckman, W. Lyons, M. Taylor, T. Nelson, and C. Wong: "Criteria for sprites and elves based on Schumann resonance observations", *J. Geophys. Res.*, Vol.104(D14), pp.16,943–16,964, doi:10.1029/1999JD900139 (1999)

( 6 ) Y. Hobara, M. Hayakawa, E. Williams, R. Boldi, and E. Downes: "Location and electrical properties of sprite-producing lightning from a single ELF site", Sprites, Elves and Intensive Lightning Discharges, M. Fullekrug, et al., Ed., pp.211–229, Springer, New York (2006)

( 7 ) T. Nakamura, M. Sekiguchi, Y. Hobara, and M. Hayakawa: "A comparison of different source location methods for ELF transients by using the parent lightning discharges with known positions", *J. Geophys. Res.*, Vol.115, A00E39, doi:10.1029/2009JA014992 (2010)

( 8 ) S.A. Cummer and U.S. Inan: "Measurement of charge transfer in sprite-producing lightning using ELF radio atmospherics", *Geophys. Res. Lett.*, Vol.24, pp.1731–1734 (1997)

( 9 ) Y. Hobara, N. Iwasaki, T. Hayashida, M. Hayakawa, K. Ohta, and H. Fukunishi: "Interrelation between ELF transients and ionospheric disturbances in association with sprites and elves", *Geophys. Res. Lett.*, Vol.28, pp.935–938 (2001)

(10) M. Brook, M. Nakano, P. Krehbiel, and T. Takeuti: "The electrical structure of the Hokuriku winter thunderstorms", *J. Geophys. Res.*, Vol.87, pp.1207–1215 (1982)

(11) K. Nakahori, T. Egawa, and H. Mitani: "Characteristics of winter lightning currents in Hokuriku district", *IEEE Trans. Power Appar.* & *Syst.*, Vol.PAS-101, No.11, pp.4407–4411 (1982)

(12) M. Hayakawa, T. Nakamura, T. Hobara, and E. Williams: "Observation of sprites over the Sea of Japan and conditions for lightning-induced sprites in winter", *J. Geophys. Res.*, Vol.109(A0): doi:10. 1029/2003JA009905 (2004)

(13) Y. Hobara, M. Hayakawa, and T. Suzuki: "Lightning effects in the ionosphere/magnetosphere", in Lightning Electromagnetics, V. Cooray, Ed., Chapter 17, pp.647–685, Inst. Engineering and Technology (2012)

(14) S. Yokoyama, A. Wada, A.A.sakawa and T. Shindo: "Study on Lightning Outage Mechanism of Wind Turbine Blades and Evaluation of Lightning Protection Methods for Them", CRIEPI Report, No.H06018

(15) T. Ushio M. Sato, T. Morimoto, M. Suzuki, H. Kikuchi, A. Yamazaki Y. Takahashi, Y. Hobara, U. Inan, I. Linscott, Y. Sakamoto, R. Ishida, M. Kikuchi, K. Yoshida, and Z. Kawasaki: "Lightning and Sprite Observation from International Space Station", *IEEJ Trans. FM*, Vol.131, pp.16–20 (2011)

(16) E. Blanc, F. Lefeuvre, R. Roussel-Dupre', and J.A. Sauvaud: "TARANIS: A microsatellite project dedicated to the study of impulsive transfers of energy between the Earth atmosphere, the ionosphere, and the magnetosphere", *aisr*, Vol.40, pp.1268–1275 (2007)

(17) J.R. Wait: Electromagnetic Waves in Stratified Media, IEEE Press, Piscataway, N.J. (1996)

(18) Y. Hobara, N. Iwasaki, T. Hayashida, N. Tsuchiya, E.R. Williams, M. Sera, Y. Ikegami, and M. Hayakawa: "New ELF observation site in Moshiri, Hokkaido Japan, and the results of preliminary data analysis", *J. Atmos. Electr.*, Vol.20, pp.99–109 (2000)


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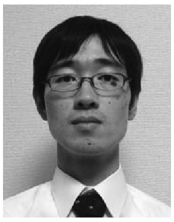

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