Initial effect of the Fukushima Accident on atmospheric electricity

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Abstract

Vertical atmospheric DC electric field at ground level, or potential gradient (PG), suddenly dropped by one order of magnitude at Kakioka, 150 km southwest from the Fukushima Dai-ichi nuclear power plant (FNPP) right after the plant released a massive amount of radioactive material southward on 14 March, 2011. The PG stayed at this level for days with very small daily variations. Such a long-lasting near-steady low PG has never been observed at Kakioka. The sudden drop of PG with one-hour time scale is similar to those associated with rain-induced radioactive fallout after nuclear tests and the Chernobyl disaster. A comparison with the PG data with the radiation dose rate data at different places revealed that arrival of the radioactive dust by low-altitude wind caused the PG drop without rain. Furthermore, the PG might have reflected a minor release several hours before this release at the distance of 150 km. It is recommended that all nuclear power plant to have a network of PG observation surrounding the plant.

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1. Introduction

The accident at the Fukushima Dai-ichi nuclear power plant (FNPP) triggered by Tohoku Earthquake on 11 March 2011 caused several different types of massive release of radioactive materials to the atmosphere (10^{17} Bq for ^{131}I and 10^{16} Bq for ^{137}Cs [NISA, 2011]), and some releases are expected to continue for some time. A risk remains for another explosive release with unexpected reasons until the reactor cools down in a few years' time. It is urgent to establish a monitoring system of the release and transport of the radioactive materials. A remote sensing method is particularly needed because of the possibility of power failure in the local measurement site. We here show how we can use the ionizing effect of radioactive materials.

A large-scale DC electric current is flowing between the ground and the ionosphere in a global scale, upward in narrow generator regions covered by electrified thunderstorm/shower clouds (lightnings add AC component), and downward in wide fair-weather regions (e.g., reviews by Rycroft et al. [2000, 2008]; Williams [2009]). This is called the global (electric) circuit. The downward current is strongly modified by electrified clouds. Since both the ionosphere and the ground are highly electrically conductive compared to the atmosphere, the current generates a relatively vertical electric field in the atmosphere except near electrified clouds. The vertical component of the electric field, or potential gradient (PG), is about 100-150 V/m at ground level.

The atmospheric electric conductivity is controlled by the ionization rate and loss rate, obeying the ion balance equation [Rosen and Hofmann, 1981; Makino and Ogawa, 1985; Rycroft et al., 2008]. The electrical conductivity of the atmosphere is low and it is sensitive to small changes in the ionization rate such as those caused by cosmic ray and radon variations.. Therefore, the PG is expected to drop if a substantial amount of ionizing radioactive materials is released that is massive enough to increase the radiation dose rate compared to natural radiation.

Such a PG drop was actually observed shortly after rain-induced radioactive fallout (i.e., wet contamination) related to nuclear tests [e.g., Harris, 1955] or Chernobyl disaster

[Israelsson and Knudsen, 1986; Tuomi, 1988, 1989] at a distance of more than 1000 km in the latter case. In these cases, the PG dropped by one order of magnitude within one to few hours. Simultaneously, atmospheric electric conductivity increased by one order of magnitude. The accumulated radioactive materials after frequent nuclear tests during 1950's to 1960's was large enough to explain the drop of annual average of the PG even at great distances [Pierce, 1959; Hamilton and Paren, 1967]. The PG decreases were observed world-wide during 1950's to 1960's [Kondo, 1959; Pierce, 1972; Harrison, 2003; Harrison and Ingram, 2005].

In both the Chernobyl case and nuclear test cases, the radioactive dust was transported to the stratosphere and upper troposphere, and settled to the ground by rain. However, the transport can be in the lower part of the troposphere for short distance, and this occurred with the Fukushima accident. Pierce [1959] showed that radioactive materials that was leaked and transported by surface wind from Windscale nuclear plant caused >50% drop of the PG at about 100 km downwind during 1952-1957. Unfortunately, no PG measurement was reported that shows the moment of the arrival of the radioactive dust by the surface wind. We have no knowledge on the time scale of the PG drop by the wind-carried radioactive dust without rain (i.e., dry contamination).

After the Fukushima accident, Kakioka 150 km southwest of FNPP recorded a sudden drop of PG by one order of magnitude on 14 March 2011, three days after the M9.1 Earthquake. Unlike the Chernobyl case, the PG dropped without rain (it did not fall until late 15 March), with a time scale of less than an hour. We show this drastic change using 1-min averaged PG data (the reported PG data that detected the Chernobyl effect is 1 hour resolution without data during night time). Unfortunately, the electric conductivity was not measured.

2. Observation

Figure 1 shows 1-hour averaged PG at Kakioka during two months including the M9.0 earthquake at 0546 UT, 11 March 2011. The sensor uses the water-dropper collector, and is placed at 2.55 m high with 1.17 m separation from the wall inside a house

[Shigeno, et al., 2001]. The data sampling rate is 1 Hz. The earthquake caused power failure for about three days. The geographical location of Kakioka is shown in Figure 2.

Fig 1

Fig 2

Before the earthquake, Kakioka's PG was about 40-100 V/m with large daily variation including the weekends except rainy days (6, 8, 10-12, 14, 17, 27-28 Feb, 1, 6-7, 9 March). The value of 40-100 V/m is normal fair-weather value after year 2000, which is 50% smaller than the value during 1970's to 1990's for unknown reasons because the instrument setting was the same. Kakioka's PG values were still normal for that site even after the earthquake when the power was recovered at around 06 UT, 14 March. However, the PG dropped to about near-zero value at 21 UT on the same day, and stayed at low values without daily variation during entire 15 March. After a short recovery on 16 March, the PG settled to 0-20 V/m with minor daily variations during the rest of the month unless rain cloud covered (15, 20-22, 25-26, 30 March). The PG normally shows smooth diurnal variation under clear sky [Kondo, 1963; Harrison, 2003; Tuomi, 1989], but the observed low and rather stable PG pattern with very weak daily variation has never been observed at Kakioka during 21st century after data was digitized.

The sudden drop of the PG and its daily variation at Kakioka is similar to those observed at Helsinki in Finland and Uppsala in Sweden after the Chernobyl disaster [Israelsson and Knudsen, 1986; Tuomi, 1988, 1989] or at Tucson in Arizona, USA after the Nevada nuclear tests [Harris, 1955]. The drops at these times were by one order of magnitude and are attributed to extra ionization of atmospheric molecules by the ionizing radiation that is emitted from the radioactive fallout. In fact, the observed atmospheric conductivities at these places increased by one order of magnitude after the first rain after the radioactive cloud arrived over the sky. Since the unusual PG values at Kakioka started on 14 March 2011 right after the FNPP accident, it is most likely related to the radioactive dust cloud from the FNPP.

Fig 3

To examine this, two-days data of Kakioka's PG (1-min average), its standard deviation, and the radiation dose rates at stations between Kakioka and FNPP (10-min resolution) are shown in Figure 3. Incidents at the FNPP during this period are also noted with green labels. The geography of all these stations is shown in Figure 2. The increase of the radiation dose rate on 14 March is the largest southbound release of the radioactive materials from the FNPP during March 2011. The drop of PG on 14 March took place during 16:30-21:00 UT and is about the same time when the radiation dose rates of the entire area increased.

The weather at Kakioka was cloudy with a constant humidity from 10 UT, 14 March to 17 UT, 15 March, and the standard deviation stayed at a few V/m (value under rain cloud is more than 10 V/m) until 20 UT, 15 March, when the first rain (< 1 mm) after this accident was recorded at Kakioka, as marked by a blue dashed line. Thus, the drop of the Kakioka's PG on 14 March is not due to the rain-induced fallout but rather to the release or arrival of the largest southbound radioactive dust cloud from the FNPP by low-altitude wind. This is different from the reported PG drops associated with the Chernobyl disaster or nuclear tests in which radioactive materials were transported by high-altitude wind and rain.

Let us examine the time sequence. The radiation dose rate at Mito (130 km from FNPP) increased by one and half order of magnitude starting at 19:40 UT with raise time of half an hour. This is about 1.5 h (start time) to 1 h (peak) after the similar increase at Kitaibaraki (70 km from FNPP), and 3 h after the similar increase at Fukushima Dai-ni (12 km from FNPP). The average transport speed is about 40 km/h (10 m/s) southward, i.e., from the FNPP to Kakioka, in good agreement with the surface wind (4-5 m/s southward) at these places during 16-20 UT. Since the wind direction and speed changes substantially with altitude up to 1 km high, the consistency with the surface wind direction support the low-altitude transport of the dust cloud.

From geographical location as shown in Figure 2, the radiation dose rate at Kakioka probably experienced the similar increase at around 20 UT, whereas a sharp drop of the Kakioka's PG started at 19:50 UT. Since this decrease ended at 21:00 UT, slightly before the hydrogen explosion at reactor #2 (green label in Figure 3), the arrival of radioactive dust cloud by the low-altitude wind is the only possible reason that can explain the near-zero PG at Kakioka afterward. The transported radioactive dust must have ionized the atmospheric molecules and enhanced the electric conductivity near the surface immediately after its arrival. Furthermore, mobile fine particles within radioactive dust clouds can themselves be high-charged to enhance the electric conductivity depending on concentration [e.g. Clement et al 1994].

The next question is the degree of the conductivity enhancement by this direct arrival effect. The expected increase of the radiation dose rate at Kakioka is the same as those at the nearest stations (we examined several stations within 10 km diameter near Mito), i.e., about one and half orders of magnitude. Since the atmospheric electric conductivity is proportional to square root of the ionization rate when the nucleus density is low (e.g., above sea), and proportional to the ionization rate when the nucleus density is high [Rosen and Hofmann, 1981; Makino and Ogawa, 1985], we expect an increase of the conductivity by one order of magnitude or more. This means that the expected drop of the Kakioka's PG is about one order of magnitude just by the ionization effect of the radiation, and this agrees with the observation.

In Figure 3, the PG also dropped at around 17 UT (first vertical dashed green line) before the final drop at around 20-21 UT (second vertical dashed green line). Both the first and second drops are from about 60 V/m to about 5 V/m. The second drop agrees with the expected arrival time of the dust cloud from the largest southward release of radioactive materials from FNPP as described above. On the other hand, the first drop coincides with two possible events: expected arrival time of a minor dust cloud and expected time of the largest southward radioactive release. Also, one may not ignore the possible effect of the weather change.

Let us first examine the possibility of unrecorded weather change. Although the local cloud coverage and humidity was constant throughout this period, it is not impossible that cloud thickness has changed to affect the PG. In fact, the standard deviation (Figure 3b) shows a minor increase of the noise level during 11-17 UT and 19-22 UT, coinciding with increases of average PG in Figure 3a. However, it is difficult to relate the first drop at around 17 UT to any increase of electrified cloud. We should further point out that it is not common to have a smooth change of PG without any spikes of signature of rain-cloud, and that the timing of the first decrease matches too well with the arrival time of a minor dust cloud to Kakioka.

In Figure 3c, a minor increase of the radioactive dose rate is seen at around 13 UT, 15 UT, and 16 UT at 10 km, 70 km, and 130 km from the FNPP, respectively. The expected arrival time of this minor event to Kakioka is about 16:30 UT, in agreement with the start of the first PG drop. If this radioactive dust cloud passed through over Kakioka without staying there, a recovery in the re-combination time of ions can also be explained. On the other hand, the increase in the radiation dose rate is only by a factor of five at Mito. This gives only a factor of two to four increase in the electric conductivity, whereas the observed PG drop by one order of magnitude. There are two possible explanations for this discrepancy. The increase of the radiation dose ration at Kakioka in the interior at around 16:30 UT could have been greater than those near Ibaraki near the coast because of the wind direction because the wind-driven transport from a point source can be very localized. Also, radioactive dust can be high charged depending on concentration to contribute the conductivity [e.g. Clement et al 1994].

One may notice the coincidence between the PG drop at Kakioka and the event at the FNPP, i.e., the opening of the vent at reactor #2 at 15:02 UT and subsequent expansion of the radioactive materials above the FNPP. By back-tracing the largest southbound release of radioactive materials on 14 March to the FNPP, the expansion most likely occurred at around 16:30-16:50 UT with a raising time of an half to one hour, which coincides with the first PG drop (The FNPP site did not detect this increase most likely because of location of the measurement). However, the distance of 150 km is much longer than the expansion height of the radioactive dust at the FNPP. We have so far no explanation in connecting these two phenomena. To understand the first short PG drop at around 17 UT, it might have been helpful if we had several PG measurements at different directions from the FNPP (about 100 km away), so that at least the weather effect can be separated.

Summary:

Variation of Kakioka's PG, together with the radiation dose rate in the related area, indicate that arrival of the radioactive materials from the FNPP by low-altitude wind (dry contamination) caused a sudden drop of PG with a similar time profile as the PG drop associated with rain-induced radioactive fallout (wet contamination) in the past. The cause of the PG drop is the ionization effect of the radioactive materials. This is the first report that showed the quick response of the PG for the case of floating radioactive dust transported by the low-altitude wind.

In this report, we did not examine PG changes after 15 March that might reflect the settlement procedure of the radioactive materials to the soil: the arrival by wind does not necessarily mean the settlement to the soil that is common for the wet contamination. Neither did we examine spread of the radioactive material into the water nor possible effect on the cloud concentration. However, the data strongly indicates that high-temporal resolution PG observation is one good monitor of the radioactive dust cloud, giving independent information from the radiation dose rate measurement. Therefore, it is strongly recommended that all nuclear power plants have a network of PG observation surrounding the power plant.

After the Chernobyl disaster, the PG recovery took many months [Israelsson, et al. 1987; Tuomi, 1988; 1989). Such a long-term change in the atmospheric conductivity and related air-earth DC electric system is considered as a possible cause of the increase of lightning [Israelsson, et al. 1987). Monitoring for a similar response after the Fukushima accident should be undertaken.

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The atmospheric electricity (PG) data is available to public through www.kakioka-jma.go.jp/cgi-bin/plot/plotSetNN.pl?lang=en. We thank T. Toya for his advice on the PG data. The radiation dose rates are published on the web site at www.pref.ibaraki.jp/20110311eq/index2.html for Kitaibaraki, www.houshasen-pref-ibaraki.jp/earthquake/doserate.html for Mito, and http://www.tepco.co.jp/nu/fukushima-np/f2/index-j.html for the Fukushima Dai-ni nuclear power plant. The meteorological data was provided by Japan Meteorological Agency through www.jma.go.jp/jma/indexe.html.

Owada measured the atmospheric electricity (PG). Takeda initiated the analyses providing an interpretation, which is discussed by Makino and Yamauchi. Yamauchi summarized them and prepared the manuscript. We thank both reviewers for helpful comments on the original draft.

References

Clement, C.F.,D.M.J. Calderbank, and R.G. Harrison (1994), Radioactive aerosol charging with spatially varying ion concentrations, J .Aer. Sci., 25(4), 623-637.

Hamilton, R.A., and J.G. Paren (1967), The influence of radioactive fallout on the atmospheric potential gradient, Meteorol. Mag., 96, 81-85.

Harris, D.L. (1955), Effects of radioactive debris from nuclear explosions on the electrical conductivity of the lower atmosphere, J. Geophys. Res., 60, 45-52.

Harrison, R.G. (2003), Twentieth century atmospheric electrical measurements at the observatories of Kew. Eskdalemuir and Lerwick, Weather, 58, 11-19.

Harrison, R.G. and W.J. Ingram (2005), Air-earth current measurements at Kew, London, 1909-1979. Atmos. Res., 76, 49-64.

Israelsson, S. and E. Knudsen (1986), Effect of radioactive fallout from a nuclear power plant accident on electrical parameters, J. Geophys. Res., 91, 11909-11910.

Israelsson, S., T. Schutte, E. Pisler, and S. Lundquist (1987), Increase occurrence of lightning flashes in Sweden during 1986, J. Geophys. Res., 92, 10996-10998.

Kondo, G. (1963), The Recent Status of Secular Variation of Atmospheric Electricity, Memoirs of Kakioka Magnetic Observatory, 11, 65-70.

Kondo, G. (1959), The Recent Status of Secular Variation of the Atmospheric Electric Elements and their Relation to the Nuclear Explosions, Memoirs of Kakioka Magnetic Observatory, 9, 2-6.

Makino, M. and T. Ogawa (1985), Quantitative Estimation of Global Circuit, J. Geophys. Res., 90, 5961-5966.

Nuclear and Industrial Safety Agency (2011), The Accident at TEPCO's Fukushima nuclear power stations, Report of Japanese government to the IAEA ministerial conference on nuclear safety, 7 June 2011, chapter VI, http://www.iaea.org/newscenter/focus/fukushima/japan-report/.

Pierce, E.T. (1959), Some calculations on radioactive fallout with especial reference to the secular variations in potential gradient at Eskdalemuir, Scotland, Pure and Applied Geophysics, 42, 145-151.

Pierce, E.T., Radioactive fallout and secular effects in atmospheric electricity. J. Geophys. Res. 77, 482-487 (1972).

Rosen, J.M., and D.J. Hofmann (1981), Balloon-borne measurements of electrical conductivity, mobility, and the recombination coefficient, J. Geophys. Res., 86, 7406-7410.

Rycroft, M.J., S. Israelsson, and C. Price (2000), The global atmospheric electric circuit, solar activity and climate change, J. Atmos. Sol. Terr. Phys, 62, 1563-1576.

Rycroft M.J., R.G. Harrison, K.A. Nicoll, and E.A. Mareev (2008), An overview of Earth's global electric circuit and atmospheric conductivity, Space Sci. Rev., 137, 83-105, doi: 10.1007/s11214-008-9368-6.

Shigeno, N., T. Takizawa, N. Itoh, M. Yokoyama, and T Owada (2001), Preliminary test for atmospheric electricity measured using an electrostatic sensor, Gijutsu Hookoku, 112, 8-13.

Tuomi, T.J. (1988), Observations of atmospheric electricity 1986, Geophysical Publications, 7, 551.506.1, Finish Meteorological Institute, Helsinki, 61pp.

Tuomi, T.J. (1989), Ten Year Summary 1977-1986 of Atmospheric Electricity Measured at Helsinki-Vantaa Airport, Finland, Geophysica, 25, 1-20.

Williams, E.R. (2009), The global electrical circuit: A review, Atmos. Res., 91, 140-152, doi:10.1016/j.atmosres.2008.05.018.

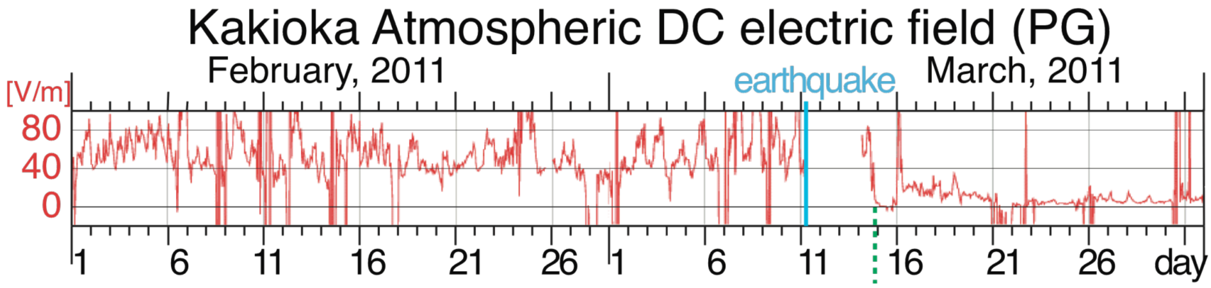

Figure 1: One-hour averaged atmospheric electric field vertical component, or potential gradient (PG) at Kakioka station measured by in-house electrostatic sensor during two months' period before and after the M9.0 earthquake on 11 March, 2011. The data gap during 11-13 March is due to the power failure at Kakioka caused by the earthquake. A sudden drop of PG is observed on 14 March, as marked by green dashed line.

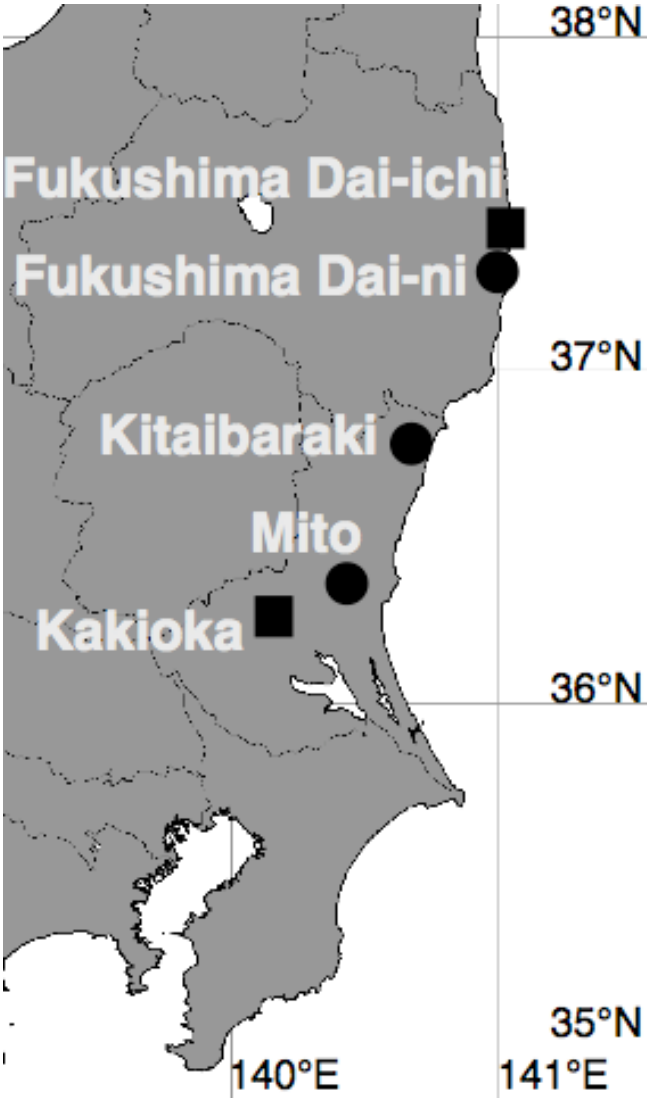

Figure 2: The locations of Fukushima Dai-ichi nuclear power plant (FNPP), Fukushima Dai-ni nuclear power plant (about 12 km south of FNPP), Kitaibaraki (about 70 km southwest of FNPP), Mito (about 130 km southwest of FNPP), and Kakioka (about 150 km southwest of FNPP).

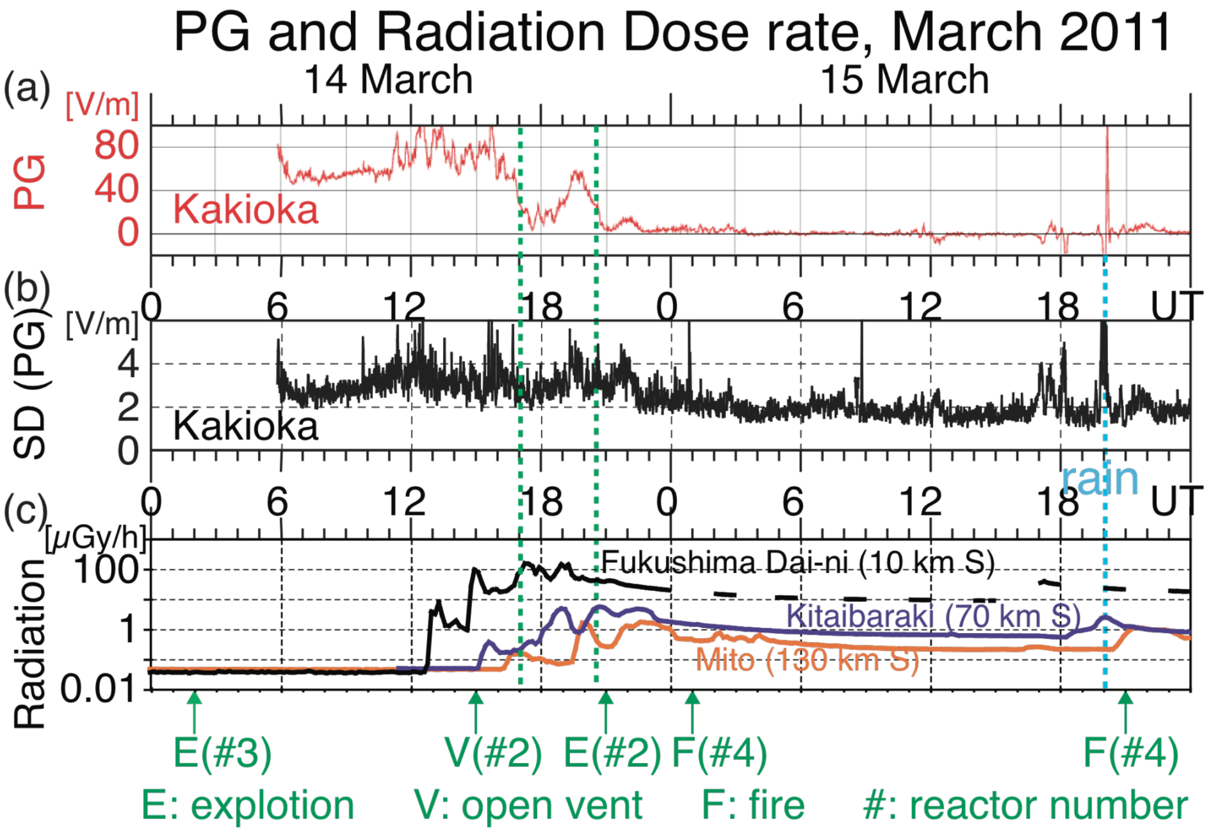

Figure 3: Two-day's data before and after the largest southbound release of the radioactive material from the Fukushima Dai-ichi nuclear power plant (FNPP) in March 2011: (a) 1-min averaged PG at Kakioka; (b) standard deviation of PG calculated from 1 Hz sampling data; and (c) 10 min resolution radiation dose rate data at three different stations between Kakioka and the FNPP. The green notes at the bottom denote incidents at the FNPP.