Unusual Intensity Enhancements of Low Frequency Atmospherics Associated with Great Eruptions of Izu-Oshima Volcano in November 1986

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Great eruptions occurred suddenly at the Izu-Oshima volcano Oshima Island, Japan from the evening of November 15 to November 22, 1986. In this period, atmospherics of 160 kHz were observed at Koganei, Tokyo which is located 101 km north of the volcano, and atmospherics of 80 kHz were observed at Inubo, Chiba prefecture, located 194 km northeast of the volcano.

For propagation distances above 100 km, hop-mode waves, via ionospheric reflection, dominate over ground-mode waves. The atmospherics from the Izu-Oshima volcano were detected only during the night at Koganei and Inubo, since LF radio waves are strongly absorbed in the ionospheric *D* region produced by solar X-rays and solar EUV radiation during the daytime.

Nighttime intensity enhancements of 160 kHz atmospherics with 10 dB or more above the normal night levels of November 14 and 15 were observed at Koganei from November 16 to 20, 1986. The nighttime enhancements of 160 kHz atmospherics from November 16 to 19 show characteristic time variations with periods from 10 minutes to 15 minutes, corresponding to the time intervals of repeated eruptions at the summit of the Izu-Oshima volcano. Nighttime intensity enhancements of 80 kHz atmospherics of 5 dB or more above the normal night level were also observed at Inubo from November 16 to 20, 1986.

According to weather maps issued by the Japanese Meteorological Agency, no meteorological phenomena occurred to cause the observed nighttime intensity enhancements of LF atmospherics, such as thunderstorms or rain clouds, in those districts during that time. Also, no local artificial noises occurred corresponding to the observed enhancements of LF atmospherics in the vicinity of the receiving sites in that period, and local noise was about 10 dB lower than the enhanced level of LF atmospherics during the nighttime.

Attenuation of electromagnetic waves in magma, wet soil and dry crust are numerically examined. It seems improbable that LF electromagnetic waves propagate through magma and moist soil from a volcano's interior to the ground because of strong attenuation, even if the LF electromagnetic waves were generated inside the volcano.

Lightning discharges generated by eruption smoke have been reported for decades and in fact, some pictures of lightning discharges over the volcano were broadcast by television during the Izu-Oshima volcano eruptions. Therefore, the nighttime intensity enhancements of LF atmospherics observed at Koganei and Inubo from November 16 to 20, 1986 seem to have been generated by lightning discharges in eruption smoke and ascending warm air currents heated locally by hot lava over the crater lake.

1. Introduction

The summit of the Izu-Oshima volcano (geographic latitude 34.8°N , longitude 139.4°E) suddenly erupted at 17:25 JST (Japan Standard Time) on November 15, 1986 after an inactive period of about 210 years. The volcano erupted repeatedly from November 16 to 20, 1986. Outflows of lava from the summit crater began on the morning of November 17, and a crater lake of lava formed on the afternoon of November 17. The lava began to flow across the inner caldera at 10:35 JST, November 19. Fissure eruptions suddenly occurred in the northern caldera floor and also on the northern slope of the outer caldera at 16:15 JST on November 21 (ENDO, 1987). During the eruption period, the electric field intensity of 160 kHz atmospherics was measured at the Radio Research Laboratory (now the Communications Research Laboratory), Koganei, Tokyo (geographic latitude 35.7°N , longitude 139.5°E), which is located 101 km north of the Izu-Oshima volcano. Also, an electric field intensity of 80 kHz atmospherics was measured at the Inubo Radio Wave Observatory, Choshi (geographic latitude 35.7°N , longitude 140.9°E), which is located 194 km northeast of the volcano. At Koganei, a vertical antenna with effective height of 6 m was used and at Inubo, a ball antenna with 30 cm diameter was used. Typical radio noise receivers used at both observatories consist of aerial tuning, HF amplification, IF amplification, power amplification and detector output.

Unusual intensity enhancements of 80 kHz and 160 kHz atmospherics were observed at both observatories on five nights, from November 16 to 20, 1986 (ONDOH *et al.*, 1988). In this paper, we discuss relationships between the unusual intensity enhancements of LF atmospherics for the five nights from November 16 to 20, 1986 and eruptions of the Izu-Oshima volcano in November, 1986, taking into account weather conditions in those districts and also propagation conditions of electromagnetic waves in the magma and earth's crust.

2. Nighttime Intensity Enhancements of LF Atmospherics Associated with Summit Eruptions of Izu-Oshima Volcano in November, 1986

In general, a radiation electric field cannot be observed at distances within five times the radio wavelength from the source (18.8 km at 80 kHz and 9.4 km at 160 kHz), because the electrostatic and induction electric fields from the source predominate over the radiation electric field. So, the nighttime intensity enhancements of LF atmospherics should not be detected in Izu-Oshima Island since the size of Izu-Oshima Island is about 7 km in the east-west direction and about 12 km in the north-south direction.

The propagation distance of 160 kHz radio waves from the Izu-Oshima volcano to Koganei is 101 km, and that of 80 kHz radio waves from the volcano to Inubo is 194 km. For these propagation distances, the receiving intensity of ground-mode waves is much smaller than that of one-hop mode waves via ionospheric reflection (CCIR Report, 1986). So, LF radio waves propagating from the Izu-Oshima volcano received at Koganei and Inubo are ionospheric reflected waves. But, ionospheric reflected waves in the LF band are strongly absorbed in the ionospheric

D region (60–100 km in altitude) which is formed by the solar X-rays and EUV radiations during the daytime (CCIR, SG-6, Rept. 256-6, 1986). Therefore, LF atmospherics propagating from the Izu-Oshima volcano are received only during the nighttime at Koganei and Inubo.

Figure 1 shows Japanese Meteorological Agency weather maps for the vicinity of Japan at 09:00 hours JST from November 13 to 24, 1986. No meteorological phenomena (no strong low-pressure regions), such as thunderstorms or rain clouds, which might have caused the nighttime intensity enhancements of LF atmospherics occurred at Koganei and Inubo during that period. Cloud pictures taken by the

Fig. 1. Weather maps in the vicinity of Japan at 09:00 hours JST (00:00 hours UT) from November 13 to 24, 1986, issued by the Japanese Meteorological Agency.

Japanese Geostationary Meteorological Satellite confirm that there were no clouds causing thunderstorms or severe rain over the receiving sites of Koganei and Inubo in the same period.

Figures 2(a) to 2(c) show intensity data for 160 kHz (± 1.2 kHz) atmospherics observed at Koganei during the nighttime (18:00–06:00 hours JST) from November 14 to 25, 1986. Intensity variations of 160 kHz atmospherics between 18:00 and 05:00 hours JST for the nights of November 16, 17, 18, 19 and 20 were considerably larger than those for the nights of November 14 and 15. The chart recorder time constant used is 10 seconds and 0 dB is 1 μV . The atmospherics activity for the nights of November 14 and 15 was quiet and at a level of about -20 dB (1.7×10^{-3} $\mu\text{V/m}$), though the summit of the Izu-Oshima volcano erupted at 17:25 JST, November 15, 1986.

As shown in Fig. 1, weather conditions in the district of Tokyo and Izu-Oshima Island from November 16 to 24, 1986 were stable and approximately the same as those on November 14 and 15, 1986. So, daily variations of LF atmospherics caused by meteorological phenomena over Koganei and Inubo for the nights of November 16 to 24 seem to be similar to those for the nights of November 14 and 15, though atmospherics activity is generally high during the nighttime because of the ionospheric conditions.

In Fig. 2(a), intensity levels (-10 dB or higher) from 21:00 to 04:00 JST for the nights of November 16–17 and 17–18 were 10 dB or more higher than those (around -20 dB) from 18:00 to 07:00 JST for the nights of November 14–15 and 15–16. Artificial noises are seen in the evening and morning of November 14–15 and 15–16, and their levels are usually below -20 dB, as seen in Fig. 2(a). Statistical results of 160 kHz atmospherics received for one year at Koganei indicate that the average intensity level of 160 kHz atmospherics increases toward the midnight level from an evening (20:00 JST) level of -20 dB, attains a maximum level of -15 dB at midnight, and decreases to a morning (05:00 JST) level of -21 dB. Thus, the time variations of 160 kHz atmospherics for the nights of November 15–16 are regarded as typical intensity variations on a normal day at Koganei. Hence, the nighttime intensity enhancements of LF atmospherics from November 16 to 19 observed at Koganei seem to be associated with unusual eruptions of the Izu-Oshima volcano from November 16 to 20, 1986.

Large intensity enhancements (2.6×10^{-2} $\mu\text{V/m}$) of 10 dB or more above the quiet night level of November 14 and 15 were observed at about 02:30 JST on November 17, 01:00 JST on November 18, 00:50 JST on November 20 and 02:00 JST on November 21. Unusual intensity variations with periods of 10 to 15 minutes were dominant for the nights of November 16, 17, 18 and 19. Especially, fine time variations with periods less than 10 minutes occurred between 22:30 JST, November 19 and 03:30 JST, November 20. Fine time variations are superimposed on large-scale time variations of one to two hours. Such unusual time variations in intensity enhancements of 160 kHz atmospherics have never been observed on normal days or even on days of thunderstorms or severe rain at Koganei. Also, such unusual intensity variations are never due to artificial noises, intensities of which are usually below -20 dB, as discussed previously. During rain, the intensity level of 160 kHz atmospherics is enhanced to -15 dB in a hump-like manner as a whole, and small intensity fluctuations below 5 dB are usually superposed on the hump-like variation

Fig. 2. Time variations of 160 kHz atmospherics intensity observed at Koganei, Tokyo, Japan from November 14 to 25, 1986. The intensity scale is in dB where 0 dB is 1 μ V.

(b)

Fig. 2. (continued).

Fig. 2. (continued).

for a few hours.

According to observer's reports from Izu-Oshima Island (Sasai, private communication) and television and newspaper reports, eruptions at the summit crater of the Izu-Oshima volcano repeated at time intervals of 10 to 15 minutes on the nights of November 16, 17 and 18. The time interval between eruptions at the summit crater became shorter on the night of November 19, as the crater lake of lava expanded. The rapid repetition of eruptions corresponds well to the fine time variations of 160 kHz atmospherics with periods less than 10 minutes between 22:30 JST, November 19 and 03:30 JST, November 20 (Fig. 2(b)).

The summit eruptions produced a huge volume of smoke, which ascended 3000 to 10000 m into the atmosphere (VOLCANO RESEARCH SECTION, JAPANESE

METEOROLOGICAL AGENCY, 1987). Thus, the characteristic variations in time interval of the summit eruptions from November 16 to 19 correspond well to the semi-periodical time variations in 160 kHz atmospherics intensity for the nights of November 16, 17, 18 and 19 observed at Koganei (Figs. 2(a) and 2(b)).

The variation period of the 160 kHz atmospherics intensity on the night of November 20 became longer than that on the previous nights, and the general characteristics of the time variation in 160 kHz atmospherics intensity on the night of November 20 changed significantly from those for the nights of November 16 to 19. Nighttime intensity variations of 160 kHz atmospherics on November 21 and 22 decreased, and then, on November 23 and 24, returned to the quiet night level, except for a large variation between 03:00 and 04:00 hours JST on November 24. The eruption mode of the volcano after the afternoon of November 20 changed remarkably from that prior to November 19 (Sasai, private communication); that is, the time interval between eruptions became much longer. Thus, the change of the eruption mode also corresponds to the slow time variation in 160 kHz atmospherics intensity on the night of November 20.

Fissure eruptions suddenly occurred at 16:15 JST, November 21 in the northern caldera floor and on the northern slope of the outer caldera. The fissure eruptions produced many flame pillars. Smoke heights of the fissure eruptions were not as great in comparison with those of the summit eruption smoke, although lava fountains in the fissure eruptions attained up to 500 m in altitude. This change in the eruption mode between November 19 and 20 apparently caused a difference in the intensity variation of 160 kHz atmospherics between the nights of November 19 and 20, as shown in Fig. 2(b).

Figure 3(a) to 3(d) show intensity variations of 80 kHz atmospherics observed at Inubo, Chiba prefecture for nights from November 13 to 23, 1986, where the intensity scale is an arbitrary relative scale in dB. Because of its distance from the volcano, ionospheric reflected waves of 80 kHz propagating from the volcano should be observed only during the night at Inubo Observatory. Figure 3(a) shows the quiet day variations of 80 kHz atmospherics intensity observed on November 13, 14 and 15, 1986. The nighttime level of 80 kHz atmospherics is about 3 dB higher than the daytime level. It should be remarked that quiet day variations for November 13 to 15 have no large intensity enhancement between 20:00 and 04:00 hours JST, though enhancements peculiar to the seaside occurred in the evening and early morning hours, since the Inubo Observatory is located on a hill of a small cape surrounded by the Pacific Ocean. The average daily variation of 80 kHz atmospherics intensity at Inubo obtained statistically from a year's data is similar to the time variation of 80 kHz atmospherics intensity on the night of November 14–15, 1986 except for the evening noises around 18:00 JST (Fig. 3(a)).

Figures 3(b) and 3(c) show large intensity variations of 80 kHz atmospherics lasting for about one to two hours between 20:00 and 04:00 hours JST for the nights of November 16, 17, 18, 19 and 20, 1986. Such a large hump-type variation for about one to two hours has never been observed during the nighttime at Inubo. Since the ball receiving antenna is located on a hilltop about 60 m from the observatory, there is no possibility of picking up local artificial noises.

Characteristic intensity variations of 80 kHz atmospherics with periods of 10 to 15 minutes, which also predominate in hump-type variations for about one to two

Fig. 3. Time variations of 80 kHz atmospherics intensity observed at Inubo, Chiba prefecture, Japan from November 13 to 24, 1986, where the intensity scale is an arbitrary one in dB.

(b)

Fig. 3. (continued).

(c)

Fig. 3. (continued).

(d)

Fig. 3. (continued).

hours, were also observed at Inubo (Figs. 3(b) and 3(c)) corresponding to the eruption time interval repeated at the summit crater of the Izu-Oshima volcano. However, intensity variations of about one to two hours were not found in the records of 160 kHz atmospherics at Koganei. The intensity enhancements of 80 kHz atmospherics during the nighttime on November 16, 17, 18 and 19 were 5 dB or more above the quiet time level. Groups of fine intensity enhancements with periods of 10 to 15 minutes repeated at time intervals of about 3 hours for the nights from November 16 to 19, but only one group of fine intensity enhancements occurred around 00:00 hours JST, November 21. So, the variation mode of 80 kHz atmospherics intensity for the nights from November 16 to 19 is clearly different from that for the nights of November 20 and 21, corresponding to the eruption mode change of the volcano after the afternoon of November 20, as discussed above in regard to the 160 kHz atmospherics. Intensity variations of 80 kHz atmospherics for the nights of November 22 and 23 returned to the quiet night level of November 13, 14 and 15, as seen in Fig. 3(d). General features of time variations of 80 kHz atmospherics intensity at Inubo for the nights from November 14 to 23, 1986 are

similar to those of 160 kHz atmospherics intensity at Koganei in the same period. No artificial radio noise source that would cause the nighttime intensity enhancements of LF atmospherics was found in the Koganei or Inubo areas from November 13 to 24, 1986.

3. Attenuation of Electromagnetic Waves in the Earth's Crust

GOKHBERG *et al.* (1979) observed anomalous increases in electromagnetic radiation at 27 kHz, 385 kHz and 1.63 MHz before a large main shock (M 7.4) of the Iran earthquake in a tunnel 50 m below the ground in Caucasus. GOKHBERG *et al.* (1982) also observed similar increases in electromagnetic radiation at 81 kHz before some earthquakes. OGAWA *et al.* (1985) detected electromagnetic radiation associated with fractures of rocks in laboratory experiments, although the energy generated from the rock fracture was small. OIKE and OGAWA (1986) reported the occurrence of anomalous electromagnetic noises at 163 kHz for a few hours to several days before and after the main shocks of shallow earthquakes in inland areas or shallow sea regions.

Underground water diffuses into a wide region associated with a deformation of the crust prior to an earthquake, and the water diffusion raises the electrical conductivity in the crust (ISHIDO and MIZUTANI, 1981). So, we calculate the attenuation of ELF-MF electromagnetic waves in dry crust, wet soil and magma, in order to discuss electromagnetic radiation associated with earthquakes and volcanic activities, although the generation region of electromagnetic waves in a volcano seems to be much smaller than that associated with an earthquake.

In general, the electric field of electromagnetic waves is expressed by $E = E_0 \exp(j\omega t + j\mathbf{k} \cdot \mathbf{r})$ and $k^2 = \varepsilon\mu\omega^2 - j\sigma\mu\omega$, where ω is the angular wave frequency, $\mathbf{k}$ the wave vector, $\mathbf{r}$ the radial vector from the radiation source, μ the permeability, ε the dielectric constant and σ the electric conductivity. The complex wave number is also given by $k = \alpha + j\beta$ ($\alpha > 0, \beta \geq 0$), $\alpha^2 - \beta^2 = \varepsilon\mu\omega^2$ and $\alpha\beta = \sigma\mu\omega/2$, where α represents the propagation constant and β the attenuation constant (STRATTON, 1941). The attenuation constant ($\beta \geq 0$) is derived as

$$\beta = \left\{ \varepsilon\mu/2(\sqrt{1 + (\sigma/\varepsilon\omega)^2} - 1) \right\}^{1/2} \cdot \omega \quad (1)$$

from $\alpha^2 - \beta^2 = \varepsilon\mu\omega^2$ and $\alpha\beta = \sigma\mu\omega/2$. The expression (1) becomes $\beta = (\sigma\mu\omega/2)^{1/2} = 1/\delta$ for $\sigma/\varepsilon\omega \gg 1$, where δ is the skin depth. The dielectric constant ε is expressed by $\varepsilon = \varepsilon_0 \varepsilon_r$ where $\varepsilon_0 = 1/(36\pi \times 10^9)$ F/m is the dielectric constant or permittivity of free space and ε_r the relative dielectric constant. The magnetic permeability μ is usually approximated by the permeability of a vacuum $\mu_0 = 4\pi \times 10^{-7}$ H/m, if the material concerned is not ferromagnetic. Relative dielectric constants of the material concerned are as follows: $\varepsilon_r = 1$ for gas, $\varepsilon_r = 80$ for water at 20°C, $\varepsilon_r = 55$ for water at 100°C, $\varepsilon_r = 4$ for sulfur at room temperature, $\varepsilon_r = 4-7$ for ceramics, $\varepsilon_r = 4.7-5$ for mica and $\varepsilon_r = 7-10$ for glass (MIYAJIMA, 1955). Also, electric conductivities of the material concerned are as follows: $\sigma = 1$ mho/m for lava, $\sigma = 3-5$ mho/m for sea water, $\sigma = 10^{-2}$ mho/m for wet soil and $\sigma = 10^{-5}$ mho/m for dry crust. Table 1 lists numerical values of $\sigma/\varepsilon\omega$ available for a proper use of the expression $\beta = 1/\delta$. Table 1 indicates

Table 1. Numerical values of $\sigma/\varepsilon\omega$ for concerned material.

f	Lava, Sea	Dry crust	Wet Soil
	$\sigma = 4-1, \varepsilon_r = 2-80$	$\sigma = 10^{-5}, \varepsilon_r = 2-80$	$\sigma = 10^{-2}, \varepsilon_r = 2-80$
100 Hz	$3.6 \times 10^8-2.3 \times 10^6$	$9.0 \times 10^2-2.3 \times 10$	$9.0 \times 10^5-2.3 \times 10^4$
1 kHz	$3.6 \times 10^7-2.3 \times 10^5$	$9.0 \times 10-2.3$	$9.0 \times 10^4-2.3 \times 10^3$
10 kHz	$3.6 \times 10^6-2.3 \times 10^4$		$9.0 \times 10^3-2.3 \times 10^2$
100 kHz	$3.6 \times 10^5-2.3 \times 10^3$		$9.0 \times 10^2-2.3 \times 10$
1 MHz	$3.6 \times 10^4-2.3 \times 10^2$		$9.0 \times 10-2.3$
10 MHz	$3.2 \times 10^3-2.3 \times 10$		

that the expression of $\beta=1/\delta$ can be properly used for electromagnetic wave attenuation of $f \leq 10$ MHz in lava or sea water, $f \leq 100$ kHz in wet soil and $f \leq 100$ Hz in dry crust. The application of $\beta=1/\delta$ for $\sigma/\varepsilon\omega \gg 1$ means that the dielectric flux current $j\varepsilon\omega \cdot E$ is negligible as compared with the conduction current $\sigma \cdot E$ in the material concerned. So, the oscillating electric field rapidly becomes small in the material concerned at distances beyond the skin depth from the boundary surface, and an incoming wave energy is effectively transmitted into the material by the oscillating current within the skin depth from the boundary. On the other hand, an oscillating electric dipole $Me^{j\omega t}$ located along the Z direction in the material emits an electromagnetic energy of $(M^2\omega^4\sin^2\theta/32\pi^2c^2r^2)\sqrt{\mu/\varepsilon}$ at distance r from the electric dipole in a direction θ from the Z axis, and the total energy emitted in all directions becomes $(M^2\omega^4/12\pi \cdot c^2)\sqrt{\mu/\varepsilon}$, where M is the magnitude of the electric dipole and $c=3 \times 10^8$ m/s the light speed. The total energy emitted from an oscillating current I of length L is given by $\pi(2\pi \cdot L^2/\lambda^2)^2(I^2/2)\sqrt{\mu/\varepsilon}$ (MIYAJIMA, 1955).

The energy emitted from the electric dipole located within the skin depth from the boundary will be carried by oscillating currents, and will be converted into electromagnetic wave energy when an emitted energy arrives at the medium in which the dielectric flux current is not negligible. However, an oscillating electric dipole located beyond the skin depth from the boundary cannot effectively transmit its energy.

Figure 4 shows relations between frequency and electromagnetic wave attenuation, $20 \cdot \log_{10}(E_0/E) = 20 \cdot \log_{10} \exp(\int \beta ds)$ in dry crust ($\sigma=10^{-5}$ mho/m, $\varepsilon_r=7$) and wet soil ($\sigma=10^{-2}$ mho/m, $\varepsilon_r=6$) at frequencies from 100 Hz to 1 MHz, where ds is a wave path element. For frequencies from 100 Hz to 1 MHz, the attenuation of electromagnetic waves in dry crust is less than 6.2 dB/km, while it is from 17.3 dB/km at 100 Hz to 1697 dB/km at 1 MHz in wet soil. Therefore, if electromagnetic radiation is generated in dry crust by rock fractures over a vast region before and after the main shock of a shallow earthquake, anomalous electromagnetic waves will be observed even in the LF band, as reported by GOKHBERG *et al.* (1979) and OIKE and OGAWA (1986). But, the possibility of this is small if underground water diffuses into a vast crust in association with crust deformation prior to an earthquake, because the attenuation of electromagnetic waves in wet soil is very strong. It also seems that the nighttime enhancements of LF atmospherics during the volcanic eruptions were not caused by electromagnetic radiation associated with rock fractures in the volcano, because moist soil and magma exist in the volcano and the

Fig. 4. Attenuation of electromagnetic waves at frequencies from 100 Hz to 1 MHz in dry crust and wet soil.

generation region of electromagnetic waves in volcanos is much smaller than the vast generation region of electromagnetic waves for earthquakes.

Then, we discuss the attenuation of LF electromagnetic waves in magma under the assumption that LF electromagnetic waves are generated by some unknown mechanism associated with magma rise inside the volcano at a boundary between the soil and the magma, since LF electromagnetic waves seem to travel upward through magma and moist soil before propagating in free space. The electrical conductivity of lava ($\sigma=1$ mho/m) is much larger than that of soil ($\sigma=10^{-5}$ – 10^{-2} mho/m). The electrical conductivity of magma is here assumed to be the same as that of lava. So, the soil-magma boundary is regarded as a kind of boundary between a dielectric and an electrical conductor.

Figure 5 shows the relationship of the skin depth in lava to electromagnetic wave frequencies from 100 Hz to 1 MHz. The skin depth is expressed as $\delta=\sqrt{2/\sigma\mu\omega}$. Here, μ is approximated by the magnetic permeability of a vacuum, $\mu_0=4\pi\times 10^{-7}$ H/m, since lava is not ferromagnetic material. The skin depth in lava at 80 kHz and 160 kHz is estimated as 1.8 m and 1.3 m, respectively. These small skin depth values suggest that LF electromagnetic waves cannot penetrate through a magma flow to the open air, even if the LF waves are generated by an interaction of the rising magma with a volcano's soil. If the soil or crust in the volcano is dry ($\sigma=10^{-5}$ mho/h), the LF waves generated by the upwelling magma at depths within 1 km from the volcano surface could penetrate through the volcano's inner flank, since an attenuation of VLF-LF waves in dry crust is below 6.2 dB/km (Fig. 4). However, since there is usually much water vapor on a volcano's slope and over its crater,

Fig. 5. Relationship of the skin depth in lava to radio frequencies from 100 Hz to 1 MHz.

VLF-LF waves should be strongly attenuated in propagation through moist soil in a volcano, as shown by Fig. 4. Only ELF electromagnetic radiation below 100 Hz generated inside a volcano will appear on the ground.

Then, we survey electromagnetic phenomena associated with the volcanic eruption.

Figure 6 shows the time variation of the difference between total geomagnetic field intensities measured at Futtsu on Izu-Oshima Island and Kawazu on the Izu peninsula of the Japanese mainland. The difference in the total geomagnetic field shows a step-like decrease of about 10 nT for about 6 hours around the time of the great eruption of the volcano on November 21, 1986. This is interpreted as a thermal demagnetization effect associated with the volcanic eruption (SASAI *et al.*, 1990).

Figure 7 shows the specific electrical resistance in the east-west direction in the caldera of the Izu-Oshima volcano measured by the electrical potential difference

Fig. 6. Time variations of differences in total geomagnetic field between Futtsu on Izu-Oshima Island and Kawazu in the Izu peninsula of the Japanese mainland before and after the great eruption of the Izu-Oshima volcano on November 21, 1986 (after SASAI *et al.*, 1990).

Fig. 7. Time variation of the specific electrical resistance in the east-west direction measured in the caldera of the Izu-Oshima volcano before and after the great eruption of the Izu-Oshima volcano from January, 1985 to February, 1987 (after YUKUTAKE *et al.*, 1987).

between electrodes at two points. The apparent electrical resistance remained at 1.05 between January, 1985 and January, 1986, and increased slowly from 0.9 in February, 1986 to 1.25 in August, 1986. Then, the apparent specific resistance decreased from 1.25 in August, 1986 to 0.50 at the time of the eruption in November, 1986, and increased rapidly to 1.10 in the middle of December, 1986. The rapid decrease in the apparent specific electrical resistance before the eruption may be produced by the magma rise from below, since magma's electrical conductivity is much greater than that of the surrounding soil (YUKUTAKE *et al.*, 1987). So, the electrical conductivity around the crater at the eruption time becomes about twice that of before July, 1986. These variations in electromagnetic parameters observed during the eruption in November, 1986 are less than one-hundredth of those associated with an auroral substorm, during which strong VLF-LF radio emissions occur in the high latitude ionosphere.

Hence, it seems that the electromagnetic energy converted from kinetic energy inside the volcano is insufficient to generate VLF-LF electromagnetic radiation.

4. Electromagnetic Radiations from Lightning Discharges in Eruption Smoke over the Volcano

In general, the eruption energy of a volcano is mostly thermal and explosive kinetic energy, by which eruption smoke rises to several thousands of meters in altitude. According to a Japanese Meteorological Agency report (VOLCANO RESEARCH SECTION, JAPANESE METEOROLOGICAL AGENCY, 1987), lava fountains attained altitudes up to 500 m and the eruption smoke rose to altitudes from 3000 m to above 10000 m over the Izu-Oshima volcano in the November, 1986 event. Also, warm air parcels locally heated by the 1200°C lava produced ascending warm air currents over the crater lake. Eruption smoke and ascending warm air currents will produce an electric charge separation in the atmosphere, such as positive charges at

upper altitudes and negative charges at lower altitudes, or vice versa. The breakdown of the electrostatic structure in the atmosphere results in atmospheric electric discharge, that is, lightning discharges. Such atmospheric electric discharges give rise to broad-band electromagnetic radiation. Lightning discharges and associated radio noises caused by eruption smoke have been reported for decades (SEKI, 1955).

The electric field E_r of a lightning discharge, which has a vertical length of discharge path h and a current $I=dQ/dt$, is given by

$$E_r = \frac{2h}{r} \left(\frac{c^2 Q}{r^2} + \frac{c}{r} \frac{dQ}{dt} + \frac{d^2 Q}{dt^2} \right),$$

where Q is the electric charge, c the light speed and r ($\gg h$) the horizontal distance between the foot of the lightning discharge and the observation point (HATAKEYAMA and KAWANO, 1955). The first, second and third terms are the electrostatic field, induction field and radiation field, respectively. The radiation field generally predominates over the other fields at distances beyond 5 times the wavelength from the lightning discharge. Table 2 gives a relation of the electrostatic field, induction field and radiation field with distance from the lightning discharge (HATAKEYAMA and KAWANO, 1955).

Table 2 clearly indicates that the electrostatic field and induction field predominate over the radiation field at distances 5 km from the lightning discharge. The distance of 5 km is comparable with the size (EW 7 km×NS 12 km) of Izu-Oshima Island. So, if the nighttime intensity enhancements of 80 kHz atmospherics at Inubo and of 160 kHz atmospherics at Koganei were caused by lightning discharges in eruption smoke over the Izu-Oshima volcano, they could not be observed on Izu-Oshima Island. Lightning discharges associated with the summit eruptions of the Izu-Oshima volcano in November, 1986 were seen in televised pictures. Therefore, the most likely mechanism for generating the electromagnetic radiation associated with the volcanic eruption seems to be atmospheric electric discharges caused by the combination of eruption smoke and ascending lava-heated air currents. The resulting broad-band radio waves generated at high altitudes over the Izu-Oshima volcano would propagate over a wide area. If a discharge path length in the eruption smoke is one-tenth of the vertical discharge path length in the normal atmosphere (Table 2), a time derivative of the discharge current, dI/dt , in the eruption smoke during the nighttime of November 19, 1986 becomes 6.5×10^{-5}

Table 2. Relation of the electrostatic field, induction field and radiation field with distance from a lightning discharge (HATAKEYAMA and KAWANO, 1955).

E -field	$\frac{c^2 2hQ}{r^3}$		$\frac{c2hI}{r^2}$		$\frac{2h}{r} \frac{dI}{dt}$	
	Q		I		dI/dt	
Distance	5 Coul	10 Coul	10000 A	50000 A	500 A/ μ s	2000 A/ μ s
5 km	14.4 V/cm	28.8 V/cm	0.48 V/cm	2.4 V/cm	0.4 V/cm	1.6 V/cm
100 km	1.8×10^{-3}	3.6×10^{-3}	1.2×10^{-3}	6×10^{-3}	0.02	0.08

A/ μ s for the intensity enhancement of 160 kHz atmospherics, 2.6×10^{-2} μ V/m, observed at Koganei. Thus, the magnitude of typical lightning discharge in the atmosphere is 8×10^6 times that of lightning discharge in volcanic eruption smoke. Consequently, lightning discharges in eruption smoke seem to be much weaker than typical lightning discharges in the atmosphere.

5. Conclusion

Nighttime intensity enhancements of LF atmospherics were observed at Koganei and Inubo, Eastern Japan, corresponding to eruptions of the Izu-Oshima volcano from November 16 to 20, 1986. The nighttime intensity enhancements of 160 kHz atmospherics observed at Koganei were 10 dB or more above the quiet night levels of November 14 and 15. At Inubo, nighttime intensity enhancements of 80 kHz atmospherics, with 5 dB or more above the quiet night levels of November 13 and 14, were also observed from November 16 to 20. At Koganei and Inubo which are 101 km and 194 km, respectively, from the volcano, hop-mode radio waves via ionospheric reflection dominate over ground-mode waves, and LF radio waves are strongly absorbed in the ionospheric *D* region formed by solar X-rays and solar EUV radiations.

Between November 14 and 24, 1986, there were no meteorological phenomena such as thunderstorms or heavy rains in the Koganei and Inubo areas. This has been confirmed by weather maps and cloud pictures taken by the Japanese Meteorological Geostationary Satellite (issued by the Japanese Meteorological Agency). No artificial noise source that would cause the unusual enhancements of LF atmospherics was found in the Kanto district encompassing Koganei and Inubo from November 14 to 24, 1986.

The nighttime intensity enhancements of 160 kHz atmospherics at Koganei from November 16 to 19 had periodical variations from 10 minutes to 15 minutes. These periodical intensity variations correspond to the time intervals of repeated eruptions at the summit crater of the Izu-Oshima volcano. The periodical variations disappeared in the nighttime intensity enhancements of 160 kHz atmospherics after November 20, since the eruption mode of the volcano after November 20 clearly changed from that for November 16 to 19, 1986. Even if LF electromagnetic waves were generated inside the volcano, the LF electromagnetic waves could not propagate through the magma or the moist soil from the volcano interior to the surface, because LF electromagnetic waves are strongly absorbed there.

Lightning discharges associated with the summit eruptions of the Izu-Oshima volcano in November, 1986 were seen over the volcano in television pictures. Therefore, the nighttime intensity enhancements of LF atmospherics associated with the volcano eruptions seem to have been caused by electric discharges in the eruption smoke and ascending warm air currents over the crater lake of hot lava.

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