Relevance of magnetic properties of soil in the magnetic observatories to geomagnetic observation

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Annual geomagnetic variations with a maximum amplitude of 5 nT, and in phase with ground temperature variations at a depth of 1–2 m, were observed in the baseline values of fluxgate magnetometers installed at three JMA magnetic observatories. A possible origin of the annual variations is a change in magnetization of the soil due to changes in ground temperature. In order to examine the effect of temperature changes on soil magnetization, we measured the magnetic properties of soil samples collected at the JMA observatories. Magnetization of soil samples in a magnetic field of 0.05 mT ranged within 0.05×10^{-3}–1.6×10^{-3} A m^2/kg and the temperature dependence of magnetization ranged within 0.3×10^{-6}–14×10^{-6} A m^2/kg $^\circ$C, except for a sample having an extraordinarily strong magnetization. Based on the measured magnetization, and their temperature dependence, of samples from Memambetsu, which shows the largest values among the samples from the three observatories, we determined the distribution of the geomagnetic field and its annual variation produced by soil magnetization. The maximum amplitude of annual variation in the geomagnetic field is 7 nT, which is consistent with the observed annual variation of the baseline value of the magnetometers.
Key words: Geomagnetic observation, annual variation, rock magnetism.

1. Introduction

Geomagnetic observatories record variations of the geomagnetic field with variometers and determine the absolute values of the records with a separate procedure called absolute measurements. Absolute measurements of the total force, inclination and declination of the geomagnetic field are carried out with proton magnetometers and magnetic theodolites. They are converted into the absolute values of the three components of the geomagnetic field at the variometer sensor location, assuming that the difference in the geomagnetic field between the variometer and the absolute measurement sites do not vary with time. The baseline values of the variometers are then calculated as the differences between the variometer records and the absolute values. The magnetic observatories operated by the Japan Meteorological Agency (JMA) (Fig. 1) employ three-axes fluxgate magnetometers as the main variometers (Oowada *et al.*, 2003) and obtain their baseline values by absolute measurements once a week.

The baseline values for the fluxgate magnetometers (96FM, 90FM and 95FM) at Memambetsu (MMB), Kakioka (KAK), and Kanoya (KNY), magnetic observatories (Fig. 2) show different annual variations. At MMB, the amplitude of the annual variation in *Z* (vertical), and *H*

(horizontal), components is 5 nT and 2 nT, and the *D* (declination) component does not show any significant annual variation. At KAK, the *H* and *Z* components have annual variation amplitudes of 2 nT, while the *D* component does not show any significant annual variation. At KNY, linearly decreasing, and increasing, trends at rates of 1–2 nT/yr are notable in the *H* and *Z* components, and an additional annual variation of amplitude 1 nT is notable in the *H*, *Z* and *D* components.

Observing conditions, such as a change in temperature and the tilt of the magnetometers, are the most plausible causes of annual variations, but cannot fully explain the observed annual variations. The annual variations shown in Fig. 2 are already corrected using tiltmeters installed in the sensors of the magnetometers, and are out of phase with the temperature variation of the magnetometers. Furthermore, differences in total geomagnetic intensities, obtained with three proton magnetometers installed at different locations within MMB, show annual variations with amplitudes of ∼1 nT (Nishimura *et al.*, 2012). As observations with proton magnetometers are not likely to be largely affected by observing conditions, the observed annual variations can be considered to be actual geomagnetic variations.

A possible origin of annual variations is a change in the magnetization of the soil due to changes in the ground temperature. In volcanic areas, the conclusion that geomagnetic annual variations are caused by a change in the magnetization of surface rock produced by a change in ground temperature (Utada *et al.*, 2000), is widely accepted. This
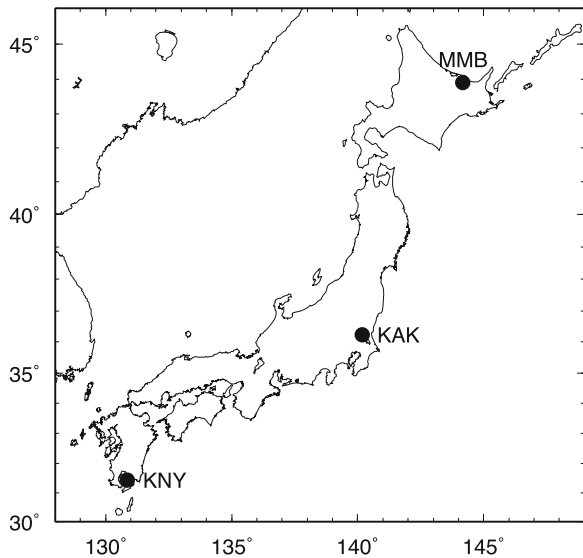
Fig. 1. Geomagnetic observatories operated by JMA. MMB: Memambetsu; KAK: Kakioka; KNY: Kanoya.
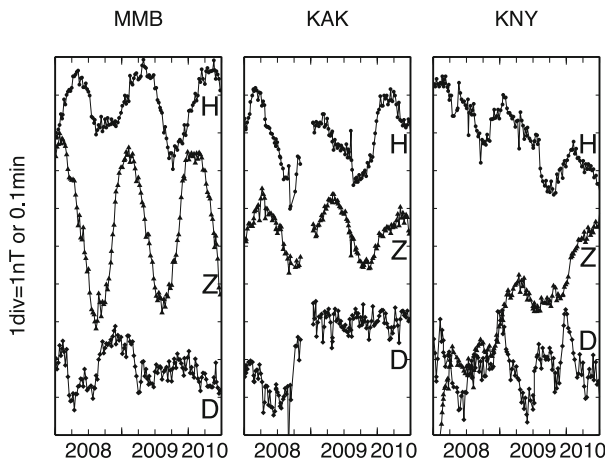

Fig. 2. Baseline values of fluxgate magnetometers installed at Memambetsu, Kakioka and Kanoya Observatories from January 2008 to June 2010.

idea is also applicable to non-volcanic areas in Japan, because surface soil in Japan often contains materials of a volcanic origin. For example, many volcanic tephra layers are widespread within sediments in Hokkaido (Machida and Arai, 2003) and some of them show strong magnetic susceptibility (Kawamura *et al.*, 2007). The change in soil magnetization produced by a change in the ground temperature has also been suggested as a possible cause of the change in geomagnetic observational data at observatories in Japan (e.g., Ogawa and Koyama, 2009; Yamazaki *et al.*, 2012). However, the non-availability of soil magnetic properties has prevented a quantitative evaluation of geomagnetic changes resulting from a temperature change of the soil.

In this study, we measured the magnetic properties of soil samples collected from the three JMA observatories, and we have examined the effect of temperature change on the soil magnetization to the geomagnetic annual variations.

2. Samples and Methods

We dug two pits with depths of 1–1.5 m within each observatory, and we collected 1–3 unoriented soil samples at separate depths inside each pit (Fig. 3, Table 1). The sampling depths of each pit were determined based on visual features, such as soil color and grain size, as well as the lithological description of the existing borehole columns drilled within the observatories. We also used a previously-collected sandy soil sample with strong magnetization (presumably volcanic ash) from the MMB observatory, which was found at a depth of 4 m when the continuous observation house was built.

The change of magnetization in response to temperature change was measured. The measurement was performed with a Quantum Design Magnetic Property Measurement System (MPMS-XL) at the Geological Survey of Japan, the National Institute of Advanced Industrial Science and Technology. A small subsample ($\sim$100 mg) of each sample was analyzed. In order to reduce the residual magnetic field in the instrument, the superconducting magnet was quenched before the measurement runs. The applied static magnetic field on a subsample was set to 50000 nT (0.05 mT) in order to impart induced and remanent magnetization. Each subsample was then heated from 2°C to 27°C, at a rate of 1°C/min, and the change of magnetization was monitored at intervals of 1°C.

Low-field magnetic susceptibility was measured with a Bartington MS2B magnetic susceptibility meter at an operating frequency of 465 Hz, a peak applied field of 0.25 mT and a temperature of 26°C. Subsamples filled into 6.86-cm^3 paleomagnetic cubes were used for the low-field magnetic susceptibility measurement. Bulk density was calculated from the weight and volume of the subsamples. Low-field magnetic susceptibility and bulk density of the M5 sample were not measured, because the amount of sample available was insufficient.

3. Results

Figure 4 shows the change of magnetization in response to temperature change. The magnetization of most samples showed a linear decrease with increasing temperature. A notable change in the decrease rate, between 11 and 19°C, was shown in the demagnetization curve of the M2 sample. The M5 sample showed a large fluctuation in the demagnetization curve and high standard deviation values in the some measurement data, possibly because the grains in the sample were coarse and loose, and slightly moved during the measurement. We calculated a magnetization value at 12°C and the temperature dependence of magnetization with their standard deviations by a linear approximation of these curves (Table 2).

Samples from KNY have the smallest decrease rate (0.3×10^{-6}–1.4×10^{-6} A m^2/kg°C) of the three observatories, though the magnetization (0.6×10^{-3}–0.9×10^{-3} A m^2/kg) is not so small. Spatial differences in magnetization and decrease rate were notable between samples from two pits at KAK (K1, K2 and K3, K4). Samples from MMB showed the largest magnetization (0.7×10^{-3}–1.5×10^{-3} A m^2/kg) and the largest decrease rate (1.7×10^{-6}–14×10^{-6} A m^2/kg °C), even excluding the M5 sample (4.3×10^{-3}A
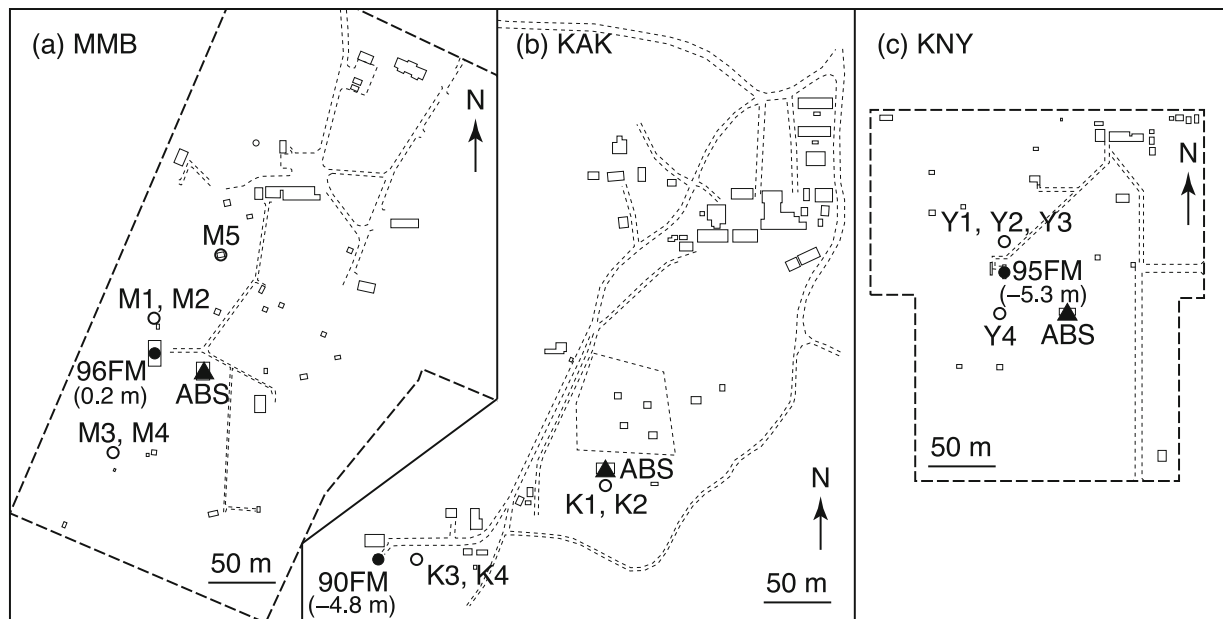
Fig. 3. The observation and sampling locations in (a) Memambetsu, (b) Kakioka and (c) Kanoya Observatories. Solid circles indicate the locations and sensor height of the main fluxgate magnetometers. Solid triangles show the absolute measurement houses. Open circles show the locations of the soil samples.

Table 1. Summary of the collected soil samples from the JMA observatories. Color taken from Oyama and Takehara (1967).

Sample	Location	Depth	Color
M1	MMB North of Variation House #2	0.5	brown
M2		1.1	yellowish brown
M3	MMB North of Total Forth (79F)	0.5	dark brown
M4		1.0	yellowish brown
M5	MMB Continuous Observation House	4.0	mixture of transparent, grayish white and black
K1	KAK South of Comparison & Calibration House	0.5	yellowish brown
K2		1.0	olive brown
K3	KAK East of Underground Variation House	0.5	dark brown
K4		1.0	dark brown
Y1	KNY North of Underground Variation House	0.3	reddish black
Y2		1.2	brown
Y3		1.5	black
Y4	KNY North of Continuous Observation House	1.4	mixture of reddish brown and reddish black

m^2/kg; 57×10^{-6} A m^2/kg °C).

The bulk density of the subsamples filled in the paleomagnetic cubes ranges between $0.87–1.63 \times 10^3$ kg/m^3 (Table 2). The variation in bulk density might be affected by compaction and the void space of the subsamples in the cubes. For convenience, we adopted 1×10^3 kg/m^3 as the bulk density in order to convert the unit of magnetization.

Low-field magnetic susceptibility ranged from 39.9–848×10^{-5} SI units (Table 2). Four samples from MMB, and two samples from KAK (K3 and K4), which have a large magnetization, show high magnetic susceptibility (569–848×10^{-5} SI). The samples from KNY show a moderately-high magnetic susceptibility (216–689 $\times 10^{-5}$ SI). Two samples from KAK (K1 and K2), which have the smallest magnetization, show the lowest magnetic susceptibility (39.9–73.4 $\times 10^{-5}$ SI).

The magnetic susceptibility range of 39.9–848 $\times 10^{-5}$ SI corresponds to an induced magnetization in the range

0.016–0.34 A/m in a AC magnetic field of 50000 nT, and is almost a third of the magnetization measured with the MPMS. A possible cause of the difference between the MPMS-measured magnetization and the calculated induced magnetization from the magnetic susceptibility might be a residual magnetic field in the sample position in the MPMS. Although efforts were made to minimize the residual field by using magnet reset, a residual field of 0.1 mT might be possible in an MPMS, which is usually operated with a strong magnetic field up to 5 T. Another possible cause of the difference in magnetization is the viscous remanent behavior of magnetic minerals in the soil. Viscous remanent magnetization may be acquired during a measurement run in an MPMS, which takes typically an hour, but not in low-field magnetic susceptibility measured in an alternating magnetic field of 465 Hz. Despite the problem of the magnetic field accuracy, in this paper we adopt the magnetic parameters measured with the MPMS, because it provides

Table 2. Summary of the magnetic properties of the soil samples.

| Sample	Magnetization (12°C) (10^{-3} A m^2/kg)	Temperature dependence (10^{-6} A m^2/kg °C)	Low-field magnetic susceptibility (10^{-5} SI)	Bulk density (10^3 kg/m^3)
M1	1.378 ± 0.002	-3.057 ± 0.186	768	1.09
M2	1.455 ± 0.006	-13.965 ± 0.737	721	1.10
M3	0.747 ± 0.000	-1.737 ± 0.041	569	1.13
M4	1.195 ± 0.003	-2.932 ± 0.374	661	1.25
M5	4.294 ± 0.098	-56.646 ± 11.940		
K1	0.057 ± 0.000	-0.476 ± 0.015	39.9	1.48
K2	0.115 ± 0.000	-0.701 ± 0.023	73.4	1.63
K3	1.579 ± 0.002	-7.807 ± 0.296	848	1.14
K4	1.628 ± 0.001	-4.371 ± 0.084	665	1.11
Y1	0.639 ± 0.000	-0.570 ± 0.057	220	0.87
Y2	0.840 ± 0.000	-0.329 ± 0.059	216	1.01
Y3	0.621 ± 0.001	-1.384 ± 0.099	482	0.91
Y4	0.885 ± 0.000	-0.900 ± 0.039	689	0.98
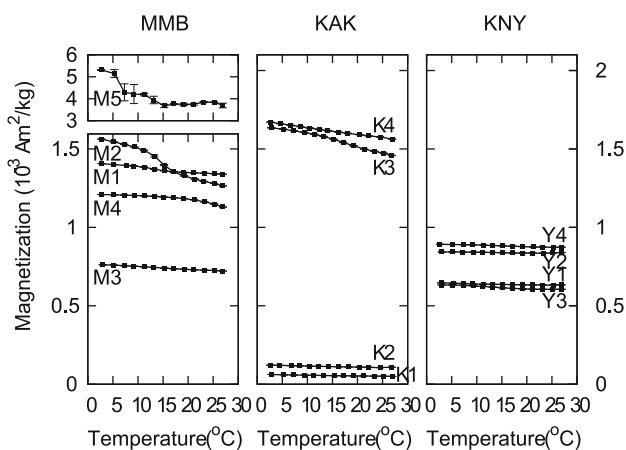
Fig. 4. Variation in magnetization during heating each sample from 2°C to 27°C in a magnetic field of 0.05 mT. Numbers correspond to sample numbers shown in Table 1.
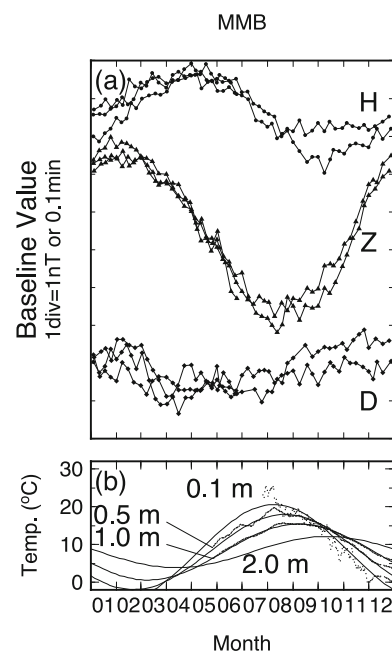

Fig. 5. (a) The annual variation in baseline values of the fluxgate magnetometer at the Memambetsu Observatory from January 2008 to June 2010. (b) Observed ground temperature at Memambetsu Observatory in 2004 (solid circles; Nishimura *et al.*, 2012) and the determined annual variation in ground temperature (lines).

the best temperature control within the ground temperature range.

4. Determination of Geomagnetic Annual Variations

We determined geomagnetic annual variations based on the annual variations of the ground temperature and the measured values of magnetization and its temperature dependence. Samples from MMB showed the largest temperature dependence of magnetization of the three observatories, illustrating that an annual variation exists at MMB. We determined the geomagnetic annual variations around the second variation measurement house and the absolute measurement house of MMB (96FM and ABS in Fig. 3), where absolute measurements are performed and a fluxgate magnetometer is installed, respectively.

The ground temperature measured at MMB between May 2004 and January 2005 (Nishimura *et al.*, 2012; Fig. 5(b)) indicates that an annual temperature variation is dominant in the ground temperature variation below a depth of 0.1 m. Assuming a simple one-dimensional thermal diffusion, the

ground temperature variation $\Delta T(z, t)$ is expressed as:

$$\Delta T(z, t) = \Delta T_0 \exp(-nz) \cos(\omega t - nz),$$

where ΔT_0 is the temperature variation amplitude at the surface, $\omega = 2\pi$ yr^{-1} is the angular frequency, and $n = \sqrt{\omega/2\kappa}$ where κ is the thermal diffusivity. According to the ground temperature record, we determined these parameters as $\Delta T_0 = 13.3$°C and $n = 0.585$ m^{-1} (Fig. 5(b)).

We considered a strongly-magnetized rectangular body, with dimensions of 20 m × 20 m × 1 m, buried within a horizontal 2-layer model (Fig. 6) as a model of the distribution of soil magnetization, for the following reasons. The depth of the magnetic anomaly body is set to 1–2 m, because the annual variation of the H and Z components of
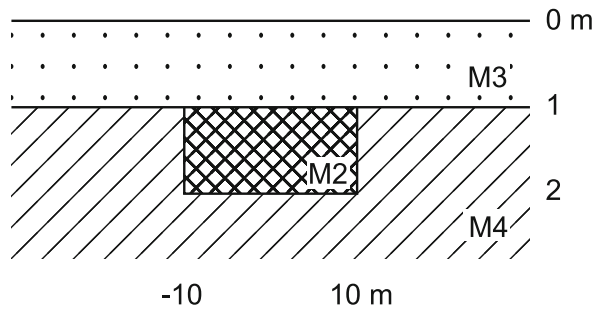
Fig. 6. A model of the magnetization distribution in the soil. We adopted the magnetization, and its temperature dependence, of the samples M2, M3 and M4 (Table 1) as those within each block.
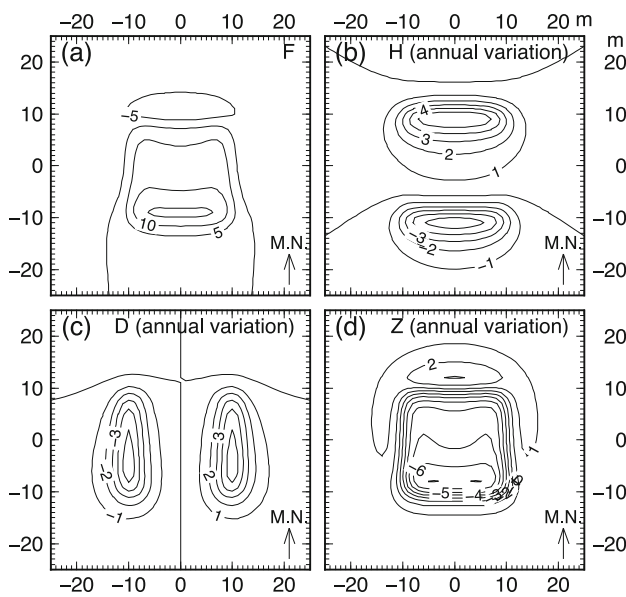

Fig. 7. The calculated distribution of the magnetic field and its annual variation. (a) Magnetic total intensity. (b)–(d) Amplitudes of annual variations for H, D and Z components, respectively. Positive and negative signs in (b)–(d) indicate an increase and decrease, respectively, during high ground-temperature periods.

the baseline values for the fluxgate magnetometer at MMB is in phase with the ground temperature at depths of 1–2 m (Fig. 5). The spatial distribution of the total geomagnetic intensity at MMB (Nishimura *et al.*, 2012) shows an area with a positive geomagnetic intensity up to ∼10 nT, with dimensions of ∼20 m, near the second variation measurement house ("96F" in figure 6 of Nishimura *et al.*, 2012), and an area with a negative geomagnetic intensity surrounding it on the north, east and west sides, suggesting a strongly-magnetized body beneath it, in addition to a northward-decreasing trend. Strong magnetization values of samples from the second variation measurement house (samples M1 and M2) support the existence of a strongly magnetized body. We adopt magnetization and its temperature dependence of sample M2 as those of the strongly magnetized body, and those of M3 and M4 as those of two horizontal layers (Fig. 6). The direction of magnetization in each layer is assumed to be parallel with the geomagnetic field direction.

We calculated the spatial distribution of total geomag-

netic intensity and the annual variations for H, D and Z components at a height of 2 m yielded by the assumed soil magnetic structure (Fig. 7). The phase of the annual variation of all components are focused either between 48–50 degrees, or between 228–230 degrees, which are in phase and antiphase to the ground temperature at a depth of 1.43–1.49 m, and are shown as positive and negative amplitudes, respectively. As for the total intensity, an area with a positive magnetic anomaly up to ∼15 nT is located above the strongly-magnetized body, while a region with a negative magnetic anomaly surrounds it on the north, east and west sides. For the annual variations of the H and D components, two regions of opposite phase, with maximum amplitudes of ∼5 nT, appeared above the edge of the strongly-magnetized body. The annual variations of H and D are in phase with the ground temperature variations above the northern and eastern edges of the strong magnetization, respectively. The annual variation of Z has a maximum amplitude of ∼7 nT, and shows a similar spatial distribution to that of the total intensity.

5. Discussion

The temperature dependence of magnetization is largest for the MMB samples, and smallest for the KNY samples. It is consistent with the amplitude of the annual variations, in the baseline values of the fluxgate magnetometers, which was largest at MMB and smallest at KNY. The small temperature dependence of magnetization in the KNY samples can also explain the insignificant annual fluctuations in the spatial distribution of the total geomagnetic intensity reported by Yamazaki *et al.* (2012).

The positive magnetic anomaly up to ∼15 nT in the calculated spatial distribution of the total geomagnetic intensity (Fig. 7(a)) is similar to the local features around the second variation measurement house described above.

The ranges of the calculated annual variation amplitudes for each component are comparable to the observed annual variation amplitudes of the baseline values. At MMB, both H and Z components show high baseline values, (i.e. low observed values of the fluxgate magnetometer) during summer and autumn when the ground temperature is high. The observed annual variations of both H and Z in antiphase to the ground temperature can be explained by a calculation locating a strongly-magnetized body beneath the north of the fluxgate magnetometer. The calculated phase of the geomagnetic annual variation is common to the H, Z and D components, and consistent with the depth of the strong magnetization. The different phase of the observed annual variations of H and Z may be explained by multiple magnetization anomalies at different depths. The calculated annual variation of D reaches up to ∼5 nT above the eastern and western edges of the strongly-magnetized body, but is smaller than 1 nT between them. The insignificant observed annual variation of D can be explained by assuming that the fluxgate magnetometer is located above the central region of strong magnetization.

6. Conclusion

The annual variations in the geomagnetic field caused by changes in soil magnetization in response to temperature

changes was determined from measuring the magnetization, and its temperature dependence, of soil samples collected from three JMA magnetic observatories. The amplitude of the determined annual variations at the MMB observatory was up to ∼7 nT, which corresponded approximately with the observed annual variations in the baseline values of the fluxgate magnetometer.

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