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Effects of atmospheric electric fields on cosmic rays

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The electric fields associated with thunderclouds change the intensity of secondary cosmic rays observed on the ground. This effect has been investigated using several detectors located at the Mount Norikura Cosmic Ray Observatory where excesses of 1% and more of the average counting rate may be observed when the Observatory is covered by thunderclouds. A frequency analysis of the time series of days with such excesses for the period 26 October 1990 to 15 January 2002 shows the expected summer maximum in the rate of occurrence and, more surprisingly, a 26-day variation. An electric field mill was installed to help determine the relationship between the intensity variations and the strength and direction of the field near the detector system: the excess is usually observed when a negative electric field (accelerating negative charges downward) greater than 10 kV/m is present in the atmosphere above the observatory. Based on Monte Carlo simulations we predict that excess counting rates measured without charge discrimination will be expected as a consequence of the excess of positive muons among the secondary cosmic rays.

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I. INTRODUCTION

In 1920, just a few years after the discovery of cosmic rays by Hess, Wilson [1,2] proposed an atmospheric theory of the origin of cosmic rays. He suggested that β rays (electrons) emitted from the ground are accelerated upward by the electric fields associated with thunderclouds, assumed to be positively charged, and once accelerated are bent downward again by the geomagnetic field. This idea did not survive but it is interesting to note that effects of the atmospheric electric field on cosmic rays entering the atmosphere have been detected, as we describe here.

Wilson was later involved in a famous debate in 1928 at the University of Glasgow with G. C. Simpson, then Director of the British Meteorological Office. This concerned the direction of the electric field in thunderclouds. Based on a hypothesis of Lenard, Simpson claimed that the tops of thunderclouds must be negatively charged. Existing data indicated that this was wrong, but Simpson nevertheless continued with balloon measurements for many years, trying to prove that he was right. Eventually, he convinced himself and everybody else that he had indeed been wrong, but the series of observations was nevertheless useful in providing a definitive set of measurements of the charge distributions in thunderclouds [3,4]. The head of the clouds is charged positively, the middle region negatively, and there may be a small region (''pocket'') of positive charge at the bottom amounting to 20–25 % of the negative charge above. The ground is always charged negatively and the ionosphere positively, both being good electrical conductors in comparison with the bulk of the atmosphere, which has a very low electrical conductivity and is able to sustain very high electric fields before breaking down. The time constants for the ground and ionosphere are such that both can be regarded as being equipotentials for our purposes.

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II. THE ELECTRIFICATION OF THE ATMOSPHERE

The atmosphere well below the ionosphere and down to ground level is continually ionized by cosmic rays, by the radioactive decay of radon and its daughter products and by gamma rays emitted from the ground. In addition, water drops may produce charged debris on freezing. However, except for the primary cosmic rays themselves, which are mainly positively charged but make a negligible contribution to the overall accumulation of charge, none of these processes leads to the production of any net charge density but rather of a weakly ionized, electrically neutral plasma.

The ions produced in these ways (called "small ions," e.g., O_2^+) are fairly immobile and to a first approximation move with the background neutral gas, unless an electric field is present when they drift slowly in the direction leading to discharge of the field. The electrons, on the other hand, are very mobile but soon "stick," either to a molecule, forming a negative small ion (e.g., O_2^-), or to a much larger aerosol particle or water droplet (A). The latter, which usually become negatively charged (A^{n-}, carrying $n \geqslant 1$ electrons), are called "large ions." They are relatively immobile with respect to the background atmosphere unless there is a strong force acting on their charge (an electric field) or their mass (gravity), in which case they can move relative to the background.

The electrons may recombine directly with positive ions (e.g., $O_2^+ + e \rightarrow O + O$) and be lost. Positive and negative ions may recombine mutually (e.g., $O_2^+ + O_2^- \rightarrow 2O_2$, etc.), or interact with large ions (e.g., $O_2^+ + A^{n-} \rightarrow O_2/2O + A^{(n-1)-}$, $O_2^- + A^{n-} \rightarrow O_2 + A^{(n+1)-}$, and so on). The overall result is that relatively few free electrons exist in the lower atmosphere and the charge resides mainly in the form of small and large ions. These gradually become neutralized by recombination if there is no continuing source, such as the cosmic radiation. In the absence of electric fields and gravity, the positive and negative ions would be in balance in terms of their net charge density.

The small and large ions produced according to the above description can be separated by an electric field and by gravity. The electric field tends to be discharged by drift of the small ions (e.g., the slow discharge of simple electroscopes) while the large ions fall under the influence of gravity unless there is a sufficiently large electric field to hold them up (e.g., as in Millikan's oil drop experiment). The large ions may also grow in size and charge by agglomeration into larger ions, by the condensation of water vapor and other nonvolatile material, or by the accretion of smaller water droplets or ice crystals. Eventually, however, the large ions fall under gravity as charged rain, hail, or snow, if the electric field permits. They are slowed but not stopped by viscosity.

The ionization produced by cosmic rays may also lead to an increase in the number of condensation centers in supersaturated regions (as in a Wilson cloud chamber) and thus increase the number of large ions [5]. In some circumstances large ions may be associated with other nongaseous phase material, notably in volcanic eruptions and large fires where small nonaqueous grains can become negatively charged, resulting in the production of lightning discharges [6]. Whatever the case, the presence of nongaseous phase material and gravity play an essential role in causing positive and negative charges to separate so that large transient electric fields can be built up, as observed in thunderstorms in the atmospheres of Earth, Venus, and Jupiter.

The above is one of the simplest descriptions of cloud electrification: its validity is supported by the observation that there was a significant increase in the occurrence of lightning following the Chernobyl disaster, when a large amount of ionizing material was released into the atmosphere [7].

Doubts have been expressed concerning the total amount of charge that can be made available by cosmic rays as an ionizing source [8]. It has been suggested that a second more efficient process independent of cosmic ray ionization, such as "riming" electrification, might be responsible for significantly enhancing the production of charge in suitable circumstances [6,9,10]. Although this process may be important in thunderclouds it can hardly account for observations of lightning activity in association with volcanic eruptions, large fires, and dust storms, or for the Chernobyl effect. The argument made originally concerning the number of ions available from cosmic ray production seems to have assumed that the sea level ion production rate (about 2 ion pairs/cm^3 sec) is typical everywhere. In fact the observed rate increases to about 400 ion pairs/cm^3 sec at 15 km above sea level (a.s.l.) [11], covering the altitudes reached by thunderclouds.

According to this scenario [12], in a stable, nonconvective cloud, water and ice droplets should accumulate into large enough drops to fall to the bottom of the cloud. Eventually, as they continue to grow, they fall to the ground as negatively charged rain or hail, leaving the cloud positively charged. The result is that the Earth becomes negatively charged, and the excess positive charge in the cloud is slowly neutralized by the drift of negative small ions toward positive regions and by the drift upward of positive small ions toward the ionosphere, which is charged positively. However, it is possible that the electric field in the cloud becomes large enough to prevent further precipitation of the less massive large ions, in which case the lower part of the cloud becomes negatively charged. In this case there may be a positively charged region at the bottom of the cloud where the water drops have locally become so large that the electric field is unable to prevent their precipitation. Further complexities may arise from large-scale overturning and convection within the clouds so that regions that have become positively or negatively charged may be moved around to produce quite complex electric field distributions. It should be noted that the speed of such convective motions is likely to be much greater than the drift speed of small ions in the electric fields.

This discussion must be modified to allow for the effects of lightning discharges, which allow charge transfer to take place along discrete paths of electrical breakdown. Lightning may be (1) intracloud, reducing internal potential differences within the cloud, (2) cloud to ionosphere causing "sprites" [13], and (3) cloud to ground. If intracloud lightning reduces the electric field responsible for holding some large ions up against gravity, there should be an accompanying burst of rain or hail, delivering more negative charge to the ground and eventually allowing cloud-to-ground discharges. The burst of precipitation and cloud-to-ground discharges deliver negative charge to the ground. Without this resupply, the negative charge on the Earth (about $-600\,000$ C) and the fair weather electric field (200–300 V/m) would dissipate in about 5 min.

III. THE EFFECTS OF ATMOSPHERIC ELECTRIC FIELDS ON COSMIC RAYS

The propagation through the atmosphere of cosmic rays, and especially their secondary particles, can in principle be affected by the presence of electric fields. The charged particles are decelerated or accelerated, depending on their charge and the direction of the field. We may expect then that variations of the fluxes of different components of cosmic rays in the atmosphere can occur in association with variations of the atmospheric electric field, rainfall, and lightning activity.

The flux of secondary cosmic rays dominates over that of primaries in the atmosphere and their energies are more commensurate with the electric potential drops (up to 100 MV) that may exist there; hence we expect any observed variations seen at ground level to be associated with secondaries. Since the secondaries consist of almost equal fluxes of positive and negative particles (muons $\mu^{\pm}$ and electrons $e^{\pm}$) with only a small excess of positively charged particles (because the incoming primaries are mainly positive), it might be difficult to determine the sense of the electric field from variations of their flux but it would be worth attempting. There is an additional problem when the electric field changes sign with height so that we must be satisfied to obtain information concerning the total potential drop along the path of each particle rather than the detailed structure of the electric field.

The Baksan group first reported noticeable effects on cosmic rays of thundercloud electric fields above the Caucasus Mountains. Alexeenko *et al.* [14] showed in 1985 that the effects are indeed of atmospheric origin and argued that they are the result of modulation of the fluxes of muons by the vertical electric field associated with thunderstorms. Recently, Khaerdinov *et al.* [15] found that an excess counting rate of cosmic ray secondary components is often associated with a negative electric field (accelerating negatively charged particles downward) at ground level.

Aglietta *et al.* [16] have observed that there are short-lived ($\sim$10 min) and long-lived ($\sim$ hours) events that appear to have different causes. On the basis of an analysis by Dorman and Dorman [17] they suggested that the short-lived events might be the result of electric fields acting on cosmic ray secondaries, including muons and possibly electrons. These could be accelerated to more than 25 MeV, thereby modifying the air shower size. The long-lived events appear to be associated with rainout (onto the detector) of atmospheric radon daughter products, since the expected gamma ray lines ($<$2.2 MeV) are observed. Brunetti *et al.* [18] have shown in their measurements made in Nepal that airborne radio-nuclides are indeed affected by precipitation and also by winds and convection from lower altitudes.

The possibility that particles of cosmic ray energies might undergo acceleration in the Earth's atmosphere has been largely overlooked since Wilson's time, but it is now clear from ground-based measurements, designed primarily to investigate air showers, that such acceleration occurs, at least in association with thunderstorms [14–16]. Particle acceleration in the atmosphere has also been observed by gamma ray detectors in space [19], once again in association with thunderstorms (sprites), but in this case it is cloud-ionosphere lightning discharges that are the cause of x- and γ-ray production [20–23] (for earlier references, see Aglietta *et al.* [16]).

IV. OBSERVATIONS AT MOUNT NORIKURA

The Cosmic Ray Laboratory of the Institute for Cosmic Ray Research (ICRR) at the University of Tokyo is situated at an altitude of 2770 m on Mount Norikura (3026 m) in the central Japanese Alps (137.56°E, 36.11°N). The observatory is equipped with several cosmic ray detectors, notably, (1) a 12-tube neutron monitor (1955/1968/1989); (2) the Nagoya 36 m^2 meson monitor (1969); (3) the Nagoya 1 m^2 neutron telescope (1990); (4) the Nagoya 64 m^2 neutron telescope (1996); and (5) a 19 m^2 muon telescope (1998).

A *neutron monitor* (NM) was first installed by the Riken group in 1955, just before the International Geophysical Year (IGY), and was replaced in September 1968 by a 4NM64 neutron monitor. The present 12NM64 neutron monitor has been operating since March 1989, and the data are used by cosmic ray physicists in Japan and worldwide. Neutron monitors have the advantage of having a high sensitivity (70%) for detecting neutrons and protons and a low sensitivity (0.7%) for background muons with energies greater than $E_{\mu}>1$ GeV. The detection efficiency of neutron monitors was calculated by Hatton in 1971 [24] and Clem and Dorman [25] and confirmed satisfactorily by accelerator measurements made at the Research Center for Nuclear Physics of Osaka University (RCNP) by Shibata *et al.* [26]. Neutron monitors can detect neutrons with energies down to 10 MeV with an efficiency of 2–5 %, negative muons with energies of about 100 MeV with an efficiency of about 10%, and protons with energies above 500 MeV with about the same efficiency as neutrons (for details see Clem and Dorman [25]).

The *Nagoya* 36 m^2 *meson monitor* consists of upper (U) and lower (L) layers of plastic scintillators, separated vertically by 1.73 m, and with each layer consisting of 6×6 separate sections of area 1 m$\times$1 m. This arrangement allows the direction of arrival of cosmic rays to be determined with the sky divided into 13 regions and the counting rate in each direction recorded on an hourly basis. The details of the construction and performance of the detector have been given by Nagashima *et al.* [27], together with results concerning the diurnal variation of the cosmic ray intensity around 10^{13} eV.

There are several trigger logics in the system but here we are concerned only with the vertical coincidence trigger (V) and the combined upper and lower triggers (U+L). V is triggered when a charged particle (energy $>$20 MeV) penetrates both the upper and lower layers from the vertical direction

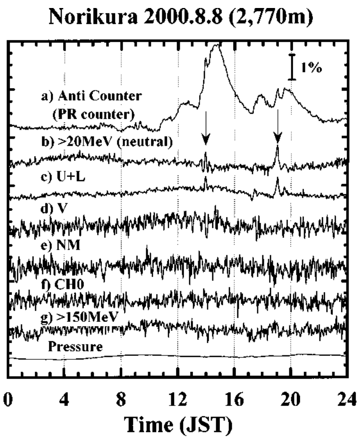

FIG. 1. The time profile of the counting rate on 8 August 2000 at Mount Norikura: (a) 64 m^2 proportional counter (anticounter), (b) 64 m^2 scintillation counter with anticounter, (c) 36 m^2 scintillation counter without anticounter, (d) the same detector but for the coincidence channel, (e) the neutron monitor 12NM64, (f) 1 m^2 $\times 50$ cm plastic scintillation detector, and (g) the above 150 MeV channel of the 64 m^2 detector. Each bin of ordinate corresponds to a 0.5% variation. As shown by the arrow, at 14 Japanese Standard Time (JST) and 19 JST, two spikes can be seen, which we discuss here as evidence for muon decay electrons produced by the thunderstorm rundown mechanism. The excess could not be seen in higher channels of which the deposit energy is higher than 150 MeV. The incident particle must have energy less than 150 MeV. The data show 3 min value. The scale is indicated by the barred line indicating 1%.

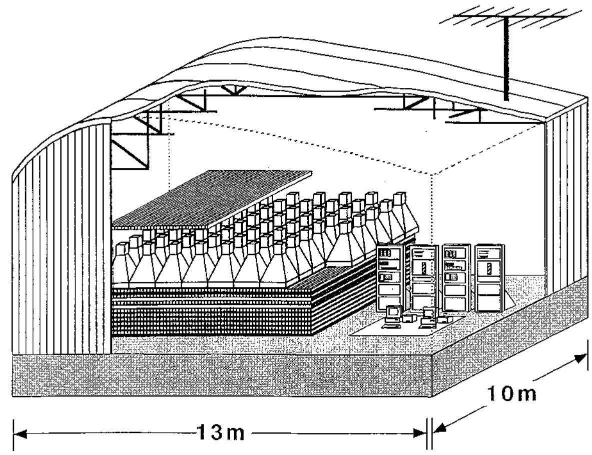

FIG. 2. A birds-eye view of the 64 m^2 solar neutron telescope. The 64 m^2 array of proportional counters installed at the top of the detector, enabling us to discriminate between charged and neutral particles (the "anti" counter). Above it there is a 5 mm layer of lead, which converts photons into electron-positron pairs. Neutrons are converted into protons in the thick layer of scintillator. These are identified and recorded as having energies greater than 21 MeV (S1) and greater than 42 MeV (S2), respectively.

and produces the necessary coincidence signal between U and L. For (U+L) we do not require coincidence but only that there is a signal in either the upper or lower layer or in both (i.e., U and/or L). The signals V and (U+L) are recorded every 10 sec.

In addition to the diurnal and other slow variations of the cosmic ray intensity, occasional "bumps" in the counting rate of (U+L) are observed, as shown in Fig. 1. (The vertical scale is explained in the figure caption.) We define a bump as a short-lived variation that exceeds 1% or more of the average value. Initially, it was thought that these might result from the low energy emissions of radioactive isotopes dissolved in rain or snow. However, the observatory is often covered by over 4 m of snow in winter and it is difficult to believe that any low energy emissions could penetrate to the detector in such circumstances. We have a quite different explanation for these variations, as described in this paper.

A 1 m^2 *solar neutron telescope* was constructed in 1990 as a pilot experiment to demonstrate its capability of detecting solar neutrons, which was achieved during the large solar flare of 4 June 1991 [28]. This telescope is surrounded by anticoincidence counters so that only neutrons with energies >50 MeV can be detected.

The *muon detector* was installed by the ICRR group in collaboration with Fujimoto [29,30]. Its purpose is to determine the fine structure of magnetized clouds coming from the Sun [Cornal Mass Ejections (CMEs)] and the associated Forbush decreases. Only the data obtained by the coincidence between the top and bottom layers of the detector are used. Above these layers there are 5 cm thick lead blocks (about eight radiation lengths) that absorb electrons and protons with energies below 400 MeV but permit muons with energies greater than 120 MeV to penetrate, removing the background of soft gamma rays.

The *Nagoya* 64 m^2 *neutron telescope* was constructed in 1996 with the aim of observing solar neutron events in detail. A general view of the detector is shown in Fig. 2. It consists of 64 boxes, each 1 m$\times$1 m, containing a plastic scintillator with dimensions 1 m$\times$1 m$\times$0.2 m and sensed from above by photomultipliers (Hamamatsu R1512). Beneath these are four layers of proportional counters used to determine the direction of arrival of charged particles. Two layers are in the east-west direction, while the other two are in the north-south direction. From the pairs of directional counters, the arrival direction can be classified into five directions, and by combining the pairs, the counting rate in 25 different directions of the sky can be obtained. Thus with trigger logic the direction is resolved into 18° bins. This telescope function can be used to identify solar neutrons from their direction of arrival. Solar neutrons are converted into protons inside the thick plastic scintillator before penetrating the four layers of proportional counters.

Beneath the telescope system there is a layer of wood and three further layers of proportional counters laid out in the X and Y (horizontal) directions (see Fig. 2). The wood is 10 cm thick and has a density of 1 g/cm^3. The total amount of matter corresponds to 3.5 radiation lengths, which can be penetrated by muons with energies greater than 150 MeV.

The trigger logic of the 64 m^2 telescope is rather complex. It has been designed to enable charged particles as well as neutrons to be recorded. In order to record neutrons, the signal from the top layer of the proportional counter is used as the anticoincidence signal ("anti") for pulses produced in the 20 cm thick plastic scintillator. The peak energy depos-

TABLE I. Detector responses. PR indicates Proportional, and BF3 indicates Boron Trifluoride.

Channels	Main particles	Energy	Detector
Anti	γ, $e^{\pm}$, $\mu^{\pm}$	>1.5 MeV	64 m^2 PR counters
Anti+S1	γ, n	>21 MeV	64 m^2 plastic scintillator
S2	$e^{\pm}$, $\mu^{\pm}$, p	>42 MeV	64 m^2 plastic scintillator
Channel 10	$\mu^{\pm}$, $e^{\pm}$	>150 MeV	64 m^2 PR counters
U+L	$e^{\pm}$, $\mu^{\pm}$	>10 MeV	36 m^2 plastic scintillator
V	$e^{\pm}$, $\mu^{\pm}$	>20 MeV	36 m^2 plastic scintillator
NM	n, p, μ^{-}	>10 MeV	12.7 m^2 BF3 counter

ited by muons is greater than 42 MeV (allowing for the inclination of the tracks). The trigger level is set at half the discriminator level [S1 (21 MeV) and S2 (42 MeV)]. The signals (anti+S1) and (anti+S2) correspond to photons that are converted to electron-positron pairs within the plastic scintillator. The simple S1 and S2 signals (energies above 21 MeV and 42 MeV, respectively) are associated with electrons, positrons, and muons.

The response properties of the detectors are shown in Table I.

At the moment our observations have been made during winter time. However, from 2004, the Observatory will operate automatically as a result of the use of low power complementary metal-oxide semiconductor circuitry operated by solar and wind power generators, which provide on average about 20 W. This system will be used for both the neutron monitor and the 64 m^2 solar neutron telescope.

V. OBSERVATIONS MADE IN SUMMER 2000

In the early summer of 2000, as is typical in the Japanese Alps, Mount Norikura was enveloped by thunder clouds every afternoon. At the end of July, a strong Pacific high-pressure zone usually covers Japan and the weather becomes very stable. In early August the high-pressure zone usually recedes so that, in the afternoons, meteorological conditions in the Alps become unstable. Water vapor produced by strong solar heating in the morning rises and cools, producing ice crystals at altitudes greater than about 5 km. These in turn become charged, by collisions, electron accretion, or otherwise, and, as a result, a three-cell charge distribution builds up in the cloud such that there is usually an excess positive charge at the bottom and top of the clouds and an excess negative charge in the middle. In summer the top of the clouds may be as high as 14 km altitude while in winter it is more like 6 km.

In the year 2000 we made observations of the variations of the count rate (U+L) and of the proportional counters at the top of the Nagoya 64 m^2 neutron telescope, on a number of occasions, including a run of five successive days. An example (8 August 2000) is shown in Fig. 3 together with other data. (The vertical scale is explained in the figure captions.) It can be seen that the (U+L) channel shows increases at the beginning and end of increases of the counting rate in the proportional counters. It seemed at the time that the weather conditions, notably lightning, might have had something to do with this effect and indeed one of us (Y.M.), while working in the laboratory, observed the occurrence of lightning and strong rainfall at the time of the peak counting rate of the proportional counters (about 1500 JST on 8 August 2000). There was no change in the counting rates of other Mount Norikura detectors [the NM data are shown in Figs. 1 and 3(e)], which is evidence that there was no electrical interference associated with the thunderstorm and that the changes in the secondary cosmic rays reflected in (U+L) were real.

Our detectors are located inside a building with a zinc-covered roof, which perhaps forms a protective Faraday cage. Internal a.c. power supplies are not significantly affected because noise filters have been installed at the power supply gate for each detector. It is interesting to note that no sudden changes of counting rate were observed at Mount Norikura after lightning, in contrast to Baksan where such changes were frequently seen during 2000 [15].

VI. OBSERVATIONS MADE TOGETHER WITH AN ELECTRIC FIELD MILL (2001–2002)

In order to investigate these phenomena further, we installed an electric field meter (''mill'') at the Mount Norikura Observatory in 2001. This measures the electric field strength by means of a rotating chopper within the mill. The device was calibrated by charging two large electrodes (diameter 31 cm) to known voltages and placing the field mill between them at a separation of 50 cm.

We define a ''positive'' electric field as having a distribution of positive charge in the atmosphere above the detector and an induced (image) negative charge at ground level so that positive muons, positrons, and protons are accelerated downward toward the detector. For a ''negative'' field there is a negative charge in the atmosphere above the detector and a corresponding induced positive charge at ground level, so that negative muons and electrons are accelerated downward toward the detector. In both cases additional gamma rays are also produced as bremsstrahlung.

Weather conditions at Mount Norikura in early August in 2001 and 2002 were quite stable and there were no large rainstorms each day, as there had been in the summer of 2000. Examples of cosmic ray ''bumps'' can be seen only in the data of 2 and 4 August 2001 and of 9 and 15 August 2002. The rainy season in Japan usually starts in early June and continues to the end of July with a rain front standing over Japan for a long period and disappearing with the onset of summer. The balance between the warm Pacific high pressure and the cold Okhotsk high pressure causes the rain front to move from south to north, and vice versa.

We have selected several examples of thundercloud effects from the observations made in 2001 and 2002, as shown in Figs. 4 and 5. In general it can be seen that the counting rates in channels (anti+S1), S1, S2, and (U+L) all increase with negative electric field whereas the V and NM channels usually do not change significantly. This pattern is clear in the events observed in 2001 and in some of the events observed in 2002, for example, on 27 June, 4 and 14

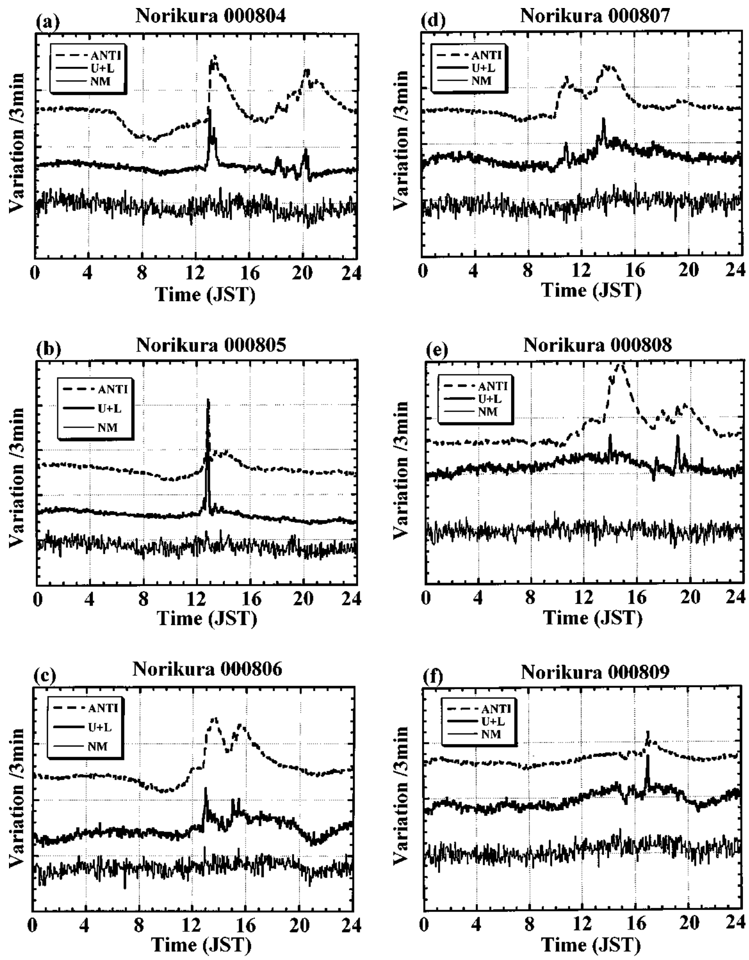

FIG. 3. (a)–(f) Time profiles of the counting rates of our detectors at Mount Norikura for 4, 5, 6, 7, 8, and 9 August 2000. Only the counting rates of the 64 m^2 anticounter (anti), the 36 m^2 scintillator upper and lower arrays (U+L), and the 12 m^2 neutron monitor (NM) are shown. The variation of the 64 m^2 proportional counter reflects the presence of "rain-out" radon daughter products. The count rate of the neutron monitor was quite stable and unaffected by the occurrence of lightning except on 6 August. [Scale 0.5%/division for anti, 0.25%/division for (U+L), and 1%/division for NM.]

August, 3 and 14 September in 2001 and on 3, 10, and 15 July and 30 September 2002.

Usually, thunderclouds form in the rainy season and at the end of summer in a similar manner, with warm air rising through cold air as the atmosphere becomes unstable. However, in 2000, conditions in the Japanese Alps must have had the effect of causing a local upward flow of air and producing almost the same kind of thunderclouds with a double structure in the counting rate as shown in Fig. 3. Weather conditions are monitored regularly at villages 13 km NW and SE of the observatory and in early August 2000 showed a clockwise wind flow, implying that there was indeed an upward flow of air around Mount Norikura at the time.

In the data of 9 June 2001, the electric field was rather flat for 4 h between 1500 and 1900 and there was only a little rainfall [Fig. 4(a)]. Two clear bumps in the particle data suggest that the counting rate might be affected by the electric field at altitudes perhaps 5–10 km higher than the observatory.

In the data of 15 July 2002, it can be seen that the counting rate does not show a clear effect when the field briefly becomes positive at 1430. There was strong rainfall between 1400 and 1800. On the other hand, just after 0900 on 10 July 2002, there are small decreases in all channels, except the neutron monitor, when the field direction was positive. This must be the result of a reduction of the flux of electrons. However, for the large event beginning at 0945 on 17 July 2002, there were even 3σ enhancements in the counting rate of the neutron monitor. When the field switched from negative to positive at 1025, there were increases in most channels, regardless of the sign of the field. We suggest that in this case the field direction at the surface changed while the general field in the cloud above remained the same.

VII. MONTE CARLO SIMULATIONS OF MUON CASCADES IN AN ELECTRIC FIELD

In order to investigate the effects of electric fields on cosmic ray secondaries (especially muons), which pass through thunderclouds, we have carried out a Monte Carlo simulation using the GEANT 4 program (version 4.4.1.p01). Our experimental results show that, at the altitude of the Mount Norikura observatory, the muon intensity is approximately twice that of the electrons and positrons (for energies

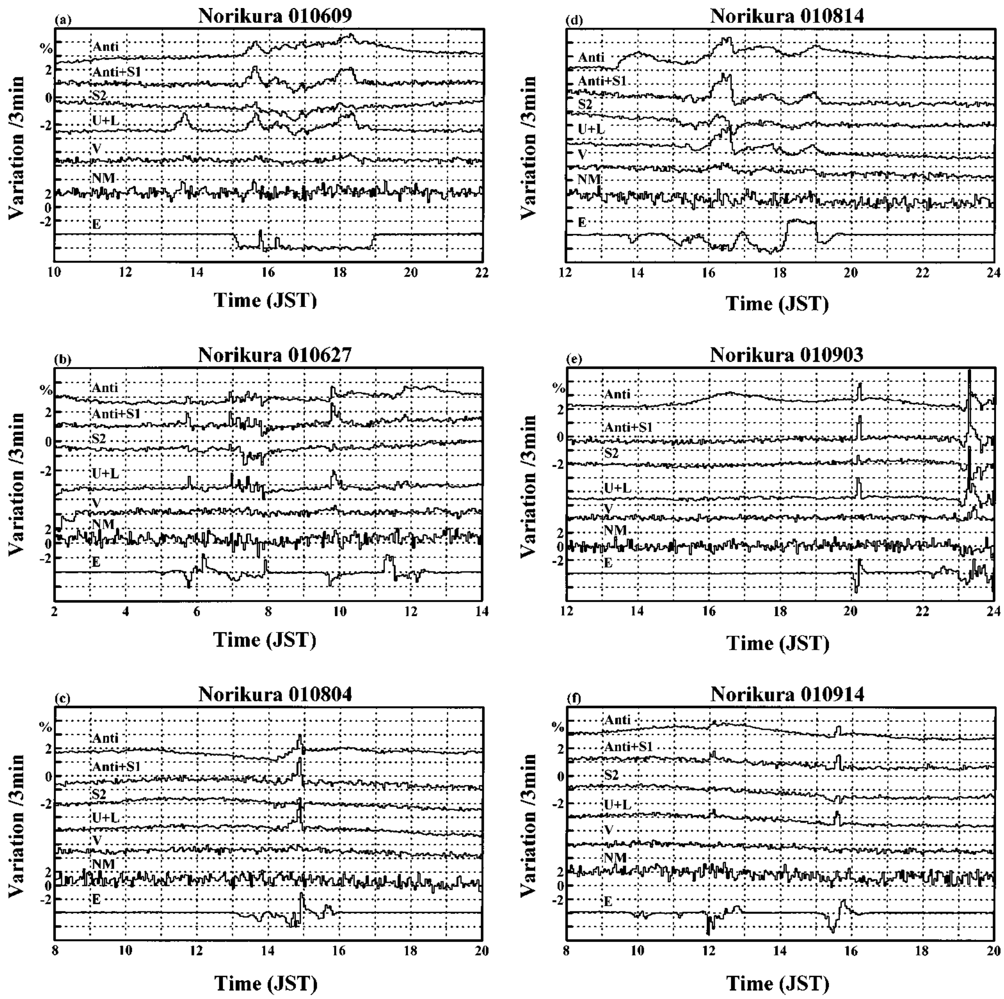

FIG. 4. (a)–(f) Time profiles of the counting rates on 9 and 27 June, 4 and 14 August, and 3 and 14 September 2001. The channels shown are, from top to bottom, the 64 m^2 anticounter (anti), anti + S1 (neutral), S1 (charged), 36 m^2 (U+L), and the neutron monitor, respectively. Corrections for the pressure effect have been applied. Each bin of the ordinate corresponds to a 2% variation. In the case of the electric field one bin corresponds to 10 kV/m. Note that the counting rates increased in the presence of a negative electric field.

$>$10 MeV). Thus we have focused our attention to begin with on following these muons and their secondaries in the presence of a constant vertical electric field.

In the cascade process, high-energy cosmic rays make nuclear interactions with the atmosphere producing charged and neutral pions. Charged pions decay soon into muons and neutrinos but some make further nuclear interactions. Neutral pions decay almost immediately into two photons and in turn produce an electromagnetic shower. According to measurements, the number of muons exceeds the number of electrons at atmospheric depths more than 600 g/cm^2 [11]. The muons are mostly produced at about 10 km above sea level and come down to the altitude of the observatory. The initial positive charge of cosmic rays is transferred to the muon charge ratio and hence a positive charge excess is observed.

Measurements made at altitudes of 2960 m and 5260 m show that the μ^+/μ^- charge ratio is approximately 1.5 in the energy range from 500 MeV to 3 GeV [31,11]. In our Monte Carlo calculations, we made the following assumptions.

(1) We used this charge ratio.

(2) We assumed that there is a uniform vertical electric field from 10 km altitude above sea level down to the altitude of the Mount Norikura Observatory (2770 m a.s.l.), resulting in acceleration and deceleration of charged particles. In fact, the tops of thunderclouds often reach altitudes of 14 km a.s.l. in summer time with the upper regions becoming positively charged. Below 10 km a.s.l., the cloud is mainly negatively charged except for a small positive pocket at the base. Thus our approximation is quite a reasonable one.

(3) We have not taken into account effects of the geomagnetic field since the bending of low-energy muons by the magnetic field is of the order of a few hundred meters horizontally, in comparison with the vertical running distance about 10 km. The effect can be neglected in the current calculation.

(4) We have not started our Monte Carlo calculation from the initial collision processes between primary cosmic rays and atmospheric nuclei. Instead, to reduce the necessary computation time, 50 000 muons have been assumed to be generated at 10 km a.s.l. and their energy spectrum and charge ratio followed as described below.

(5) The muon energy spectrum in the atmosphere has

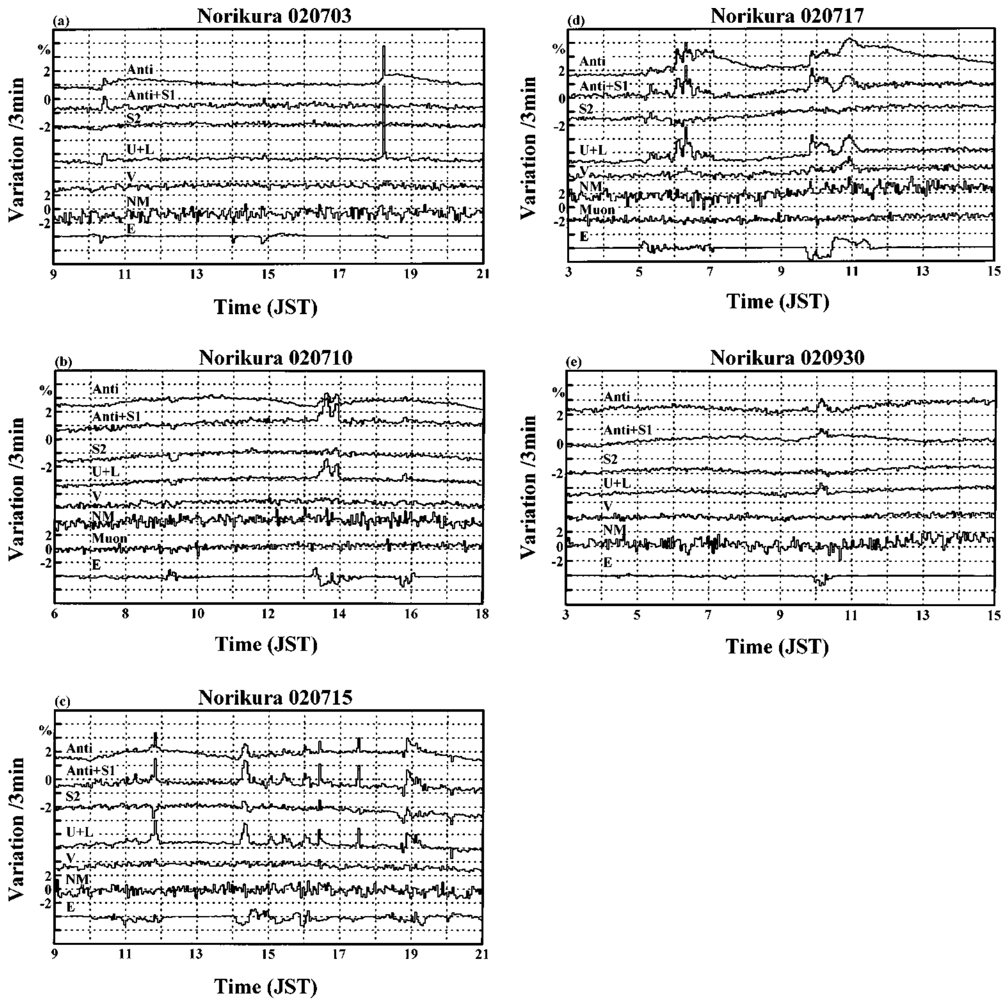

FIG. 5. (a)–(e) Time profiles of the counting rates observed on 3, 10, 15, and 17 July and 30 September 2002. The excesses were associated with negative electric fields. An exception is seen at 11 h of local time on 17 July (d). The 19 m^2 muon data are added in (b) and (d). The scale is the same as in Fig. 4.

been measured *in situ* at 10 km a.s.l. by Coutou *et al.* [32]. We have used this spectrum in the range 300 MeV to 40 GeV together with the associated angular distribution of muons within 10° of the vertical direction as inputs for our simulation.

(6) Muons are assumed to have been generated with the observed angular distribution between 0° and 10°.

(7) The atmosphere was taken to be the U.S. Standard Model.

(8) The simulation volume was taken to be 5 km$\times$5 km $\times$10 km (altitude).

The calculated variation of the total muon intensity at the level of the Mount Norikura Observatory, with varying vertical electric field strengths, is shown in Fig. 6, for muon energies from 100 MeV to 3 GeV and a muon charge ratio of 1.5. The number of muons detected at Mount Norikura with $E_\mu > 100$ MeV is 10 800 events. This arises because we have generated muons with $E_\mu > 300$ MeV and the low-energy muons decay and are absorbed in the atmosphere before reaching Mount Norikura. For muon energies $\leqslant 2$ GeV, the electric field has no significant effects in the range -80 kV/m to about $+20$ kV/m, but there is a clear increase (10–20 %) in the range above $+65$ kV/m. For muon energies exceeding 3 GeV there is no significant effect in the range -80 to $+80$ kV/m. The corresponding variation of the "soft" component (electrons, positrons, and gamma rays) is shown in Fig. 7. These particles, in contrast to the muons, tend to show increases for large electric fields outside the range ± 40 kV/m regardless of charge. This soft component is produced either by the decay of muons or by the knock-on processes from high-energy muons. Photons are also produced as bremsstrahlung from these electrons and positrons. We have taken into account all of these processes in the Monte Carlo calculations. The number of electrons and positrons with energies higher than 40 MeV [Fig. 7(a)] is approximately 2000 and of photons [Fig. 7(c)] is 2350, whereas the number of photons with energies higher than 20 MeV is 4300.

The differing behaviors of the lower-energy muons can be accounted for by noting that the muons are produced predominantly at an altitude of about 10 km a.s.l. Muons with energies above 1 GeV can reach the altitude of Mount Norikura, losing energy by ionization loss (on passing through about 500 g/cm^2 of atmosphere), and occasionally

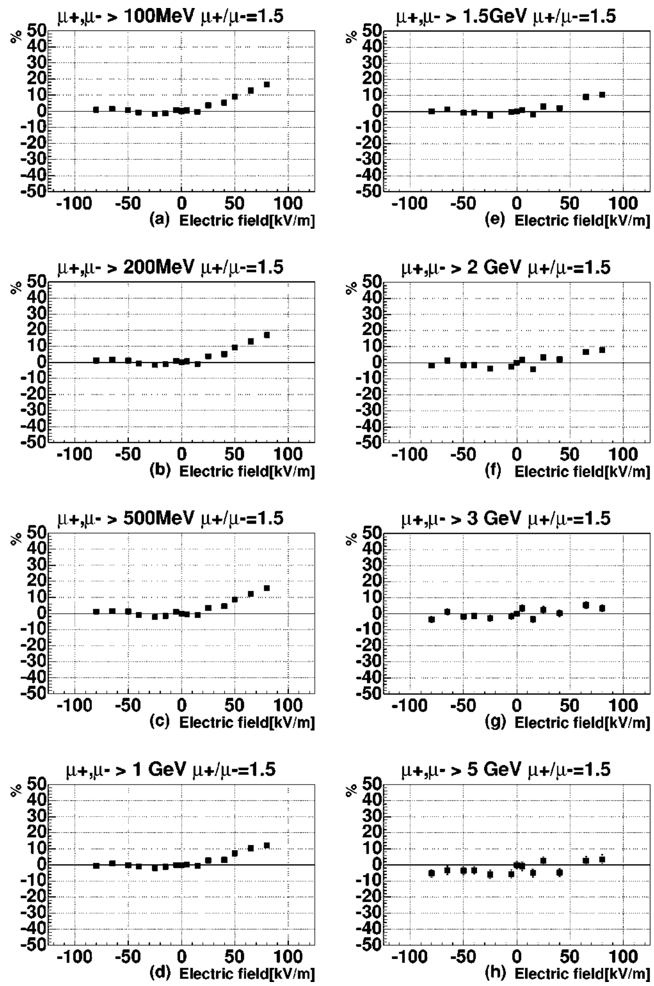

FIG. 6. (a)–(h) Results of Monte Carlo simulations of the effects of electric fields on air showers. The variation of the total muon intensity is shown as a function of the thundercloud electric field (assumed to be constant below 10 km altitude). For positive and negative muons in the energy range $>$100 MeV to $>$2 GeV, there is no very obvious dependency on the field. Variations are expected in the case of positive rather than negative electric fields because the predominance of positive muons in the shower ($\mu^+/\mu^-\approx1.5$). However, for muons $>$3 GeV, the variations should not be expected within the range of field strengths $\pm$80 kV/m.

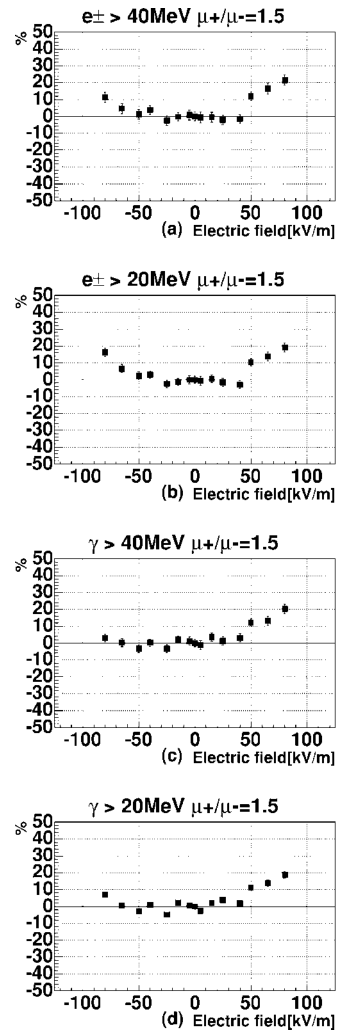

FIG. 7. (a)–(d) As for Fig. 6 but for electrons and positrons produced by the decay of low-energy muons or for muon-produced knock-on electrons. The threshold energy is $>$20 MeV and $>$40 MeV. The variation of photon flux is shown in (c) and (d). These photons are produced as bemsstrahlung from electrons and positrons.

decaying to electrons and positrons (which in their turn produce gamma rays by annihilation). This is evident from the spectrum measured at mountain altitudes, which has a shoulder around 1–2 GeV [31]. Thus particles observed at lower energies (0.1–2 GeV) originate at significantly higher energies where the change in energy associated with the electric field is relatively small and hence the electric field does not appear to affect them as much as one might have expected.

It is important that the muon charge ratio should exceed unity as we have assumed; otherwise the variations in the muon flux would largely disappear. This is because the enhancement associated with muons that have been accelerated by the electric field is effectively compensated by the depression of the intensity of those that have been decelerated (see Fig. 8).

For the ''soft'' components, namely, electrons, positrons, and gamma rays associated with muon decays and bremsstrahlung, the effects of the electric field are quite different, especially if the signals associated with electrons and positrons are combined as in our detection system. The results of simulations are shown in Figs. 9 and 10. There is a clear effect on individual species, as shown in Fig. 9, but when combined the fluxes of positrons and electrons show little change except for electric fields greater than about $\pm$50 kV/m. The same holds for gamma rays, which are mainly produced as bremsstrahlung by these particles.

VIII. PERIODICITIES IN THE OCCURRENCE OF "BUMPS"

We have accumulated enough data since the Nagoya 36 m^2 meson monitor was installed to be able to investigate periodicities in the occurrence of ''bumps,'' which are pre-

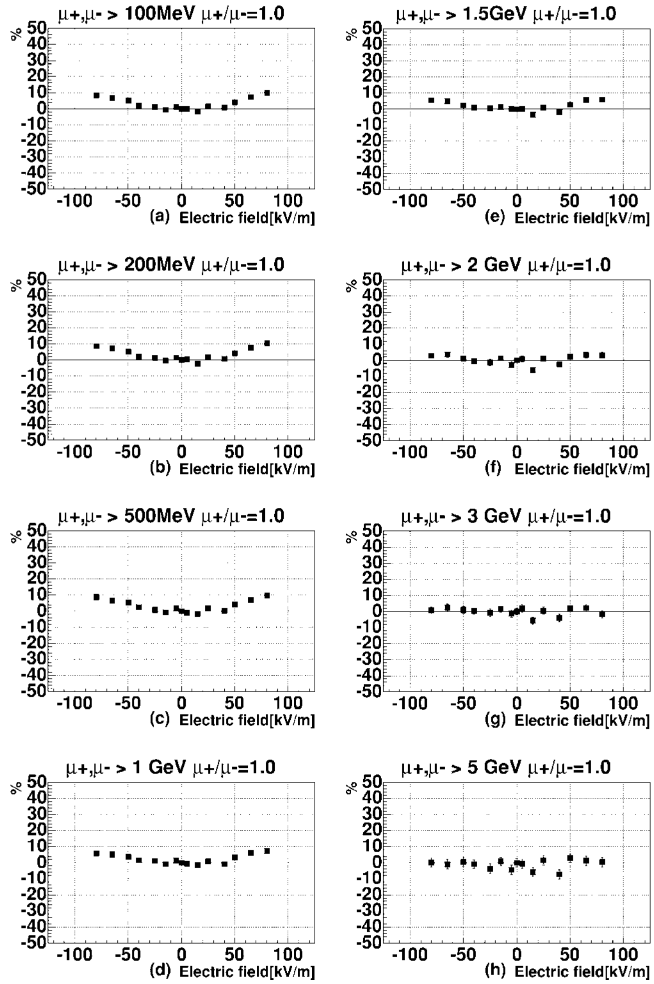

FIG. 8. (a)–(h) The variation of the total muon intensity in the (unrealistic) case of equal muon intensities ($\mu^+/\mu^- = 1$). A symmetrical variation of the intensity with respect to positive and negative fields is to be expected. However, for higher-energy muons (>2 GeV), the variation is absent. (Since cosmic rays are mainly positively charged, this property is transferred to the muons, which accordingly have a charge ratio of about $\mu^+/\mu^- = 1.5$.)

sumably associated with electrical activity in the atmosphere above Mount Norikura as described here. The months when events occurred are shown in Fig. 11: it is clear that they occur mainly in summer but there are occasional events also in winter. This is consistent with the occurrence of thunderstorms.

We have analyzed almost 11 yrs of continuous data obtained between 26 October 1990 and 15 January 2002 from channels (U+L) of the 36 m^2 scintillation detectors of the meson monitor. The events were defined as intervals in which the count rate exceeds the average of the 3 min count rate by 1%. The days on which the event(s) occur are flagged (1) and those with no events are flagged (0). In this way we have constructed a time series, on a daily basis, for the whole period of 11 yrs. We have used this to search for periodicities on the basis of the maximum entropy method. The result is that a periodicity of 26 days is apparent in the data.

We have also generated 20 000 artificial time series based on randomly occurring events. Each artificial data set contains the same number of events as observed during 11 yrs, that is, 318 events are distributed randomly in 4016 days. For each randomly generated data set (generated by the uniform random number distribution), a search for periodicities has been made, again using the maximum entropy method and searching for periods between 2 days and 100 days. It has been found that one apparent period with power exceeding 0.14 is realized for every 370 time trials and one for every 20 000 time trials with power exceeding 0.20. In other words, on the basis of the maximum entropy method, the probability of seeing this 26-day periodicity is once per 220 000 yrs, corresponding to 4σ. The dashed line and dotted line of Fig. 12 show the 4σ and 3σ limits expected for white noise.

As shown in Fig. 12, the results are quite surprising: there

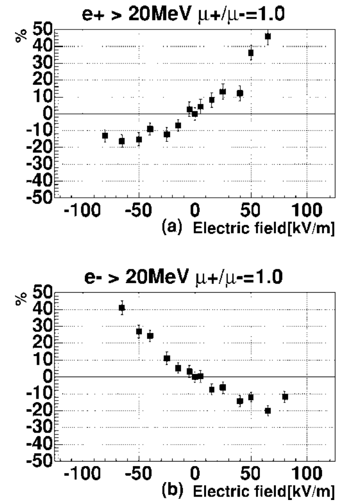

FIG. 9. (a),(b) The variation of the soft components ($E > 20$ MeV) with electric field strength for (a) positrons and (b) electrons separately in the case of $\mu^+/\mu^- = 1$, showing a clear dependence on the field direction.

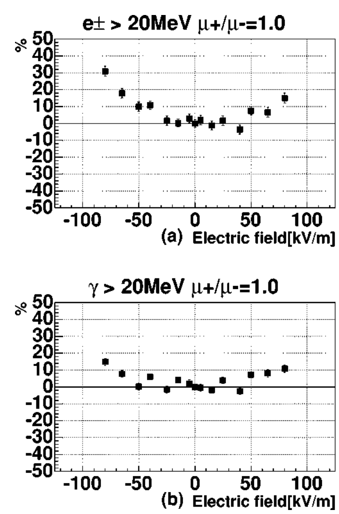

FIG. 10. (a), (b) On combining the electron and positron intensities the variations shown in Fig. 9 almost cancel, except where the electric fields are strong: (a) electrons and positrons combined; (b) gamma rays.

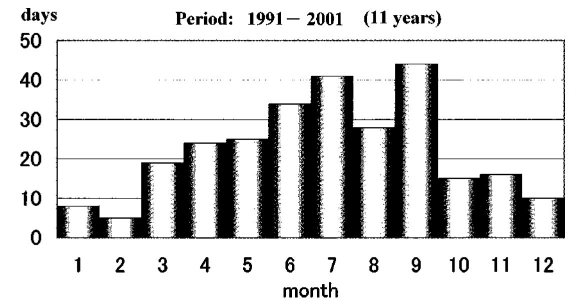

FIG. 11. Monthly occurrences of thunderstorm-related events for a period of almost 11 yrs, running from 26 October 1990 to 15 January 2002. It is clear that the events occur mainly in the summer although a few are observed in winter (the corresponding solar cycles are 22–23).

is a clear 26-day period with a statistical significance exceeding 4σ. We repeated the analysis, separating the data into years of high solar activity (1991–1992, 1999–2001) and low activity (1994–1998) and found that, whereas the periodicity is absent during periods of low activity, it is clearly present during periods of high activity (about 3σ). This confirms that there is a solar cycle effect. Furthermore, since 26 days is close to the apparent period of rotation of the sun at latitudes where solar activity occurs, it seems reasonable to associate the two phenomena. Indeed, there is a tendency of the cosmic ray intensity observed at ground level to show such a quasiperiodicity with the same solar cycle dependence [33]. However, we cannot be certain at this stage that the periodicity is not associated with some atmospheric tidal effect [34,35].

It has been suggested that cosmic ray variations might influence the weather on the Earth as a result of associated variations in the production of condensation centers for water vapor in clouds [5]. We have shown that there does indeed appear to be an association, based on the analysis of our results and the general discussion given in Sec. II. However, we recommend caution at this stage since the geomagnetic cutoff at Mount Norikura is 9 GeV and the solar cycle and

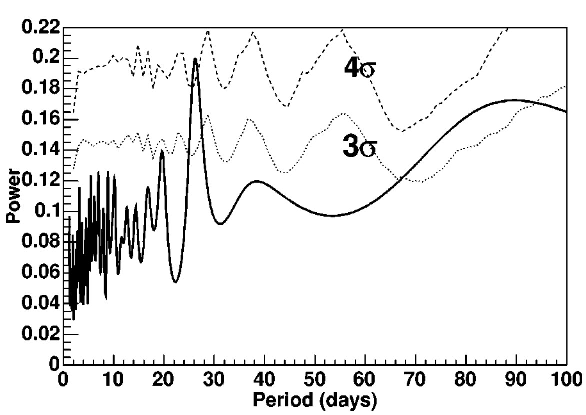

FIG. 12. A maximum entropy analysis of periodicities in the thunderstorm-related events shown in Fig. 11, showing the presence of a 26-day period (line). The dashed line and dotted line correspond to 4σ and 3σ fluctuations expected for white noise in each period, respectively.

26-day variations of cosmic ray intensity at such energies are small (a few percent at most). Perhaps a more important effect is that suggested originally by Ney [36], who noted that the changes in atmospheric electrical conductivity that should be associated with cosmic ray variations might cause changes in thunderstorm activity and hence changes in cloud cover. Furthermore, Ely *et al.* [37] discovered a clear correlation of sunspot number with the occurrence of lightning and suggested that there is a relationship between the 22-year modulation of the ionization density at the 300 mbar level to the sun-weather problem in general.

IX. SUMMARY AND CONCLUSIONS

With the aid of data obtained from an array of cosmic ray detectors at Mount Norikura Observatory, we have investigated the behavior of the fluxes of cosmic ray secondaries in the presence of thunderclouds. We have observed ''bumps'' in the data which are often associated with thunderclouds and which have the following properties.

(1) The bumps occur mainly in summer but also occasionally in winter.

(2) The occurrence of bumps is correlated with bad weather, especially thunderstorms.

(3) They are not the result of electrical interference induced by thunderstorms in our detectors.

(4) Bumps were observed predominantly in association with negative electric fields at the ground but sometimes also with positive fields.

(5) The 64 m^2 proportional counter sometimes showed long-term increases in association with rainfall which were evidently produced by the rain-out of radon daughter products.

(6) In a very few cases the neutron monitor showed a small excess in association with a bump.

(7) Monte Carlo simulations show that the effects of electric fields greater than ± 40 kV/m are apparent even with a muon charge ratio of unity.

(8) For a more realistic muon charge ratio of 1.5, observable bumps are expected for field strengths outside the range -80 kV/m to $+20$ kV/m, which was found to be the case.

(9) The occurrence of bumps showed a significant 26-day periodicity (spectral power 0.02). This suggests that there could be some kind of solar modulation of the occurrence of thunderstorms and/or the behavior of the associated electric fields. However, tidal effects with almost the same period might conceivably be responsible.

(10) A solar cycle variation was found in the 26-day periodicity with spectrum intensity (<0.14) during years of high solar activity (1991–1992,1999–2001), which is consistent with the properties of the 27-day variations of comic rays. However, the periodicity is absent during periods of low solar activity (1994–1998).

With regard to point 4, it has been reported by Dorman *et al.* [38] that decreases (-0.4%) of neutron monitor counting rates occur for very strong negative electric fields (<-80 kV/m) but no changes were found for positive fields. In this case the neutron monitor was shielded by a Faraday cage. Our observations indicate that, during periods when the neutron monitor counting rate showed an increase, the coincidence channel of the muon detector did not change. We suggest that protons were accelerated by a positive field to produce the excess and that this is the first evidence for proton acceleration by thunderstorm electric fields. A neutron monitor can detect low-energy negative muons and hence the decreases reported by Dorman *et al.* could represent a decrease of the counting rate of positive muons as a result of their deceleration in a strong negative electric field.

We intend to carry our investigations further, making use of additional equipment to allow us to determine the relationship of atmospheric and cosmic ray effects. For example, we will install a simple lightning monitor, which will give us information concerning the occurrence of bumps and lightning activity. We will also monitor the rainfall rate more carefully: at present the time resolution is only 1 h and yet there are some obvious correlations. Furthermore, we will investigate the possibility of using a rain current meter in order to relate changes in the current to the ground with changes in the electric field and cosmic ray behavior. We must extend Monte Carlo calculations which include not only muons and also all charged particles, electrons, positrons, and protons. Finally, we will endeavor to remove the effects of compensation of flux changes when electrons and positrons are measured together (see Fig. 9), by attempting to monitor the positrons separately: this may be possible by observation of the annihilation gamma ray line at 1.022 MeV.

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