Real-time monitoring of environmental radiation in Tunguska (Siberia)

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[1] The results of the environmental radiation (ER) monitoring obtained during the Tunguska expedition of July 1999 with a NaI(Tl) scintillation detector are reported. Some interesting meteorological effects related to the airborne radioactive components (radon and thoron decay products) have been observed. The main effects observed are (1) the doubling of the ER during two quite different rain-out episodes and (2) a fairly regular diurnal wave in the intensity of the total radiation. The rain-out phenomenon allows us to approximate the timescale for the removal by precipitation of radioactivity from the air, while the wave phenomenon gives us the opportunity to develop a simplified model for estimating the time-averaged, dry weather surface radon concentration. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0932 Exploration Geophysics: Radioactivity methods; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 9320 Information Related to Geographic Region: Asia; *KEYWORDS:* environmental radiation monitoring, meteorological effects, rain-out, diurnal wave, radon concentration

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1. Introduction

[2] In July 1999 the Physics Department of Bologna University, in collaboration with researchers from the Institute of Marine Geology (CNR, Bologna) and from the Turin Astronomical Observatory, organized a 2-week scientific expedition known as "Tunguska99" http://www-th.bo.infn.it/tunguska/) to the region of Vanavara, a village of central Siberia near the site of the 1908 catastrophic event of cosmic origin [*Longo and the Tunguska99 Expedition Team*, 1999; *Amaroli et al.*, 2000]. The main objectives of the expedition were to study the Cheko Lake sediments (at about 70 km NNW of Vanavara), searching for possible traces of the cosmic body that impacted with the Earth, and to carry out an aerial photographic survey to be compared with the one made in 1938, in which the forest devastation was still clearly visible.

[3] During the same occasion a detector for monitoring the environmental radiation (ER), gamma radiation with $E >$ 25 keV coming from very low secondary cosmic rays and from airborne radionuclides of natural (radon and thoron daughters) and artificial (e.g., ^{137}Cs) origins, was operated. Interest in this monitoring arose from the possibility of investigating for the first time the ER characteristics and temporal variations in a region, such as the Tunguska area, with meteorological and climatic conditions typical of midlatitude continental zones. Measured ER variations could then be compared with results previously obtained from totally different sites, e.g., Antarctica [*Cecchini et al.*, 1997a; *Galli et al.*, 1997; *Brunetti et al.*, 1999a] and the Arctic [*Cattani et al.*, 2001], and at different altitudes [*Brunetti et al.*, 1999b, 1999c; *Aglietta et al.*, 1999]. Moreover, it would be interesting to discover if peculiar levels of ER could be detected and to investigate their possible relationship to the Tunguska event.

[4] In the present paper we report the most significant results from observations of airborne radioactivity. Some preliminary information on this issue is discussed by *Longo et al.* [2000]. Particular attention is paid here to some interesting meteorological effects related to the activity of the principal radon daughters (^{214}Pb and ^{214}Bi) and thoron daughter (^{208}Tl) γ ray emitters. The former are by far the most important radionuclides that can be detected with the aid of our instrument [*Cecchini et al.*, 1997b]. Having short half-lives (26.8, 19.7, and 3.1 min, respectively), they are very good tracers for many atmospheric transport processes on timescales from a few minutes to several hours. This is because while radon and thoron are absolutely inert and remain as gaseous components of the atmosphere after their emanation from the soil, their decay products are heavy metals in the form of strongly reactive ions, a large number of which attach themselves to aerosol particles suspended in the air in $\sim$1–100 s [*Porstendörfer*, 1994]. As a consequence, they experience similar processes, such as diffusion, turbulence and transport by the winds, and removal

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(mainly by rain), resulting from washout processes inside the clouds, with final deposition to the ground. However, significant differences exist between the behavior of ^{214}Pb and ^{214}Bi and the behavior of ^{208}Tl, as we will see. As has been shown by our previous monitoring campaigns, the capability of our detector to collect data with a short sampling time (starting from a few minutes) in different conditions offers interesting possibilities for studying these processes in real time, especially if accompanied by more traditional measurements of the same type.

2. Detector and Acquisition System

[5] The detector used in the present campaign is a slightly modified version of the one described by *Cecchini et al.* [1997b]. It is based on a cylindrical NaI(Tl) monocrystal (10 cm $\times$ 20 cm) shielded by a layer of Pb (2 cm thick), with Cu (0.1 cm) and Al (0.3 cm) shaped around the scintillation crystal and the photomultiplier tube (PMT) (see Figure 1). We specially designed the detector to be easily transported and disassembled and reassembled without difficulty, thus allowing its transportation to places that are difficult to reach.

[6] It must be noted that 2 cm of lead is not enough to shield the detector from all the radiation coming directly from the ground, but we could quite comfortably assume this contribution to be almost constant through time (at least during the short period of measurement), so that it could be ignored when studying, as we did, the temporal variations of environmental radiation (this is evident in Figure 4, which shows a series of prominent peaks in the curve of the total radiation residing on a constant level background).

[7] An idea of the amount of the radiation contribution from the ground can be deduced (Figure 4), in which the effect of shielding when the detector has been turned upside down is shown. In this phase the NaI detector was only 20 cm from the ground. Considering the combination of the two effects (shield and closer distance of the source), we think that the shielding of the 2-cm Pb layer is quite satisfactory; that is, the radiation contribution from the ground represents only a small part of the counting rate. From measurements made with a similar detector, but with only 1 cm of Pb shielding the detector, we have observed that the contribution of a radioactive source placed at a fixed distance below the detector was <10% of that of the same source placed above the detector (with a nonshielded crystal). We expect that with a 2-cm Pb shield, this contribution should be further reduced for the energy band of the ER. If one considers that the observed variations, either during the rain episodes or during the diurnal waves, are conspicuous, then the small contribution coming from the ground, however variable, can be considered negligible for our purposes.

[8] The stability of the PMT gain was assured by the intrinsic stability of the high-voltage power supply provided by the Canberra acquisition card coupled with the PC performing the data acquisition (DAQ). The system records the pulse amplitude spectra of detected γ rays over 2048 channels with a preselected sampling time. In the present case, the sampling time interval was 15 min and the energy per channel was set to 3.3 keV. Two parts compose the DAQ program. The first part performs the spectrum accumulation and is shown on the display in real time. The second part can be activated independently and makes it possible to obtain the plots of the time series of the counts, collected in different properly chosen energy bands, up to the last completed acquisition (see Figure 2). Thus it is possible to make a fast inspection of the time behavior of different ER components and relate them to the observed meteorological conditions. The instrument was located at 60°57′49″N, 101°51′21″E, inside a tent at the expedition base camp close to Cheko Lake. Unfortunately, it has not been possible to ensure the absolute continuity of the DAQ due to numerous interruptions of the power supply generator.

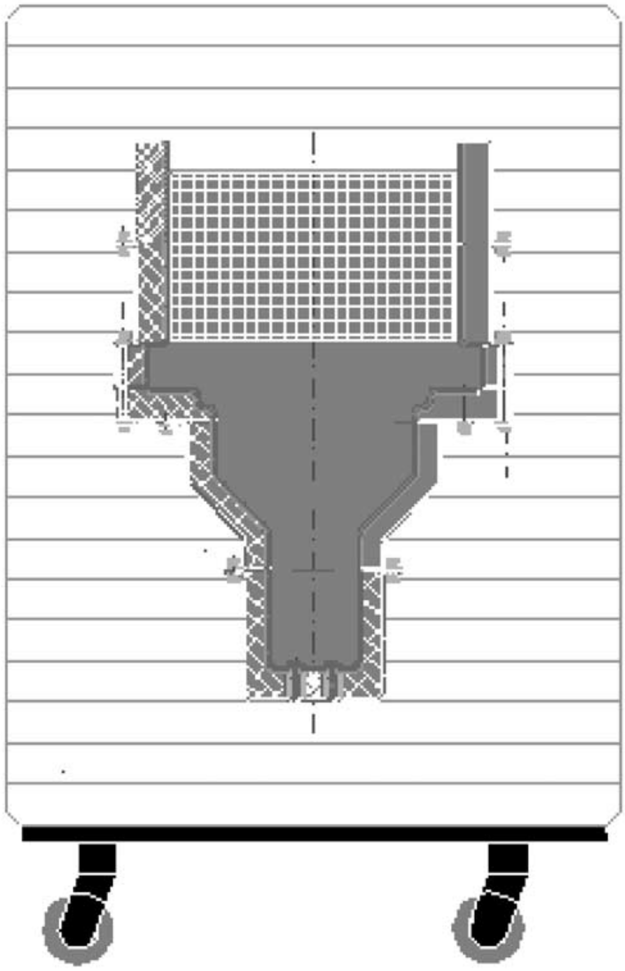

Figure 1. Drawing of the new version of our standard detector. The NaI(Tl) monocrystal together with its photomultiplier tube (PMT) is embedded in a thermal insulator.

[9] Few and sparse meteorological data have been collected and recorded in the absence of a dedicated instrumented station. However, it has been possible to make a partial a posteriori reconstruction of weather conditions on the basis of in situ visual observations and information from the closest meteorological station in Vanavara.

3. Observations

[10] Cheko Lake (~700 m long and ~300 m wide) is located NNW of Vanavara at 354 m above sea level on the

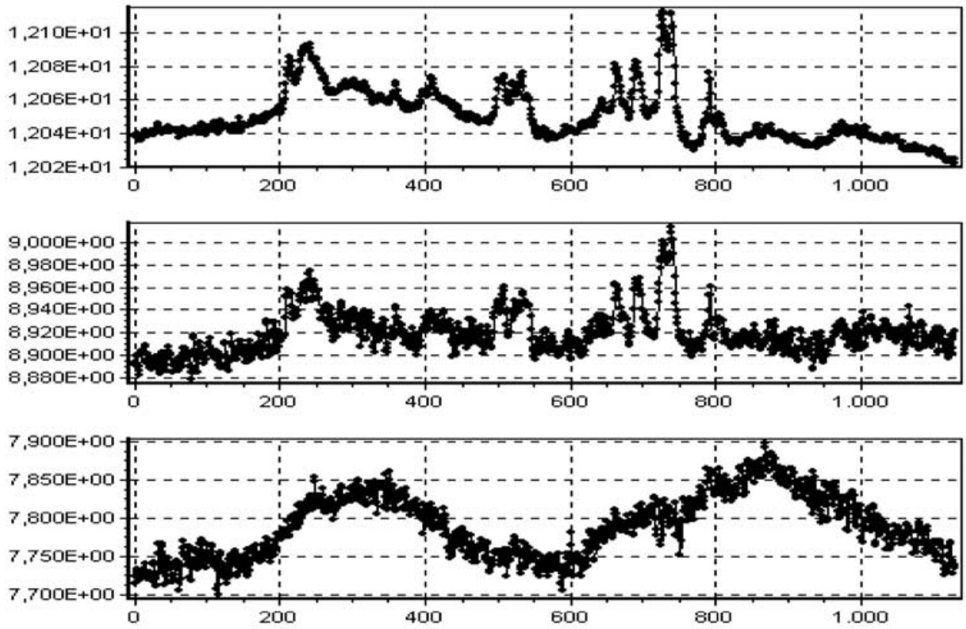

Figure 2. Plot of the data acquisition quick-look for the period 11 March 2000, 0732 UT to 23 March 2000, 0411 UT. Here only the three time series of the logarithm of counting rates with a 4-min sampling time are presented. (top) Total spectrum. (middle) ^{214}Bi in the band 550–640 keV. (bottom) Cosmic ray component in the band 3–10 MeV.

central Siberian highland and is surrounded by forest and swamps (see Figure 3). The permafrost layer starts at 35 cm under the dry soil and at 60–90 cm under the swamps and extends down to an estimated depth of 30 m.

[11] During the period of detector operation, from 19 to 28 July 1999, two types of meteorological conditions occurred: a first phase of perturbed weather with three rain episodes on 19, 21, and 23 July, and a second phase, starting from 24 July, with very stable weather accompanied by strong day-night temperature excursions.

[12] Figure 4 shows the time series of the γ counting rates registered for two energy bands. The first one, in the energy interval 3–10 MeV, corresponds to the cosmic ray component; the second one, in the energy interval from 25 keV to 3 MeV, includes contributions from cosmic rays with energy <3 MeV and from the actual airborne radioactivity. One can notice a remarkable radioactivity enhancement registered on 21 July accompanied by an equally remarkable decrease of the cosmic ray component. These are caused entirely by the fact that the detector has been turned upside down in order to face the ground directly and to make a comparison between the two sources. In Figure 4 one can observe time variations of a sporadic nature, with fast increases and subsequent slow decreases of activity in time intervals of several hours (e.g., 19 and 23 July) and regular diurnal variations occurring from 24 July onward.

[13] In Figure 5 we report the hourly counting rates of the cosmic ray component. Systematic atmospheric pressure data at the site not being available, the correction for the pressure effect has been carried out using atmospheric data recorded by the meteorological station in Vanavara, supplemented by pressure data from the Yakutsk (62°01′12″N, 129°43′12″E) and Irkutsk (52°28′12″N, 104°18′00″E) cosmic ray stations. Our corrected data series are in fair agreement with the observations made by the Neutron Monitor stations in Apatity (67°33′00″N, 33°19′48″E), Yakutsk, and Irkutsk when the differences in the geomagnetic cutoff [*Smart and Shea*, 1997] and in the response function of the different detectors [*Cattani et al.*, 2001] are taken into account. Unfortunately, the Forbush decrease at the end of 27 July almost coincides with the end of detector operation.

3.1. Rain Events of 19 July and 23 July 1999

[14] Figure 6 shows the time behavior of the ER component in the energy band from 25 keV to 3 MeV during the thunderstorm that occurred on the evening of 19 July. As can be seen, a rapid increase lasting about 1 hour, followed by an

Figure 3. Cheko Lake and its surroundings. See color version of this figure at back of this issue.

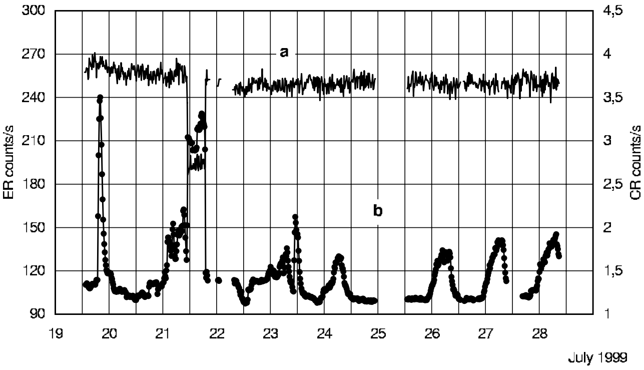

Figure 4. Time history of the counting rates of environmental radiation (ER) at Cheko Lake in two energy bands. Cosmic ray component in the interval 3–10 MeV (curve A). Total radiation (cosmic ray and airborne radioactivity) in the interval 25 keV to 3 MeV (curve B). Note the two rain episodes and the diurnal wave starting on 24 July (see text).

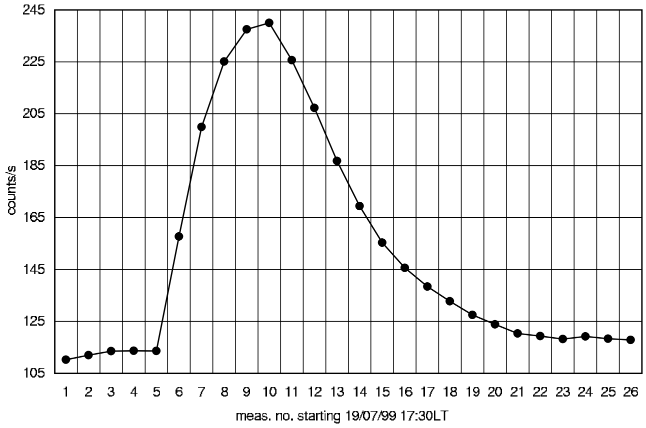

Figure 6. ER intensity enhancement registered at the base camp of Cheko Lake during the thunderstorm on 19 July. Note the steep rise in counting rate while it is raining, followed by an approximately exponential decay. At the maximum the intensity is doubled.

almost exponential decrease to the original counting level, is observed. The variation amplitude is equal to ~100%.

[15] An examination of the difference between the ER spectrum at the variation peak and the counting level just before the beginning of the enhancement (see Figure 7) reveals the presence of photopeaks attributable to short-life daughters of radon (^{214}Pb and ^{214}Bi). This is a typical phenomenon of rain-out already observed during our other ER monitoring campaigns [e.g., *Brunetti et al.*, 1999b, 1999c; *Cecchini et al.*, 2001]. In fact, it is well known that large quantities of aerosol particles (radioactive and non-radioactive) behave as condensation nuclei for the formation of water droplets and precipitation (nucleation scavenging). On the other hand, many of them are incorporated into droplets by impact (impaction scavenging), either inside the clouds or below them [*Pruppacher and Klett*, 1997].

[16] However, it should be noted that in the spectrum of Figure 7, the photopeak at 2614 keV originated by ^{208}Tl, a member of the radioactive family of thoron (^{220}Rn), is absent. This can be explained by considering that the thoron half-life (56 s) is much shorter than that of radon (3.8 days), so that it decays rapidly and accumulates in the very low troposphere. For this reason, large quantities of ^{208}Tl and/or of its daughters cannot reach the altitudes where cloud formation and precipitation normally take place.

[17] This is indirectly confirmed by theoretical computations [*Jacobi and André*, 1963; *Beck and Gogolak*, 1979] on radon and thoron altitude distributions as functions of the turbulent diffusion coefficient *K*, which varies with altitude depending on the stability of the atmosphere. When the mixing is normal (NNN as in the classification by *Jacobi and André* [1963]), ~50% of the radon nuclei are still present above a 2-km height, whereas 80% of thoron nuclei should decay before reaching a height of 20 m.

[18] In Figure 8 the time sequence of a portion (25–1025 keV) of the spectra recorded every 30 min during the time interval 1900–2100 LT is shown. Here the time behavior of the ^{214}Pb (352 keV) and ^{214}Bi (609 keV) photopeaks can be seen in more detail. In particular, it is interesting to consider the ratio between the amplitudes of these two peaks as a

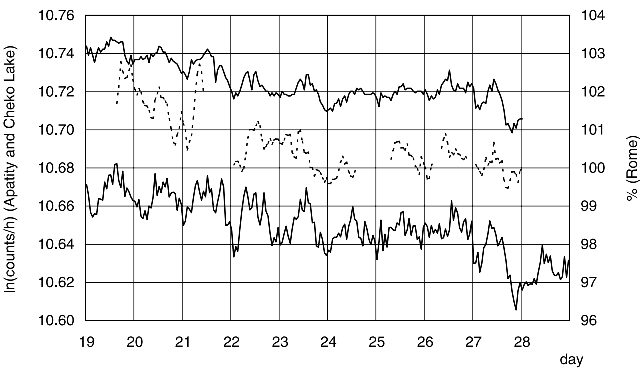

Figure 5. Pressure-corrected hourly counting rates of the cosmic ray component in the energy band 3–10 MeV at Cheko Lake (60°57′49″N, 101°51′21″E) compared with the hourly counting rate at the Neutron Monitor in Apatity (67°33′00″N, 33°19′48″E) and with Rome for the same period: Apatity (top curve); Cheko Lake (middle curve); Rome (bottom curve).

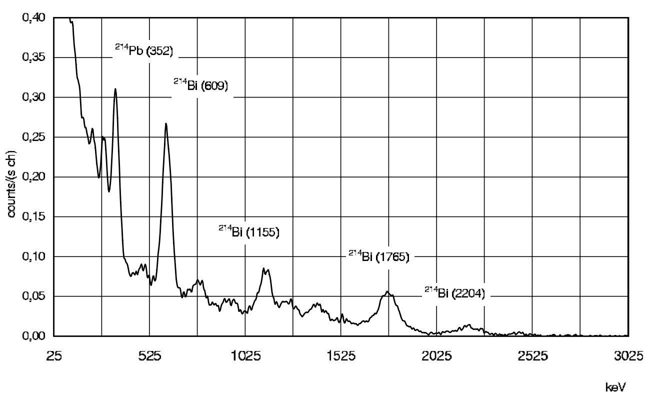

Figure 7. Spectrum of the γ radiation during the rain event on 19 July. The principal emission lines of the short-life daughters of radon (^{214}Pb and ^{214}Bi) are clearly visible, thus indicating that this is a washout/rain-out phenomenon. On the contrary, the photopeak relative to the thoron decay product ^{208}Tl is totally absent.

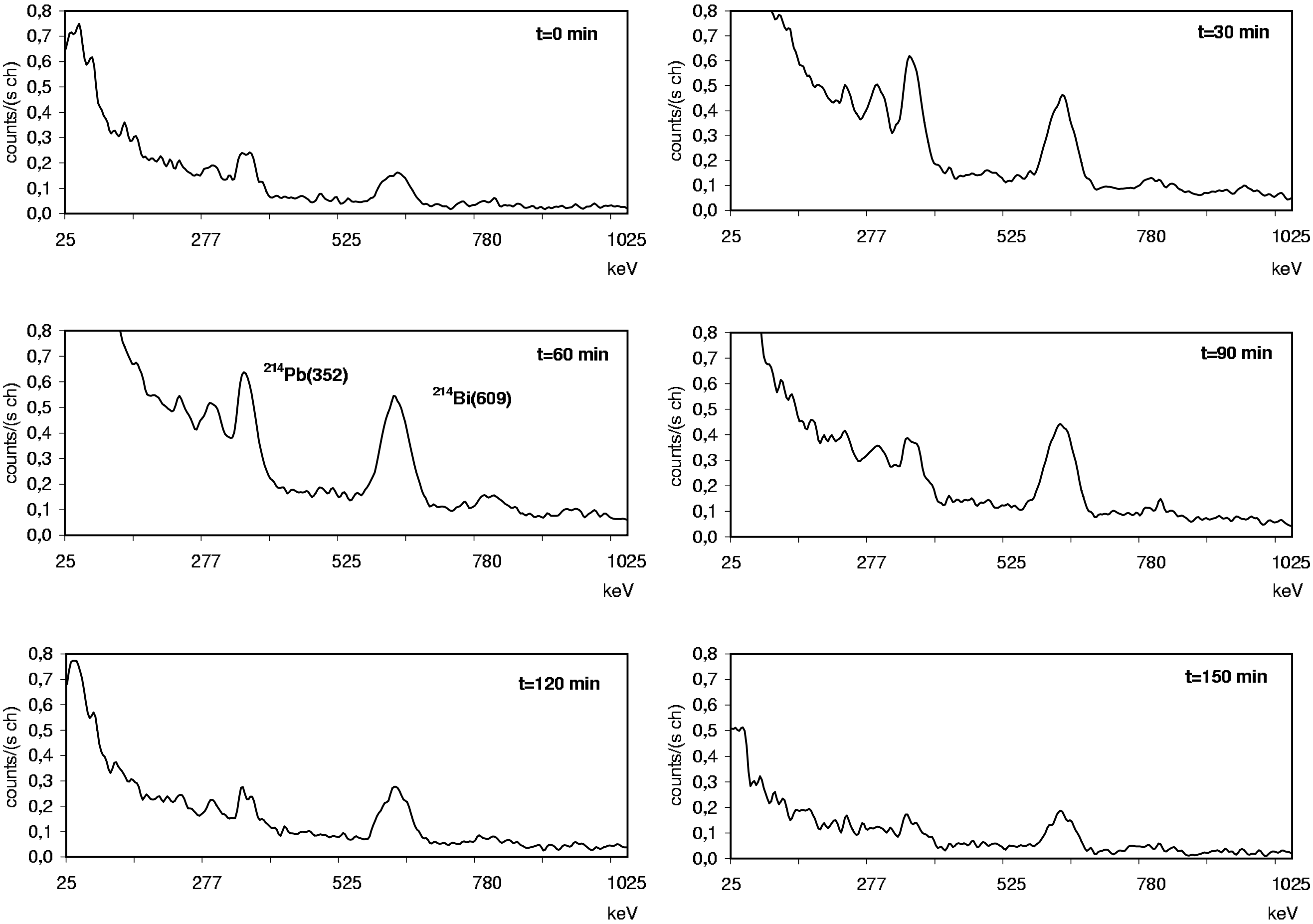

Figure 8. Time sequence of a portion of the 15-min spectra recorded every 30 min during the 19 July thunderstorm (see Figure 7) from the start of rain to the almost complete spontaneous disappearance of the additional radioactivity contained in the rain.

function of time. In Table 1 we report the ratio of activity concentrations ^{214}Bi/^{214}Pb, taking into account their emission probabilities. In Figure 9 the time behaviors of the two concentrations are shown separately. Our observations agree with the hypothesis that ^{214}Pb and ^{214}Bi were still in secular equilibrium in the fresh rain and were probably also in equilibrium with ^{218}Po, which precedes them in the radioactive chain but cannot be detected. Afterward they spontaneously decayed until their complete disappearance.

[19] Indeed, in normal weather conditions, not too close to the soil, and already above 100 m for any value of *K* following *Jacobi and André* [1963] or above 1000 m following *Beck and Gogolak* [1979] and *Kumar et al.* [1999], radon is assumed to be in secular equilibrium with its daughters. On the other hand, only the decay products of radon participate in the various processes that lead to the formation of rain (from the condensation of the first droplets to the actual precipitation) and that can break the radioactive chain.

[20] Unfortunately, the effects of the most violent thunderstorm, which for a few minutes around 1630 LT of 21 July threatened to dismantle the base camp, are difficult to interpret. Indeed, that event occurred while, following the program, the detector was put upside down, thus masking the storm effect. Though we cannot exclude that the activity peak around 1700 LT of 21 July in Figure 4 (see curve b) is related to that event, its quantitative analysis is not possible.

[21] Except for the same absence of ^{208}Tl, the rain event that occurred on 23 July was completely different from the rain event on 19 July. An analysis of the 23 July rain event, similar to the one applied to the 19 July rain event, has revealed the activity concentration ratios reported in Table 1. Contrary to the previous episode, here the ^{214}Pb and ^{214}Bi were not in equilibrium in the fresh rain, as deduced from

Table 1. Activity Concentration Ratio ^{214}Bi/^{214}Pb as a Function of Time During the Thunderstorm of 19 July and the Rain Event of 23 July

Time, min	19 July	23 July
0	1.13	2.02
15	0.95	1.43
30	1.21	1.55
45	1.34	1.69
60	1.70	2.02
75	2.26	2.55
90	2.35	1.71
105	2.58	2.09
120	2.62	2.60
135	2.52	2.53
150	2.28	4.25

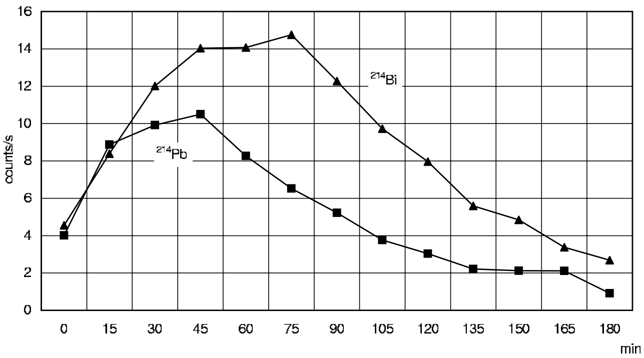

Figure 9. Time sequence of the activity concentrations of ^{214}Pb and ^{214}Bi computed from the spectra taken every 15 min during the 19 July thunderstorm (t = 0 marks the approximate start of rain). Note that in the fresh rain the two radionuclides are still in equilibrium, but afterward the equilibrium is upset.

the relatively high value of the ratio ^{214}Bi/^{214}Pb at the start of the rain.

[22] The possibility of measuring in real time the degree of disequilibrium between ^{214}Pb and ^{214}Bi during rain episodes is extremely interesting, as it is strictly related to the processes going on, inside and outside the clouds, during the formation of the precipitation. For example, the pickup of the radioactive material essentially takes place during the condensation phase (rain-out process), while the falling rain droplets are not very efficient in that process (washout process). It is evident that the lack of equilibrium depends on the time elapsed between the beginning of the condensation and the beginning of the precipitation. An activity concentration ratio ≤ 2 such as we found should imply a very short time interval of the order of 1 hour or less [*Bhandari and Rama*, 1963]. Furthermore, the quantitative knowledge of the degree of equilibrium between the short-life radon daughter activities allows us to estimate the average rate of radioactivity removal from air by the rain, following the model of *Bhandari and Rama* [1963].

[23] In practice, one defines a removal constant λ_r, whose inverse represents the average time after which the air activity concentration reduces its initial value by 1/e, exclusively because of the mechanical elimination by means of rain droplets that is in the making. In steady state, when the production rate due to the radioactive progenitor is assumed to balance the removal rate, it is possible to demonstrate that the constant λ_r is given by

$$\lambda_r = \lambda_{\mathrm{Bi}}[(N_{\mathrm{Bi}}\lambda_{\mathrm{Bi}}/N_{\mathrm{Pb}}\lambda_{\mathrm{Pb}}) - 1],$$

where $N_{\mathrm{Bi}}\lambda_{\mathrm{Bi}}$ and $N_{\mathrm{Pb}}\lambda_{\mathrm{Pb}}$ are the activity concentrations of ^{214}Pb and ^{214}Bi, respectively, and λ_{Bi} and λ_{Pb} are their decay constants.

[24] We obtained a removal constant λ_r for the events of 19 and 23 July 1999 equal to 0 and 0.035 min^{-1}, respectively. Obviously the former does not provide any useful information, as it implies an infinite time of removal (no elimination at all). The latter, in contrast, indicates a removal time constant of $\sim$30 min, which is in good agreement with the average value estimated by *Bhandari and Rama* [1963] through their study of several rain events in Bombay. It is risky to draw final conclusions from the analysis of only two cases, especially if one considers the extreme complexity of the processes at work and the approximations of the model used. However, it is worth noting the similarity of the results obtained from measurements carried out at such different sites and times and with completely different methods.

3.2. Diurnal Wave

[25] Figure 10 shows in more detail the time variations of the ER that exhibit a large diurnal wave from 24 to 28 July, the last days of the expedition to the shore of Cheko Lake. The cosmic ray data do not show a similar behavior (see Figure 4). This suggests that the effect has a local origin and is not related with atmospheric pressure variations.

[26] The activity variation starts at sunset, increasing linearly during the night hours and reaching its maximum level early in the morning. After that it decreases very rapidly to a minimum level that remains constant until the subsequent sunset. This behavior is not explained by a temperature effect influencing the exhalation rate of radon and thoron from the soil. Indeed, that effect should imply a maximum level of activity during the warmest hours, not the reverse, and, in any case, this effect is known to be negligible compared with the ones produced by other meteorological variables [*Porstendörfer*, 1994].

[27] The most plausible explanation is the presence of a nocturnal thermal inversion repeated with time regularity. This is quite frequent in flat continental areas when a very clear sky, a strong diurnal heating, and a strong nocturnal irradiance from the soil characterize the weather. In these conditions we have a particularly stable air layer in contact with the ground. Its thickness depends mainly on the temperature gradient and on the velocity of the wind blowing at the top of the boundary layer, which can reach a height of several hundred meters. Inside it, the vertical motion of turbulent diffusion is reduced, thus allowing radon and thoron to accumulate in high concentrations.

[28] The inversion layer starts to dissolve at sunrise when the air close to the ground heats up again and drives the first convective motions that rapidly disperse the radioactivity.

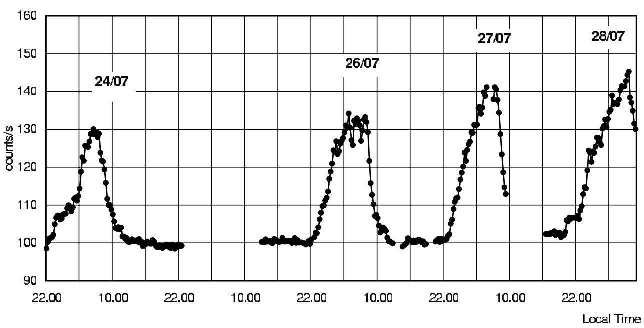

Figure 10. Detail of the ER counting rate from 24 to 28 July, the last days of the expedition to Cheko Lake. Here the impressive regularity of the diurnal wave (see text) is particularly evident. It is probably connected to a strong nocturnal thermal inversion.

This is revealed by the saw-toothed shape of the diurnal wave, with the increases systematically slower than the decreases.

[29] We observed a similar phenomenon during the monitoring campaign at Laboratorio Piramide Ev-K2-CNR (Nepal) at 5005 m above sea level [*Brunetti et al.*, 1999c]. In Nepal, the maximum and minimum sequence of the activity concentration appeared to be determined by the periodic rise of radon-rich air from the lower valley, caused by the convective motions of early morning and followed by successive wind dispersion.

[30] One of the tasks of the Tunguska99 expedition was to search for possible anomalous levels of ER in this area. To study this question, we propose here a simple model that makes use of the diurnal wave phenomenon to estimate approximately the radon exhalation rate from local soil. To perform our calculations, some assumptions regarding the mechanism of radon dispersion in air under thermal inversion conditions are needed. Note that in a recent paper [*Greenfield et al.*, 2002], in which the results of measurements of γ ray count rates from radon progeny at ground level and at 15 m elevation are reported, an analogous suggestion for using the amplitude of the diurnal cycle to measure changes in local radon concentrations has been made.

[31] Our idea consists of considering the layer of thermal inversion as a "box," closed at the top, almost tight to any flux inside/outside and vice versa, but open at the bottom, thus allowing the radon entrance. This is justified by the fact that the inversion layer is decoupled from the layer above it [*Garratt*, 1995], so that the transfer of momentum, heat, and matter of any kind is strongly inhibited. Moreover, as the wind is also strongly reduced inside the inversion layer, it is reasonable to assume that the progressive accumulation of radon and its daughters is with a good approximation a consequence of continuous exhalation from the soil and is not altered by contributions from neighboring areas.

[32] To compute the exhalation rate (or flux density, i.e., the number of radon atoms per unit time per unit area of soil), we make the following assumptions:

1. The ^{214}Pb photopeak at 352 keV is used as a reference, and the detector efficiency at this energy is assumed to be $\sim$100%. Furthermore, this radiation is considered to be emitted inside a hemisphere with a radius of 300 m. These two hypotheses appear reasonable for the large dimension of the monocrystal and the knowledge that the attenuation length for γ rays of this energy is 75 m, corresponding to a 98% attenuation over a distance of 300 m.

2. The thickness of the inversion layer at its maximum development before the sunrise is $\sim$300 m; the thickness is obviously dependent on many parameters, but it is always about a few hundred meters over the continent [*Garratt*, 1995] so that the assumed value seems reasonable.

3. The radon exhalation rate from soil is constant and uniform, i.e., the horizontal distribution of ^{238}U in the ground is homogeneous.

4. Only the soil exhalation and the spontaneous decay processes take place both for the radon and for its daughters. We do not consider other removal or generating processes, such as deposition by impact on the vegetation, electric field influence on the radioactive ions, etc. Moreover, it is not necessary to know the fraction of radionuclides attached to the aerosol with respect to their total amount in the whole air volume considered. This is a consequence of the fact that our instrument does not distinguish between the two quantities.

5. Inside the inversion layer the radon and its daughters are uniformly distributed and in radioactive equilibrium. This is probably the most critical of our assumptions. In fact, it is well known [see, e.g., *Greenfield et al.*, 2002] that the γ radiation from radon progeny is strongly dependent upon elevation, whereas our measurements have been taken close to ground level only. However, this assumption seems quite plausible to us for two reasons. First, the weather conditions that give origin to the thermal inversion are the same for which theoretical computations estimate an almost already perfect equilibrium above 100 m [*Jacobi and André*, 1963; *Beck and Gogolak*, 1979; *Kumar et al.*, 1999]. Second, the activity concentration values are considered here at the maximum of the nocturnal increase, in accordance with assumption 2, and the accumulated radon certainly had sufficient time to reach equilibrium with its daughters. In view of all of these considerations it can be said that the quantity we estimate by our model is not just a unique determination of radon exhalation rate, although we will continue to use this term, but rather a measurement of the time-averaged surface radon concentration during a period of dry weather conditions.

[33] Let us suppose that our detector is placed at the center of the hypothetical hemispheric box, whose base has an area of σ m^2. We indicate with E the radon exhalation rate and consider the activity of radon and its daughters ^{214}Pb and ^{218}Po in equilibrium. On the basis of the hypotheses mentioned above, the time evolution of the three nuclides inside the box is given by the following differential system of equations:

$$(dN/dt)_{\mathrm{Rn}} = E\sigma - \lambda_{\mathrm{Rn}} N_{\mathrm{Rn}}$$

$$(dN/dt)_{\mathrm{Po}} = \lambda_{\mathrm{Rn}} N_{\mathrm{Rn}} - \lambda_{\mathrm{Po}} N_{\mathrm{Po}}$$

$$(dN/dt)_{\mathrm{Pb}} = \lambda_{\mathrm{Po}} N_{\mathrm{Po}} - \lambda_{\mathrm{Pb}} N_{\mathrm{Pb}},$$

with initial conditions $\lambda_{\mathrm{Rn}} N_{\mathrm{Rn}}(0) = \lambda_{\mathrm{Po}} N_{\mathrm{Po}}(0) = \lambda_{\mathrm{Pb}} N_{\mathrm{PB}}(0)$.

[34] The solution of interest for us is the one relative to ^{214}Pb. Let us recall that our detector registers the counts in constant time intervals of finite duration, Δt s, which implies that the effectively measured quantity is given by the integral of $\lambda_{\mathrm{Pb}} N_{\mathrm{Pb}}(t)$ over the interval [0, Δt]. Indicating the latter with $M_{\mathrm{Pb}}(\Delta t)$, it can be shown that it is of the form

$$M_{\mathrm{Pb}}(\Delta t) = aN_{\mathrm{Pb}}(0) + b(\mathrm{E}\sigma),$$

where a and b are functions of the three decay constants, λ_{Rn}, λ_{Po}, and λ_{Pb}, and of Δt.

[35] To obtain the desired quantity $E\sigma$, and then E, it is necessary to eliminate the unknown $N_{\mathrm{Pb}}(0)$; to this end we can consider two equations for two distinct values of Δt, for example, Δt_1 = 3600 s and Δt_2 = 7200 s:

$$M_{\mathrm{Pb}}(\Delta t_1) = a_1 N_{\mathrm{Pb}}(0) + b_1(E\sigma)$$

$$M_{\mathrm{Pb}}(\Delta t_2) = a_2 N_{\mathrm{Pb}}(0) + b_2(E\sigma).$$

By substituting the known values of $M_{Pb}(\Delta t_1)$ and $M_{Pb}(\Delta t_2)$, we can solve the system for $E\sigma$ and, dividing this by σ (which is known also on the basis of the hypotheses made about the dimensions of the box), at last we find that

$$E \approx 2 \times 10^4 \text{atoms m}^{-2}\text{s}^{-1},$$

which is equivalent to

$$E \approx 0.04 \text{ Bq m}^{-2}\text{s}^{-1}.$$

[36] Our estimate is characterized by an uncertainty that is difficult to evaluate due to the assumptions and approximations made. First, having neglected the unavoidable leakage of radon outside the box, this value could be a lower bound. It would be interesting to compare it with others obtained in the same place by means of more traditional and direct methods, but, as far as we know, nothing similar exists in the literature. In any case, a comparison can be made with the values measured all over the world. For example, *Nazaroff* [1992], in a thorough review article on radon transport from soil to air, reports an average value of the exhalation rate for different kinds of soil ranging from 0.015 to 0.048 Bq m^{-2} s^{-1}, while *Porstendörfer* [1994] quotes an interval of measured values ranging from 0.001 to 0.05 Bq m^{-2} s^{-1}. Our result agrees very well with those found experimentally in other parts of the globe and allows us to conclude that the Tunguska site has nothing anomalous, at least concerning the level of natural radioactivity.

4. Discussion and Conclusions

[37] The Tunguska99 expedition was a very good opportunity for testing once more the effectiveness of our real-time detection system of environmental radiation in a remote site, and the results obtained are comfortable. As far as we know this is the first time that an analysis of the phenomena like those described is performed in this way. The main points of the present work are (1) the study of equilibrium/disequilibrium relations between the short-lived radon daughters in fresh rain without the necessity of collecting large amounts of it and (2) the derivation of a fundamental quantity, such as the local exhalation rate of radon from soil (or, better, the time-averaged surface radon concentration), by means of a simple model that relates the latter to an episode of nocturnal thermal inversion. However, the rain-out episode analysis should still be considered preliminary. We plan to further this analysis by comparing the present data with those we have acquired in other occasions and places.

[38] The model for the calculation of the radon exhalation rate has some weak points because some fundamental information about the actual structure of the surface inversion layer is lacking; therefore we have to guess its real height because we were measuring at a single specific elevation without the necessary information about the radon progeny altitude profile. Nevertheless, the figure obtained agrees with figures reported in the literature, thus testifying for a general validity of the model. This implies that the association of standard and consolidated methods of atmospheric soundings with unconventional means of radiation monitoring can be extremely useful.

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Figure 3. Cheko Lake and its surroundings.