Monitoring precipitation and lightning via changes in atmospheric gamma radiation

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Abstract. Atmospheric γ−radiation has been measured since 19991 and recently at three elevations 220m from the first site to ascertain position dependency and optimal elevation for observing γ-rays from radon and radon-progeny found in precipitation. Radiation from time-independent and diurnal components was minimized in order to ascertain the reliability, accuracy and practicality of determining precipitation rates from correlated γ-rates. Data taken with 4-12.9cm³ NaI detectors at elevations above ground of 9.91, 14.2, 15.7, and 21.4 m were fit with a model assuming a surface and/or volume deposition of radon progeny on/in water droplets during precipitation which predicts γ-ray rates proportional to the 2/5 and/or 3/5 power of rain rates, respectively. With mostly surface deposition and age corrections for radon progeny, the correlation coefficients improved with elevation and reached a maximum at 0.95 around 20m. Atmospheric γ-radiation enables monitoring precipitation rates to 0.3 mm/h with time resolution limited only by counting statistics. High γ-ray rates, decreasing with 40-minute half-life following lightning may be indirectly due to ions accelerated in electric field.

INTRODUCTION

Relationships between time-dependent atmospheric γ radiation, measured at a distance above ground level (DAG) of 14.2 m, and both rain and snow precipitation rates (herein designated as RPR and SPR, respectively) have been established.1,2 The relationships between γ-ray flux rates (GRR) and RPR or SPR, 0.18 ± 0.02 (mm/hr)/Bq and 4.02 ± 0.04 (mm/hr)/Bq, respectively, were found to be reliable and reproducible. The unit Bq rather than Bq/m³ is used as a convenient way to refer to un-normalized decay rates which would give rise to observed, relative, time-dependent, background-subtracted GRR from the effective volumes viewed by 12.9cm³ NaI detectors with solid angles of about 2π and with energy dependent efficiencies.

The prospect of using these reproducible relationships between RPR-GRR and SPR-GRR as a means of reliably measuring precipitation rates has been noted.1 Increases in GRR during periods of precipitation have been well documented.3-18 Time and position variations in the rates at which radon is exhaled and accumulated at ground level6,7,19-25 may have obscured and/or discouraged attempts to quantify this effect in real time. Observations at 15-20 m elevation over 32 months suggest that RPR-GRR correlations are nearly independent of local ground level radon concentrations if GRR from the latter is treated as noise1. Figure 1 shows the background subtracted GRR at 15 m versus time for 90 days in 2001. Peaks are correlated with precipitation1 and other variations in GRR are relatively minor1-18. The goals of this work were to find optimal DAG for monitoring RPR and SPR and to understand the physics of the process. If successful application of RPR-GRR and SPR-GRR correlations would enable real-time, remote sensing of precipitation rates solely upon measurement of GRR. These rates are essentially integrated and averaged over areas on the order of the mean free path of γ-rays in air and are not subject to the same collection or sampling difficulties associated with standard precipitation gauges such as magnitude and direction of wind velocity, evaporation or sublimation in the case of snow6 (see below). Since increased GRR during periods of precipitation has been observed in widely varying (and remote) locations6,7,9-11,14,15,26,27 it has been suggested1, and recently demonstrated, that there is a sufficient pool of radon and progeny in the upper atmosphere to enable the use of RPR and SPR monitors in remote locations27. Since the correlations depend on upper atmospheric progeny concentrations which may be in secular equilibrium, they may be globally applicable5,26 requiring only regional renormalization.

Figure 1. Time dependent background subtracted gamma ray rates as a function of time.
The amplitude of the diurnal variation in GRR is shown in Fig 2. At ground level the amplitude of this cycle, which is proportional to (and may be used as a monitor of) local radon concentration, is comparable to the time independent background. It was observed to be a factor of about 20 less on top of the 14.2 m Natural Science Building (NSB). This effect is thought to be due to pooling and subsequent mixing and transport to the upper atmosphere of radon and radon progeny originally exhaled from the ground into the lower atmosphere. The diurnal amplitude decreases with DAG (due to decreasing radon concentration) thus the signal to noise ratio for GRR associated with RPR at increasing DAG should improve. It is well known that local radon exhalation rates are greatly affected by changes in meteorological conditions.

The presence of radon and radon progeny in rain and snow may be a complex function of atmospheric radon concentration, the manner and history of the cloud formation, the length of time the radio-isotopes were resident in the clouds prior to precipitation, radon-progeny concentrations in the lower atmosphere during precipitation, the type (rain and/or snow) and relative surface area to volume. The precipitation type is especially important since snow yields an order of magnitude more radiation per unit mass than rain, and the radioactivity of snow has been observed to change by a factor of four depending on the "wetness" or relative surface area of the snowflake. Similar complexities exist in the scavenging of acidic aerosols by rain and snow.

Although the multi-faceted nature of this problem makes it virtually impossible to isolate and independently measure each of these factors it is useful to measure how the sensitivity and reliability may be optimized. This work focuses on using radon progeny as a tracer of precipitation rates, but progeny could as well be used as tracers for radon exhalation rates, evaporation rates, and physics of cloud formation.

Figure 3 and 4 show the cross-correlations between the GRR obtained during periods of precipitation for detectors positioned at different positions and elevations, respectively, indicating that the phenomena were reproducible over distances of hundreds of meters and elevations on the order of tens of meters.

It was originally reported that the RPR-GRR and SPR-GRR correlations were linear for rain rates in excess of 8 mm/h. The relatively small change in GRR with change in RPR (for RPR greater than 8 mm/h) obscured the fact that the relationship was non-linear. Radon progeny are in secular equilibrium until falling to the ground after which the activity decays with the half-life of the dominant progeny. Using an “age adjustment” to correct for this and a surface model determinations of RPR and SPR to a few tenths of mm per hour during storms with rain rates of up to 20 mm/h and of durations up to 20 hours were possible.

EXPERIMENTAL METHOD

One goal of this work is to determine the practicality and economy of using this method to monitor RPR and SPR, so relatively small 12.9 cm NaI detectors were used, the geometry and efficiency of which are given.

![Figure 2](image2.png)

**Figure 2.** Diurnal variation of GRR at 14.2 m above ground. The curve is: GRR = a + b cos(τ + ϕ), where a, b, τ, and ϕ are adjustable and t is the time. The best fit is for τ = 1.01 ± 0.03 days, and phase ϕ yields maximum amplitude at sunrise.

![Figure 3](image3.png)

**Figure 3.** Correlation (r coefficient = 0.96) between GRR during precipitation at locations separated by 220 m.

![Figure 4](image4.png)

**Figure 4.** Correlation (r coefficient = 0.98) between GRR during precipitation at locations separated by 6 m in elevation.
elsewhere.\textsuperscript{1,35} One of these was placed on top of the Natural Science Building (NSB) at the International Christian University (ICU) in Tokyo, Japan in the same position ($35^\circ 42' 18''$ N, $139^\circ 31' 44''$ E and 14.2 m above ground) as that for which extensive data were taken and reported upon in 1999-2000.\textsuperscript{1,2,27} Three other detectors were positioned at 21.4 m (level 1), 15.7 m (level 2), and 9.9 m (level 3) above ground within the bell tower (IBT) of the ICU church ($35^\circ 42' 12''$ N and $139^\circ 31' 48''$ E) which is located 220 m from NSB\textsuperscript{2}. Those detectors were above one another and fully exposed to the atmosphere except for lead shielding between the detectors and the concrete tower wall. Each viewed an unshielded solid angle of a bit less than $2\pi$, comparable to, but oriented at right angles to, that viewed by the detector positioned on top of (NSB).

The purpose of these measurements was to ascertain the optimum elevation for maximizing the signal from $\gamma$-radiation in rain relative to the noise from the diurnal component\textsuperscript{1,27} fed by exhalation of radon from soil and building materials. Measurements on top of moderately tall buildings would be more practical than those made at significantly higher DAG. Thus, if increasing DAG beyond 15-20m does not improve the signal to noise ratio, then measuring there might outweigh any advantages obtained by increasing DAG without limit.

Continuity\textsuperscript{38} insures that the density of precipitation in a unit volume of atmosphere is independent of the wind velocity. Since the flux of $\gamma$-rays from a given volume of air is isotropic, the detector geometries should yield the same atmospheric GRR from rain even though they are viewing the atmosphere at right angles to each other. The time independent backgrounds (from the ground, buildings and cosmic rays) were the same to within 10% for all geometries and measured with sufficient statistical accuracy (about 0.8%) such that they could be subtracted from the time varying component without contributing significant error.

All GRR in excess of 300 KeV were integrated over 6-min intervals at level 3 and 30-min intervals at levels 1, 2, and NSB. Level 3 data revealed relatively short time fluctuations and summed over 5 successive bins could be compared with data from the other stations. The structures observed in the level 3 data (see figure 5) have better GRR response time to RPR than the rain gauges used by most weather bureaus. Precipitation, integrated over 30-minute intervals, was measured to an accuracy of 0.5 mm\textsuperscript{36}. The RPR and SPR were assumed to be the same at level 1, 2, and 3 detectors as for the NSB detector, positioned 6 meters from the rain gauge.

\section*{DATA AND ANALYSIS}

In earlier work\textsuperscript{1} RPR and SPR were correlated with background-subtracted GRR, but only for RPR of less than 8 mm/h. In recent work\textsuperscript{2} a model assuming that radon progeny producing the increase in GRR are deposited on the surface and/or within the volume of raindrops was established and enabled GRR - RPR correlations with as little as a few tenths of mm/h.

The correlation coefficient $(r = 0.96)$ for the NSB-level 1 and similar correlations between NSB and the other levels for RPR (SPR) verify that GRR response to a given RPR (SPR) is not location dependent up to 220m, and the coefficient $(r = 0.98)$ between changes in GRR measured during precipitation between level 1 and level 2 (6m directly below it) along with similar correlations $(0.93<r<0.95)$ between the other detector pair combinations (not shown) indicate that features of GRR during precipitation are elevation correlated.

The rain flux entering any volume will be equivalent to that leaving irrespective of the speed and direction of the raindrops through the unit volume. If evaporation and condensation below the cloud base\textsuperscript{31} are neglected, the quantity of radon progeny per unit volume of atmosphere is proportional to the total surface area of droplets within that volume, the expected GRR would then be proportional to the product of the number of drops per unit volume $(n)$, the surface density of radioisotopes $(\sigma_r)$, and the average surface area $(A_{ave})$ of the raindrops at any moment. The instantaneous GRR observed by a detector viewing a constant volume of atmosphere would then be given by:

\begin{equation}
    \text{GRR} = C_1 \ n \ \sigma_r \ A_{ave} = C_1 \ n \ \sigma_r (4\pi r_{ave}^2)
\end{equation}

Where $C_1$ is a time independent normalization constant. The value $r_{ave}$ is the average radius of the raindrops or the average of the root-mean-squared radius, $r_{rms-ave}$ if the raindrops are not spherical. Drop size spectra are complex and time dependent with large drops overtaking and combining with slower, smaller drops. The shape and time dependence of $r_{ave}$ is expected to be small and neglected in this model.

The rain precipitation rate (RPR) is proportional to the product of the average volume of the raindrops $(V_{ave})$, the number density of drops, and the average

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5.png}
\caption{GRR (error bars reflect statistical errors) integrated over 5 min as a function of time during precipitation}
\end{figure}
terminal velocity of the raindrops \((v_{\text{term}})\) which according to Stokes Law\(^{39}\) is a constant for a given average raindrop surface area. Thus RPR is given by:

\[
\text{RPR} = C_2 n \nu_{\text{term}} V_{\text{ave}} = C_2 n \nu_{\text{term}} (4\pi r_{\text{ave}}^3/3) \quad (2)
\]

where \(C_2\) is a normalization constant (theoretically equal to one) and independent of the size of the raindrops and the rate at which they are falling. The terminal velocity can be expressed according to Stokes’ Law as follows:

\[
v_{\text{term}} = \frac{2}{9} \left( r_{\text{ave}}^2 g / \eta \right) \left( \rho_w - \rho_a \right) \quad (3)
\]

where \(g\) is the acceleration due to gravity, \(\eta\) is the viscosity of air, \(\rho_w\) the density of water and \(\rho_a\) the density of air, which are all approximately constant at a given elevation, pressure, and temperature. Eliminating \(v_{\text{term}}\) from equations (2) and (3) one obtains:

\[
\text{RPR} = C_2 n \frac{2}{9} \left( r_{\text{ave}}^2 g / \eta \right) \left( \rho_w - \rho_a \right) \left( 4\pi r_{\text{ave}}^3/3 \right) \quad (4)
\]

Eliminating \(r_{\text{ave}}\) from equations 1 and 4 one gets:

\[
\text{GRR} = (\text{RPR})^{3/5} \left[ (C_2 8g/27\eta) (\rho_w - \rho_a) \right]^{2/5} 4\pi^{3/5} n^{3/5} \rho_r \quad (5)
\]

If one instead assumes that progeny are uniformly mixed throughout the volume of the raindrop with density \((\rho_r)\) then equation (1) may be modified:

\[
\text{GRR} = C_1 n \rho_r V_{\text{ave}} = C_1 n \rho_r \left( 4\pi r_{\text{ave}}^3/3 \right) \quad (6)
\]

Eliminating \(r_{\text{ave}}\) from equations (4) and (6) one gets:

\[
\text{GRR} = (\text{RPR})^{3/5} \left[ (C_2 8g/27\eta) (\rho_w - \rho_a) \right]^{3/5} \frac{C_1 4\pi^{3/5} n^{3/5} \rho_r}{3} \quad (7)
\]

Due to the consistency of renormalized, background-subtracted GRR per unit RPR observed since 1999 (and with detectors having separation of 220 m and DAG differences of up to 12 m) the product of the terms to the right of RPR in equations (5) and (7) is observed to be time independent. Since the terms in the square brackets are constant, the product of the 3/5th or 2/5th power of the number density of raindrops with the progeny surface or volume densities, respectively, must not vary radically within a given rain storm. Thus a larger numbers of droplets each will consume a smaller fraction of the available radon progeny per unit time.

Progeny densities in and on rain decay in time with the weighted average mean half-life of the dominant radon progeny after they are deposited upon any surface. Thus the GRR observed per unit volume of rain depends upon the “age” of the water (the time since the droplets stopped acquiring progeny). Correlations between GRR and powers of the adjusted RPR data were varied between 2/5 and 3/5 to determine the best fit to the data.\(^{2}\) Good fits to the data were obtained with exponents of 0.45 ± 0.05. This suggests progeny were mostly adsorbed on the surface as per equation (5) and to a lesser extent absorbed within the volume as per (7).

In earlier work it was reported that each unit of melted snow yielded up to 20 times more GRR (most likely do to its increased surface/volume) than for an equivalent volume of rain.\(^{1,2}\) This number was found to be 4-5 times that for rain in a recent measurement (see figure 6), since it was a wetter snow presumably with less surface per volume. This is consistent with a surface model since snow has considerably more surface area per unit volume than rain, and dry snow more than wet snow. The SPR indicated in figure 6 in mm/h of equivalent melted snow are measured with a bin size of 0.5mm/h. Since the surface area per melted volume and fall speed vary significantly for different types of snow, a power law like that established for rain which has a well-defined surface area per unit volume cannot be established. The linear correlation shown as the solid line yields a correlation coefficient, \(r = 0.97\).

Figure 7 shows a plot of GRR and the age adjusted \((\text{RPR})^{-0.45}\) for the NSB detector as a function of time during a lengthy rain storm. The GRR are joined by a smooth curve. Similar plots for the GRR of each level as well as that averaged over all four detectors with the

![Figure 6. Snow precipitation (error bars reflect gauge resolution) versus GRR (error bars reflect statistical errors) with GRR (diamonds - error bars reflect statistical error) and RPR (open circles - error bars reflect rain gauge resolution) as a function of time during precipitation.](image-url)
Figure 8. Correlation between (RPR)$^{0.45}$ and GRR for the NSB, with correlation coefficient $r = 0.94$

adjusted (RPR)$^{0.45}$ were of similar quality. The two rates vary similarly with time not only for the single NSB detector, which was 6 m from the rain gauge but also for the IBT detectors 220 m from the rain gauge.

Figure 8 (above) shows the correlation between (RPR)$^{0.45}$ and GRR for the NSB, for which a correlation coefficient of 0.94 was obtained. Vertical errors reflect the rain gauge binning and horizontal errors reflect the statistical error of the NSB detector.

Similar plots for the levels 1, 2, and 3 detectors (not shown) yield coefficients of 0.87, 0.86, and 0.84, respectively. Changes in RPR of a few tenths of mm/h are observable by tracking corresponding changes in the GRR. In order to reproduce the amplitude and the fine structure for small RPR it was necessary to use the surface model, and to get the proper phase relation it was necessary to use age corrections mentioned above.

The signal to noise ratio and the resulting quality of the RPR-GRR correlations improved with elevation (r from about 0.8 to 0.9). The 0.45 power of RPR (age adjusted for the radon progeny half-life) and GRR measured at 30 min. intervals were obtained at all four locations. Although one cannot uniquely convert GRR (effect) to RPR (cause), inverse correlations between GRR to the $1/0.45 = 2.22$ power and age adjusted RPR give self-consistent determinations of RPR from GRR.

Signal to noise ratios and resulting correlations improved with elevation (r from about 0.8 to 0.9). The electric fields associated with positive lightning. Further data and the details of such processes will be discussed in detail in future work.

**SUMMARY AND CONCLUSIONS**

The elevation and position dependence for observing $\gamma$-rays from radon-progeny in rain was determined by measuring $\gamma$-radiation at three equally spaced distances above ground and a fourth location separated from the first three by 220 m. The response of RPR to GRR was correlated at all locations. The GRR-RPR correlations were consistent with a model assuming radon progeny are adsorbed predominantly on the surface of raindrops (see equations (5) and (7)). Excellent correlations between the 0.45 power of RPR (age adjusted for the radon progeny half-life) and GRR measured at 30 min. intervals were obtained at all four locations. Although one cannot uniquely convert GRR (effect) to RPR (cause), inverse correlations between GRR to the $1/0.45 = 2.22$ power and age adjusted RPR give self-consistent determinations of RPR from GRR.

**Figure 9.** Exponential decay of activity observed in the NSB detector shortly after lightning. The solid curve is a $(t_1/2=40\text{min})$ arbitrarily normalized exponential decay.

**Figure 10.** GRR are closed circles (error bars reflecting statistical errors) and RPR are open circles (error bars reflecting rain gauge resolution) as a function of time. Lightning occurred during period indicated by arrow.
been observed in widely varying locations6-11,14,15,27 (errors reflect rain gauge resolution) as a function of time. Lightning occurred during time indicated by arrow. The solid curve is a smooth line through the closed circles. The dashed curve is a smooth line drawn through the uncorrected GRR.

The remarkable reproducibility and reliability of these correlations for rain rates up to 25 mm/h and 20 hours duration enables real time determination of RPR (SPR) to within 0.3 mm/h (0.2 mm/h). The time resolution depends only on GRR statistics and was measured to within better than 6 min. The total integrated rainfall (snowfall) is obtainable under nearly all conditions. For large wind shear this method, which is independent of the magnitude of the horizontal speed of rain droplets, might be more reliable than standard gauges. For snow, neither wind shear nor the sublimation of snow (before it is melted) contributes significant error.

It may also be possible to determine the number density and other properties of moderate rainfalls by determining surface $\sigma$, and/or volume $\rho$, densities of radioisotopes, and GRR/(RPR)\textsuperscript{2,5} and/or GRR/(RPR)\textsuperscript{3,5}, respectively, along with geometric constants\textsuperscript{27,40-42}. The amplitude of the diurnal cycle of GRR may be used as a monitor of local radon concentrations and exhalation rates which may give insight into the substratum and tectonic activity.\textsuperscript{1,3,45} An international collaboration is exploring all of the above in dispersed locations.\textsuperscript{27}

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REFERENCES