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Distance of flight of cosmic-ray muons to study dynamics of the upper muosphere

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Abstract

The Earth can be divided by main layers, including the atmosphere, geosphere (solid Earth), and biosphere, depending on its predominant component. In this work, the layer of the Earth which constantly contains a high concentration of muons (~8 × 10^{12} muons) and its upper border are respectively defined as the muosphere and muopause. The altitude of the muosphere spans from the lower stratosphere to the upper crust of the Earth. In order to study its dynamics, the muopause height was spatiotemporally studied with a new kind of technique called the distance of flight (DoF) which utilizes variations in the muon's decay length. In this work, (A) numerical modeling was performed, and it was clarified that seasonal variations in the cosmic muon flux are predominantly ruled by muopause dynamics, (B) the muon data were compared with the balloon-based measurement results, and it was confirmed that muopause dynamics is closely related with lower-stratospheric height variations. Since the muopause is the region spanning between the upper troposphere and the lower stratosphere, the potential of the current DoF approach needs to be further investigated by cross-comparing related case studies and other atmospheric climate datasets.

Introduction

The Earth can be divided into its main layers including the atmosphere, geosphere (solid Earth), biosphere, depending on its predominant component: gas in the atmosphere, solid rock/metal in the geosphere, biological activities in the biosphere. Muons are secondary particles generated in the Earth's atmosphere as a result of hadronic interactions between the incident primary cosmic rays (primaries) and atmospheric nuclei such as nitrogen and oxygen. These primaries usually do not interact with matter within the top region of the

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Earth's atmosphere due to the low number density of atmospheric nuclei. However, as primaries' injection depth increases, the density of the atmosphere increases, and these primaries start to interact with nuclei, producing mesons such as charged pions and kaons which eventually decay into muons. Once these mesons decay into muons, there will generally be no further interaction to generate new particles since muons do not strongly interact with matter. Therefore, muons are extensively produced within particular altitude regions of the atmosphere. The muons' production rate increases as a function of the atmospheric depth such that: <0.01%, ~0.2%, ~2%, ~30%, and ~80% (of the entire muons we observe at sea level) up to an atmospheric depth of 5 hPa, 10 hPa, 50 hPa, 100 hPa, and 200 hPa, respectively, and almost all muons are generated up to an atmospheric depth of 300 hPa (Particle Data Group, 2022; Boezio *et al*., 1999; Boezio *et al*., 2000). On the other hand, due to its strong penetration power, the muons also exist in the geosphere with a rock/water depth up to ~5/~10 km. Consequently, muons are predominant in the region defined on the altitude coordinate as ranging from 30 km and -10 km which also partly overlaps with regions of the humanosphere. This region (from +30 km to -10 km from sea level) is here defined as the muosphere. Accordingly, the muopause is defined as the upper boundary of the muosphere (as with the tropopause defining the upper boundary of the troposphere) which is located at 30 km asl. The key characteristics of the muons within the muosphere are: (A) an abundance of $\sim 8 \times 10^{12}$ muons ((1.6×10^{2} $m^{-2}s^{-1}$) [averaged muon flux] × (5×10^{14} m^{2}) [Earth's surface area] × (3.5×10^{4} m) [thickness of the muosphere] / (3×10^{8} ms^{-1}) [speed of muons]) with a concentration of $\sim 5 \times 10^{3}$ muons km^{-3} are constantly present in the muosphere, (B) $\sim 8 \times 10^{16}$ muons are generated in the muosphere every second and (C) $\sim 5 \times 10^{16}$ muons arrive at sea level every second. The exception to this would be neutrino-induced muons which exist throughout the geosphere (Particle Data Group, 2022), but the concentration of these neutrino-induced particles within the geosphere is too small ($< 10^{-9}$ muons km^{-3}) to categorize them as being part of the muosphere.

The thickness of the muosphere spatiotemporally fluctuates due to processes near the surface of the Earth: mainly crustal deformation and land temperature variations. Crustal deformation alters the density of the shallow crust and local topography. When this occurs, the underground depth threshold for muons to reach will be altered; hence the position of the bottom part of the muosphere is regionally altered, but the time scale of this change is very long (over millennia). On the other hand, the near-surface temperature variations will alter the isobaric surface height near the muopause in much shorter time scales.

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Since muopause height variations are closely related with the upper-tropospheric and lower-stratospheric isobaric surface height variations. Studying muopause dynamics has the potential to contribute to research in this field. For example, it was reported that the 2020 and 2021 ozone holes were both associated with large decreases in polar lower stratospheric heights (Yook *et al*., 2022). SSWs are characterized by large geopotential height rises at the pole (Kretschmer *et al*., 2018). The 2022 Hunga Tonga–Hunga Ha'apai volcano eruption, Tonga resulted in a substantial injection of water vapor into the upper atmosphere (Millán *et al*., 2022; Vömel *et al*., 2022). Such changes in the atmospheric composition should have had a noticeable impact on the muopause.

The established muographic imagery techniques have been applied to natural phenomena such as volcanoes (Tanaka *et al*., 2014), cultural heritage (Morishima *et al*., 2017), tropic cyclones (Tanaka *et al*., 2022a), meteotsunami (Tanaka *et al*., 2022b), and contraband detection (Gnanvo *et al*. 2011). These techniques take advantage of known properties of muon transmission and scattering through matter. In this work, the DoF technique is added, and it will be shown that the muopause height variations can be measured with this technique based on the quantitative analysis of the time-sequential muon data. Since muons are leptons with a decay constant of 2.2 microseconds, the distance traveled has an influence on the muon's survival rate. Consequently, the sea-level muon flux will decrease/increase as the muopause uplifts/lowers. This is the basic principle of the DoF approach. In this work, the aim was to show balloon-based lower stratospheric height variations are well reproduced by applying the DoF approach to the time-sequential muon observation data.

There are a number of reports exploring barometric and temperature effects in the muon flux (Tanaka *et al*., 2022a; Tilav *et al*. 2010; COSINE-100 Collaboration, 2020; Myssowsky and Tuwim *et al*. 1926; Blackett, 1938; The IceCube Collaboration, 2019; Adamson *et al*., 2010) including a recent detailed review (Dmitrieva *et al*. 2011). However, many of these works focus on either tropospheric barometric effect or stratospheric temperature effect. In this work, DoF approach was modeled and applied to the 1,044-day time sequential muon data to compare with the Japan Meteorological Agency's balloon data.

As a result, the following three major characteristics were identified: (A) seasonal variations in the muon flux due to the isobaric surface height effect are much larger than seasonal variations due to the barometric effect, therefore, (B) the isobaric surface height

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derived by the DoF technique is consistent with the balloon-based upper-atmosphere isobaric surface height measurement results. In this paper, a detailed description of the process to arrive these results is provided. A brief discussion of its current limitation and potential improvements are also described.

2. Principle of the DOF technique

The atmospheric cascades of secondary pions and kaons are developed as a result of the competition between the hadronic process and the decay process in the atmosphere. Therefore, muons are not generated at a specific altitude, but instead they are generated within a certain altitude range (Boezio *et al*., 1999; Boezio *et al*., 2000).

Figure 1 shows the layer span of the muosphere on the Earth and the principle of the DoF technique. As shown in Figure 1A, the muosphere covers the region from the lower stratosphere, troposphere, and shallow region of the geosphere (shallow crust and ocean). Topography of the muopause is determined by the isobaric surface height distribution of the upper atmosphere, and is generally related to the height of tropopause. However, the tropopause region does not usually overlap with the muopause region. The isobaric surface height is high when the surface temperature is high and low in when the surface temperature is low since the larger vertical temperature gradient causes deeper convection in the troposphere, pushing the isobaric surface, upwards; hence seasonally varied. More detail descriptions can be found later in the "Balloon-based studies near the muopause" section. As shown in Figure 1B, variations in the height of the muopause will affect the muon generation point; hence the muon's DoF. The number of muons decreases when the muopause is uplifted. If the isobaric surface height effect is comparable to or stronger than the barometric effect on the muon flux, the spatiotemporal variations in the muopause can be measured by using the local barometric data. Detailed descriptions about two essential aspects of the DoF technique, (1) modelling of the seasonal barometric effect on the muon flux and (2) modelling of the seasonal isobaric surface height effect on the muon flux, are given in the following subsections.

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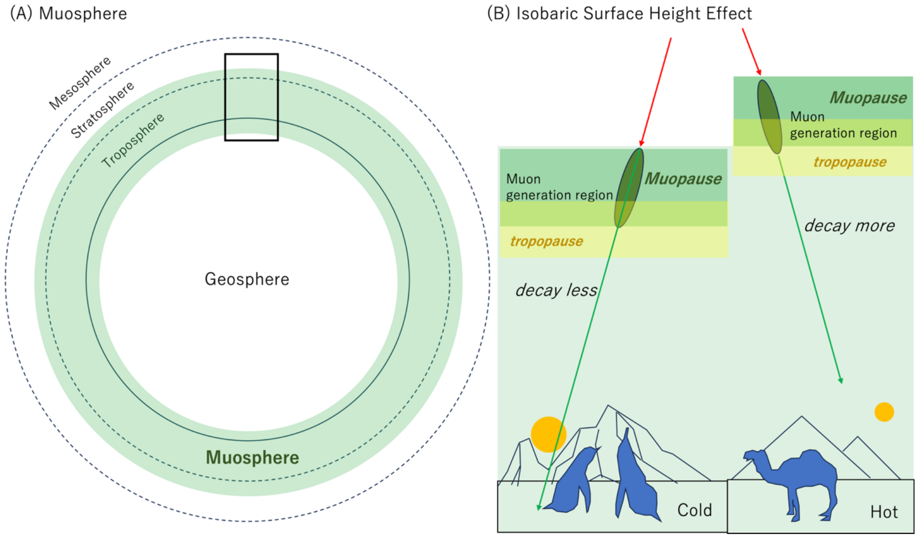

Figure 1. Definition of muosphere and the principle of the DOF technique. The span of the muosphere is shown along with other layers of the Earth (A). The black box indicates the muosphere for the region shown in (B). Red arrows and green arrows respectively indicate the primary cosmic rays and muons. Additionally, (B) shows an example of the contrast between the average height of the muopause above colder surface temperature and the height of the muopause above warner surface temperature. Dark green ovals indicate the muon production regions. As is indicated with yellow-filled boxes, the tropopause and the muopause do not exactly overlap with each other.

3. DoF Modeling

3.1 Modeling of the seasonal barometric effect on muon flux

The cosmic muon flux is also influenced by ground-level barometric variations because the amount of muon energy loss depends on the total areal density along their trajectories. In this work, we took advantage of muon flux variations associated with the presence of a cyclone to derive variations in the muon counts in the detector as a function of the ground-level pressure in Kagoshima city. The advantage of using the cyclone data is that since the cyclone moves quickly (typically within 24 hours) and will dramatically alter the ground-level atmospheric pressure (sometimes by more than 40 hPa), barometric muon flux variations can be evaluated without being influenced from the longer-time-scale isobaric surface height effect. Figure 2A compares the temporal variations in the muon flux and the temporal variations in the ground-level atmospheric pressure induced

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by the 2018 Typhoon No 24. Figure 2B shows the relationship between the muon flux and the atmospheric pressure (both measured in Kagoshima city). The metrological data in Figure 2 were taken from Reference (Japan Metrological Agency, 2023). The data points were fitted by a linear function and the result is shown in the following equation:

$$\Delta N = 0.0012\Delta P\ [\text{hPa}] + 2.2159. \quad (1)$$

This result indicates that the muon flux varies by 1.2% if the ground-level atmospheric pressure changes by 10 hPa. Since the detector used for measuring this cyclone effect on the muon flux is identical to that used for the DoF measurements, the external factors including the zenith angular dependence of the muon flux, geometrical acceptance of the detector, etc. are canceled out. The fractions of the number of the data points are respectively 60%, 82%, and 100% for deviations of ≤1σ, ≤1.5σ, and ≤2σ from the estimated line. The SD of the data points from the estimated line (0.0065) which is close to the statistical error associated with the data points (0.0052-0.0054). The difference between them (0.0037) can be the fitting uncertainty which adds an uncertainty of ~18 m in estimation of the muopause height (See below). Eq. (1) was used for the barometric correction to the muon flux in the current work.

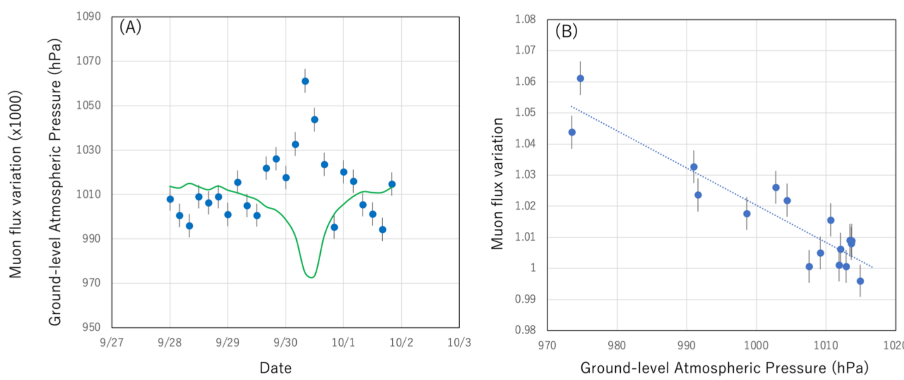

Figure 2. Variations in the muon flux induced by the ground-level atmospheric pressure variations. The muon flux variations (blue filled circles) are compared with the ground-level atmospheric pressure variations (green solid lines) induced by the 2018 Typhoon No 24 (A). The muon flux variations (blue filled circles) are shown as a function of the ground-level atmospheric pressure. The dotted line indicates the linear function fitted to these data points (B).

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With Eq. (1), seasonal variations of the muon flux caused by variations in the ground-level atmospheric pressure (P-driven muon flux variations) were evaluated. Figure 3A shows seasonal variations in the ground-level atmospheric pressure measured at the Kagoshima Meteorological Observatory in the period between August 2017 and August 2020. Figure 3B shows the corresponding P-driven muon flux variations based on Eq. (1).

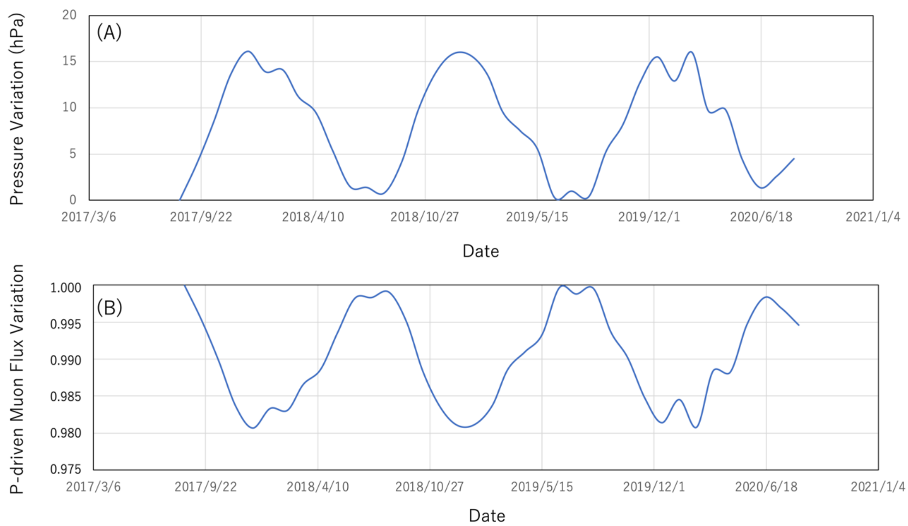

Figure 3. Seasonal variations in the ground-level atmospheric pressure (A) and variations of muon flux due to variations in the ground-level atmospheric pressure (B). The data are shown in the period between August 2017 and August 2020. The ground-level atmospheric pressure data were taken from Reference (Japan Metrological Agency, 2023).

3.2 Balloon-based studies near the muopause

Japan Meteorological Agency launches a balloon from Kagoshima city twice a day (09:00 and 21:00 JST) to monitor the upper atmosphere. The monthly measurement results acquired in 2018 and 2019 are shown in Figure 4. As shown in this figure, the altitude of the muopause varies ΔH ~ 500 m, reflecting seasonal variations (i.e., altitude that increases in the summer time) of the muopause. While the muon generation depth has a certain span (50-300 hPa), as can also be seen in this figure, the isobaric surface height corresponds closely with the variations in this span. Therefore, we can conclude that the isobaric structure of the upper muosphere is simply pushed further from sea level in summer and pushed closer to sea level in winter (dark green ovals in Figure 1B). Consequently, it is expected that variations in the muon survival rate at sea level is a function of the muopause height.

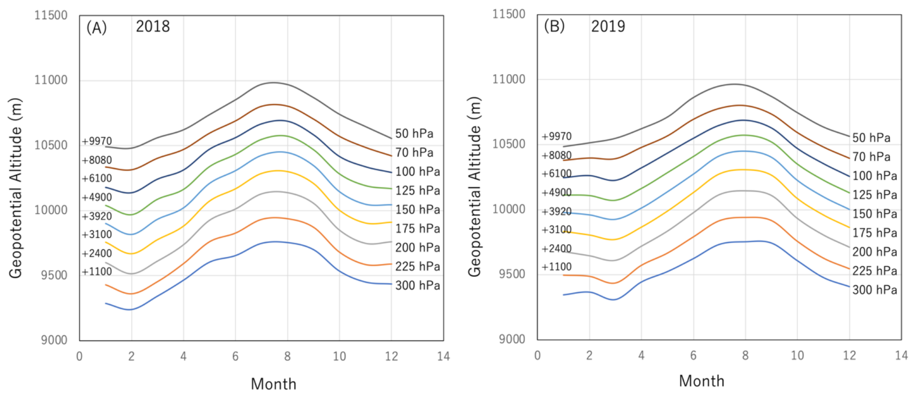

Figure 4. Seasonal changes in the geopotential altitude of the upper troposphere and the lower stratosphere. The data acquired in 2018 (A) and the data acquired in 2019 (B) are shown. The data were taken from the Japan Metrological Agency survey (Japan Metrological Agency, 2023). The numbers on the left side of each panel indicate the offset of the altitude in units of meters.

3.3 Modeling of the seasonal isobaric surface height effect on the muon flux

As was described in the previous subsection, the isobaric surface height variations ΔH (H) are independent from H in this span. The modeling procedure is summarized as follows.

(A) The zenith-angular dependent open-sky muon spectrum data points are taken from various prior experimental works (Allkofer *et al.,* 1985; Haino *et al.,* 2004; L3 Collaboration., 2004).

(B) These muon spectrum data points are interpolated to derive $I_0(E,\theta)$ by using the Thompson and Whalley analytical formula (Thompson and Whalley, 1977).

(C) Calculations of the angular-dependent muon flux are done, based on the following formula:

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$$n(\theta,\phi) = \int I(E,\theta)dE, \qquad (2-1)$$

$$I(E,\theta) = I_0(E,\theta)\exp(-\Delta H(\sin\theta)^{-1}/660\gamma(E)[\mathrm{m}])(1-\Delta N), \qquad (2-2)$$

where E and θ are respectively the muon's energy and the arrival angle from zenith at sea level, $I_0(E,\theta)$ is the reference muon flux, and γ is the Lorentz factor. Figure 5 plots Eq. (2-1) for $\Delta H = 0$ m (Figure 5A) and $\Delta H = +500$ m (Figure 5B). The positive and negative signs attributed to ΔH respectively indicate respectively upward variations and downward variations. If θ approaches the value of zero, $(\sin\theta)^{-1}$ will be diverged, so in this case, the spherical curvature of the Earth has to be considered (for $\theta = 90°$).

(D) Calculate the number of muons recorded by the detector with:

$$N = \int_{\phi_0}^{\phi_1}\int_{\theta_0}^{\theta_1} n(\theta,\phi)d\theta d\phi, \qquad (3)$$

where θ_0, θ_1, ϕ_0, and ϕ_1 are respectively the detector's zenith (θ_0-θ_1) and azimuth (ϕ_0-ϕ_1) angular acceptance. Eq. (3) was used for the isobaric correction to the muon flux in the current work.

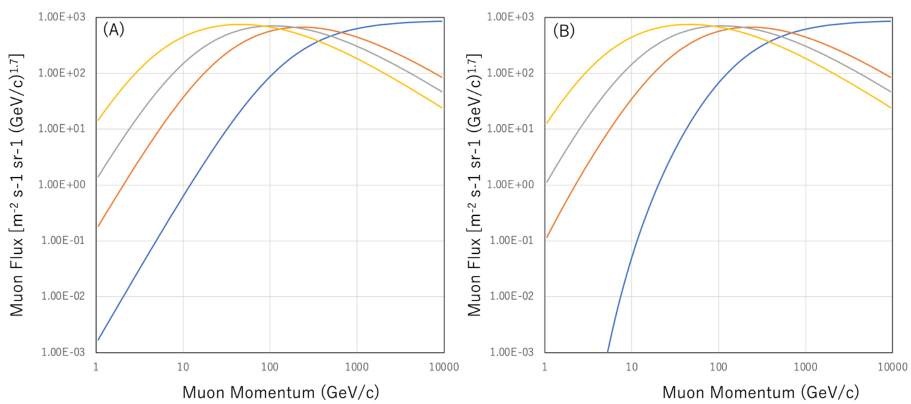

Figure 5. Differential muon flux for different isobaric surface altitudes. The spectra calculated for the reference isobaric surface altitude ($\Delta H = 0$ m) are shown in (A) and for the case when the isobaric surface is uplifted by 500 m in (B) for various muon's arriving

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angles: 90º (blue), 80º (orange), 70º (gray), and 50º (yellow). Only slanted muons are shown due to the geometrical configuration of the current detector setup (see below).

With Eq. (2-1), seasonal variations of the muon flux due to the isobaric surface height effect (H-driven muon flux variations) were calculated. Figure 6A shows the balloon-based ΔH value averaged over the altitudes which ranged between 50 hPa and 300 hPa. Figure 6B shows the corresponding H-driven muon flux variations based on Eq. (2-1). In order to match the angular acceptance of the racker (described in the next section), the zenith-angular integration range of Eq. (2-1) was set to be 50º-80º. It was assumed that the muon's arriving angles are azimuthally isotropic. These results are subsequently used for the muon flux modeling process which will be described in the following subsection. As can be compared between Figure 4 and Figure 6, the seasonal isobaric surface height effect (up to 8%) is much larger (by a factor of 4) than the seasonal barometric effect (up to 2%).

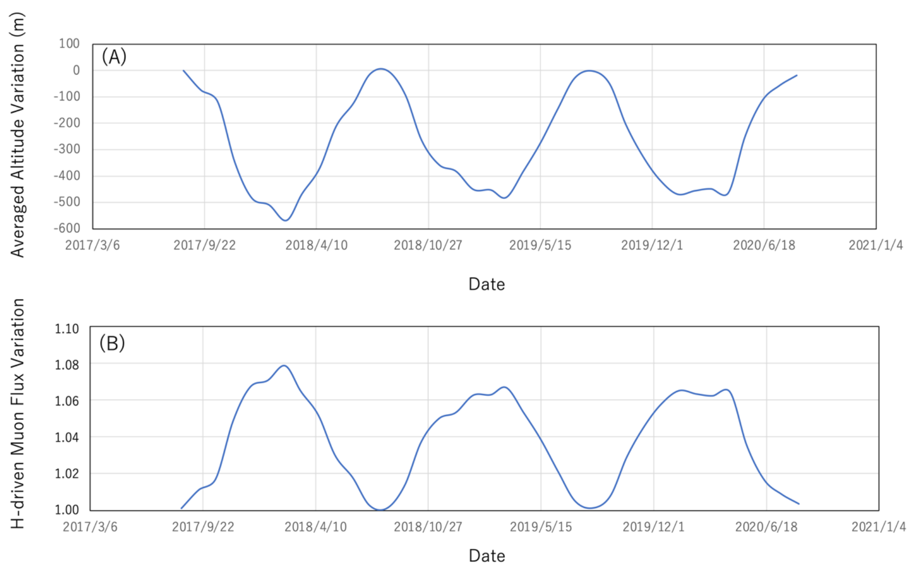

Figure 6. Balloon-based isobaric height variations averaged over the altitudes between 50 hPa and 300 hPa (A) and H-driven variations of the muon flux without the barometric correction (B). The data are shown for the period between August 2017 and August 2020. The balloon-based isobaric height data were taken from Reference (Japan Metrological Agency, 2023).

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4. Apparatus

The muon tracker used in this study consisted of 90 scintillator strip detectors. Each scintillator strip detector consisted of a plastic scintillator (Bicron BC-408) strip connected to a photomultiplier tube (PMT; Hamamatsu R7724) via an acrylic light guide. The typical pulse height outputted from the PMTs were 3-5 V while the threshold level of the discriminator was set to be 50 mV, so that the counting rate would not be easily influenced by the drift of the PMT gain and the discriminator's threshold level caused by variations in ambient temperature. The width and the length of the plastic scintillator strip were respectively 100 mm and 1500 mm. These strips were arranged vertically and horizontally to form three position sensitive detectors (PSDs) Three PSDs were vertically arranged with a spacing of 60 cm. In order to reject electromagnetic components, (such as positrons/electrons) a 10-cm thick lead block and a 3-cm thick stainless-steel with a thickness of 3 cm were inserted into each interval between the PSDs.

Each of the resultant PSDs consists of a segmented plane with 15 × 15 segments having a 1.5 × 1.5 m^2 active area with a spatial resolution of 10 cm. Since the distance between the uppermost stream detector and the lowermost stream detector is 120 cm, the angular resolution of this detector is 83 mrad. This angular resolution is equivalent to the spatial resolution of 830 m at a location 10 km from the tracker, but it is reduced to 8.3 km at a location 100 km from the tracker. The elevation and azimuth angular acceptance are respectively 0 ° - 51° and ±51°. However, since the active area is drastically reduced for muons injecting at higher angles with respect to PSD planes (e.g., for muons arriving at an elevation angle of 51° and an azimuth angle of 51°, the tracker's active area is reduced to 1/225), for practicality, a much smaller angular region (14 °- 32 ° for elevation angular region and ±28° for azimuthal angular region) was employed. For tracking, all vertices are examined but only the vertices that are aligned (along a straight line) are counted as an event to ensure that only muons were selected. Lead and stainless-steel shields within the detector decrease the background noise, however they also increase the possibility of muon scattering events. However, these scattering angles (10-20 mrad) are considered to be negligible in comparison to the current tracker's angular resolution (>80 mrad). The muon tracker used in the current experiment was located in Kagoshima city, Japan and it was pointed towards the southern direction. The measurement period was between August 20, 2017- June 30, 2020 (1,044 days).

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5. Comparison between the model and the experimental data

Figure 7 shows the seasonal variation in the muon flux data acquired in the period between August 20, 2017- June 30, 2020. As was expected, the muon flux showed a negative correlation between the ambient temperature and the muon flux, indicating that the isobaric surface height effect is predominant in seasonal variations in the muon flux. In this period there were not any specific extraterrestrial events (such as a Forbush decrease) that could have affected the primary flux. The muon counts in each bin (bin width = 3 days) ranged between 7×10^5-7.4×10^5. The muon flux variations were normalized to the value observed on August 20, 2017. The muon flux modeling results with barometric and isobaric corrections are overlaid on this plot (red solid lines in Figure 7). The root mean square (RMS) of the deviations between the theoretical values and the observational values is 0.00987. The measured seasonal variation in the muon flux is well explained by combining the current barometric and isobaric correction models.

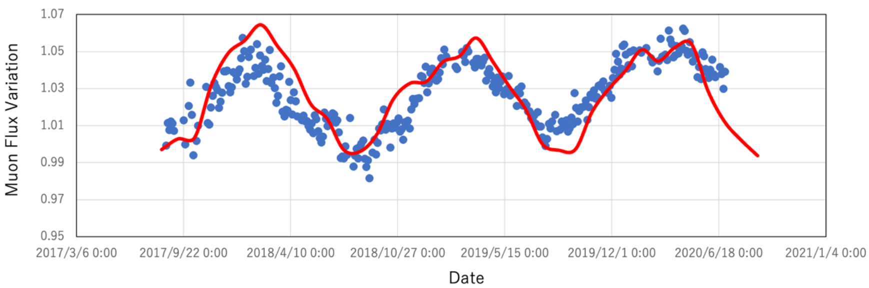

Figure 7. Seasonal variation in the muon flux data acquired in the period between August 20, 2017- June 30, 2020. The observation values (blue filled circles) and theoretical values (red solid lines) are shown. The statistical errors associated with each data point fit within the size of the circles.

6. Limitations and potential improvements

The RMS deviation of the observed muon flux variations from the DoF modeling results (~1%) induces an error of ~60 m in the estimation of the muopause height with the DoF technique. The DoF time resolution is 3 days. These characteristics, the accuracy and time resolution, are both significantly lower than the accuracy and the time resolution that can

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be attained with the GPS-loaded balloons (~5 m and 1 second). This is the main limitations of the DoF approach in its current stage of development. These limitations mainly come from (A) the statistics and (B) the modeling accuracy. Regarding factor (A), the detector size needs to be enlarged to record more muon events. In order to confirm this detector size effect, further DoF measurements with larger sized detector (4.5 m^2) are currently ongoing. Regarding factor (B), more precise modeling developments are ongoing with the extended air shower (EAS) Monte Carlo (MC) simulation. The current work is based on the assumption is that the muons travel straight forwardly without experiencing scatterings; however, it must be noted that after the muons are generated near the tropopause, they travel through a material with a thickness equivalent to 20-meter water equivalent (m.w.e.) - 40 m.w.e. for the muons arriving from an elevation angular region between 14 °- 32 °, having a tendency to scatter to cause longer track lengths in the troposphere. This effect must be taken into account in our future work to make improvements to factor (B). The discrepancy between the balloon position and the muon generation region may also influence how closely the compared data sets match. The muospheric layer thickness seasonally oscillates, but its amplitude is likely to depend on location of the measurement on the Earth since the near surface temperature is regionally varied. If the surface temperature is different between the location underneath the ballon and the location underneath the region of interest of the muopause, the muopause height in this region and the balloon-based isobaric surface altitude will not coincide. Since the balloon's trajectory is random, and it is difficult to control it, the next step in development is to compare the DoF data with the satellite-based stratospheric sensing data.

7. Conclusion

In conclusion, a new muographic technique called DoF was proposed, and with this technique, it was found that the muopause height interlocks with the isobaric surface height in the upper troposphere and lower stratosphere. This work defined (A) the position of the muopause and the layer span of the muosphere on the Earth; additionally, it was shown that (B) the muopause is located in the lower stratosphere, (C) seasonal variations in the muon flux are predominantly ruled by muopause dynamics, (D) muopause dynamics can be visualized with LOF muography by taking advantage of directional patterns of cosmic-ray muon's survival probabilities, and (E) muopause dynamics is closely related with isobaric surface height variations in the lower stratosphere.

Muopause dynamics has the potential to contribute to research focused on the upper tropospheric and lower stratospheric dynamics. In future studies, the potential of LOF

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muography for application to studying the dynamical processes occurring in the upper troposphere and lower stratosphere will be further investigated by performing related case studies and making specific comparisons with other atmospheric climate datasets.

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Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author Contribution

H.K.M.T. wrote the text. H.K.M.T. prepared the figures. H.K.M.T. reviewed the manuscript.

Competing interests

The author is a member of the editorial board of Geoscientific Instrumentation, Methods and Data Systems.