

Earth and Space Science



RESEARCH ARTICLE

10.1029/2019EA000655

Middle-Atmosphere Dynamics Observed With a Portable Muon Detector

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Key Points:

- We report muon rate variations associated to temperature changes in the middle atmosphere observed with a portable muon detector
- The effect is significant both for seasonal and short-term temperature variations, even under low-opacity conditions at midlatitudes
- We highlight potential applications on atmosphere dynamics and the need to account for these phenomena in geophysical applications

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Citation:

Tramontini, M., Rosas-Carbajal, M., Nussbaum, C., Gibert, D., & Marteau, J. (2019). Middle-atmosphere dynamics observed with a portable muon detector. *Earth and Space Science*, 6, 1865–1876. <https://doi.org/10.1029/2019EA000655>

Received 1 APR 2019

Accepted 26 AUG 2019

Accepted article online 29 AUG 2019

Published online 15 OCT 2019

Abstract In the past years, large particle physics experiments have shown that muon rate variations detected in underground laboratories are sensitive to regional, middle-atmosphere temperature variations. Potential applications include tracking short-term atmosphere dynamics, such as Sudden Stratospheric Warmings. We report here that such sensitivity is not only limited to large surface detectors under high-opacity conditions. We use a portable muon detector conceived for muon tomography for geophysical applications, and we study muon rate variations observed over 1 year of measurements at the Mont Terri Underground Rock Laboratory, Switzerland (opacity of ~700 meter water equivalent). We observe a direct correlation between middle-atmosphere seasonal temperature variations and muon rate. Muon rate variations are also sensitive to the abnormal atmosphere heating in January–February 2017, associated to a Sudden Stratospheric Warming. Estimates of the effective temperature coefficient for our particular case agree with theoretical models and with those calculated from large neutrino experiments under comparable conditions. Thus, portable muon detectors may be useful to (1) study seasonal and short-term middle-atmosphere dynamics, especially in locations where data are lacking such as midlatitudes, and (2) improve the calibration of the effective temperature coefficient for different opacity conditions. Furthermore, we highlight the importance of assessing the impact of temperature on muon rate variations when considering geophysical applications. Depending on latitude and opacity conditions, this effect may be large enough to hide subsurface density variations due to changes in groundwater content and should therefore be removed from the time series.

Plain Language Summary Temperature variations in high altitudes of the atmosphere remain to be fully understood. During winter, sudden heating of this region can perturb its normal dynamics and result in extremely low temperatures at the surface of the Earth. We found that tracking the amount of muons at the Earth's surface may be a key tool to study these variations. Muons are elementary particles produced by the interaction of cosmic rays with the atmosphere. The flux of muons arriving at the Earth's surface is about 1 muon per minute per square centimeter. In fact, this flux depends on the atmospheric temperature distribution. Up until now only large muon detectors, developed for experiments under the most advantageous conditions, had measured changes in the flux of muons due to sudden heating of the high atmosphere. Here we show that these phenomena can also be observed by smaller, portable detectors built for geoscience applications. The technology to study sudden temperature variations in the atmosphere is expensive and only able to sample punctual points in the sky. Through an improved data coverage, the muon technique may bridge the gap towards a better understanding of the thermal state of the atmosphere and its dynamics.

1. Introduction

First observed in 1952 using radiosonde measurements (Scherhag, 1952), Sudden Stratospheric Warmings (SSWs) are extreme wintertime circulation anomalies that produce a rapid rise in temperature in the middle to upper polar stratosphere (30–50 km). SSW effects on middle-atmosphere dynamics have lifetimes of approximately 80 days (Limpasuvan et al., 2004). They are the clearest and strongest manifestation of dynamic coupling throughout the whole atmosphere-ocean system (Goncharenko et al., 2010; Liu & Roble, 2002; O'Callaghan et al., 2014). Following a major SSW, the high-altitude winds reverse to flow westward instead of their usual eastward direction. This reversal often results in dramatic surface temperature

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reductions in midlatitudes, particularly in Europe, which suggests the possibility of monitoring the stratosphere for predicting extreme tropospheric weather (Thompson et al., 2002). The frequency of SSWs may increase due to global warming (Kang & Tziperman, 2017; Schimanke et al., 2013). While many studies have focused on the characterization of SSWs through observation and modeling dynamics at high-latitude regions, observation studies at midlatitudes are rare and could be crucial to better understand the phenomena (Sox et al., 2016; Yuan et al., 2012).

Cosmic muons represent the largest proportion of charged particles reaching the surface of the Earth, yielding a flux of $\sim 70 \text{ m}^{-2} \cdot \text{sr}^{-1} \cdot \text{sr}^{-1}$ for particles above 1 GeV (Tanabashi et al., 2018). They are a product of the primary cosmic rays interaction with the atmosphere, which produces short-lived mesons, in particular, charged pions and kaons. These particles decay into muons that easily penetrate the atmosphere and may reach the surface of the Earth. The flux of muons decreases as muons travel through an increasing amount of matter. Thus, only the most energetic muons can reach underground detectors (Gaisser et al., 2016). The muon production process requires that the parent mesons did not undergo destructive interactions with the propagating medium before they decay (Grashorn et al., 2010). Thus, changes in the atmospheric properties, in particular in its density, may have large impacts on the muon flux measured at ground level, either by affecting the parent mesons survival probabilities before decay or by affecting the rate of absorption of the muons themselves along their path down from their production level.

An increase in the atmospheric temperature lowers the atmospheric density. Temperature changes in the atmosphere may therefore affect the production of muons (Gaisser et al., 2016). The decrease in atmospheric density increases the mean free path of the mesons and therefore their decay probability, thus increasing the muon flux. The effect is more important for high-energy muons, which result from high-energy mesons with larger lifetime due to time dilation and therefore with longer paths in the atmosphere. This increases their interaction probability before decay (Grashorn et al., 2010); thus, one expects high-energy muons to be more sensitive to temperature changes. The opacity is the integrated density along a travel path. It is used to quantify the amount of matter encountered by the muons and is generally expressed in meter water equivalent (mwe). Detectors in high-opacity conditions are then more likely to register the effects of temperature variations in the atmosphere simply because they only register high-energy muons. Notice that the low-energy muons may also be affected by temperature changes because their own interaction probability with the atmosphere along their path down to the Earth depends on the atmospheric density. Indeed, this effect has been observed in low-opacity conditions (e.g., Jourde et al., 2016) but is not relevant for detectors deeper than 50 mwe (Ambrosio et al., 1997). The variations in the cosmic muon flux caused by atmospheric temperature changes can be treated in terms of an effective temperature (Ambrosio et al., 1997; Barrett et al., 1952). This effective temperature is a weighted average of the atmosphere's temperature profile, with weights related to the altitudes where muons are produced (Grashorn et al., 2010).

Modulation of the cosmic muon flux produced by seasonal variations in the atmospheric temperature has been reported for large detectors (AMANDA: Bouchta, 1999; Borexino: Agostini et al., 2019; Daya Bay: An et al., 2018; Double Chooz: Abrahão et al., 2017; GERDA: Agostini et al., 2016; IceCube: Desiati et al., 2011; LVD: Vigorito et al., 2017; MACRO: Ambrosio et al., 1997; MINOS: Adamson et al., 2010, 2014), OPERA: Agafonova et al. 2018). Osprey et al. (2009) and Agostini et al. (2019) also report that measured muon rates are sensitive to short-term variations (day scale) in the thermal state of the atmosphere, such as the occurrence of SSWs. Agafonova et al. (2018) observed short-term, nonseasonal variations in latitudes as low as 42°N, in Italy.

The previously mentioned studies highlight the potential of muon measurements to characterize and monitor middle-atmosphere dynamics. However, all these studies were conducted by large-scale, general purpose particle detectors, specifically built for neutrino and high-energy particle experiments. Most of them were placed hundreds of meters underground, which improves data sensitivity to atmospheric effects by filtering out low-energy muons. The detection surface of these systems are huge compared to portable ones, which are used for geoscience applications such as characterizing the density structure of volcanoes (e.g., Rosas-Carbajal et al., 2017). Recently, muon rate variations following the passage of a thundercloud were reported by Hariharan et al. (2019) using a relatively large detector ($6 \times 6 \times 2 \text{ m}^3$). To the best of our knowledge, no experiment has reported the sensitivity of portable muon detectors to middle-atmosphere dynamics, especially under relatively low opacity conditions.

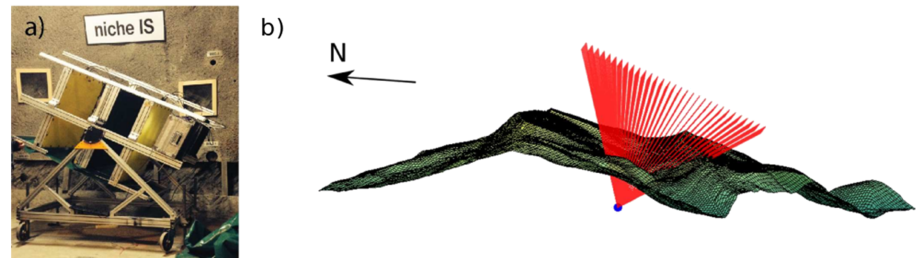


Figure 1. (a) The muon telescope deployed in the Mont Terri Underground Rock Laboratory. (b) Telescope's position (blue) and axes of observation (red), along with the topography.

In this paper, we study seasonal and short-term variations in the muon rate observed with a portable muon detector installed at the Mont Terri Underground Rock Laboratory (Switzerland, 47.4°N). We first present our detector and the general conditions under which the measurements were taken. We then analyze the variations observed and compare them to atmospheric temperature and middle-atmosphere dynamics data. Finally, we discuss the implications of our observations both for the atmospheric science and geophysics communities, the latter aiming to characterize density variations in the subsurface with muon data.

2. The Muon Detector

Our portable muon detector was conceived for geoscience applications by the DIAPHANE project (e.g., Marteau et al., 2012, 2017). It is equipped with three plastic scintillator matrices of 80 cm width composed by $N_x=N_y=16$ scintillators bars, in the horizontal and vertical directions, whose interceptions define 16×16 pixels of 5×5 cm². When a muon passes through the three matrices (i.e., an “event” is registered), three hits are recorded in time coincidence, with a resolution better than 1 ns (Marteau et al., 2014), enabling us to reconstruct its trajectory from the sets of pixels fired in each matrix. We apply a selection based on the goodness of the reconstructed trajectory in order to filter out random coincidences, that is, three coincident fired pixels that do not align. If the reconstructed trajectories using two consecutive matrices differ by more than one pixel, in either the horizontal or the vertical direction, the event is discarded. More details on the hit selection and the technique applied to determine the propagation directions of muons through the detector matrices can be found in Jourde (2015) and in Marteau et al. (2014). The distance between the front and rear matrices is set to 100 cm for this study (Figure 1a). Because of the large volume of rock studied compared to the detector size, we admit a point-like approximation of the detector (Lesparre et al., 2010). With this approximation, given that two points are sufficient to uniquely determine a direction, events whose pair of pixels in the front and the rear matrices share the same relative direction are considered to correspond to the same trajectory. This yields a total of $(2N_x-1)\times(2N_y-1)=961$ axes of observation studied (represented in Figure 1b).

The passage of muons is detected with wavelength shifting optical fibers that transport the photons generated by the scintillators to the photomultiplier, where they are detected based on a time coincidence logic. The optoelectronic chain has been developed from high-energy particle experiments on the concept of the autonomous, Ethernet-capable, low-power, smart sensors (Marteau et al., 2014). In order to support strenuous field conditions, besides being sensitive, the detector is also robust, modular, and transportable (Lesparre et al., 2012). In this experiment, the muon detector was deployed in the Mont Terri URL and acquired data for 382 days between October 2016 and February 2018. The minimum and the maximum amount of rock traversed by muons registered by the detector are of approximately 200 and 500 m, respectively. Prior to the underground measurements, a calibration experiment was performed by measuring the open-sky muon flux at the zenith, from which we register a total acceptance of 1,385 cm².sr for our data set (Lesparre et al., 2010).

3. Methodology

Our data set consists of a list of muon detections called “events”. Each event is characterized by the arrival time and the direction of the particle (possible directions shown in Figure 1b). From these data, we compute the average cosmic muon rate, R , using a 30-day width Hamming moving average window (Hamming, 1998).

In order to increase the signal to noise ratio and, therefore, to improve the statistics in our analysis, we merge the signals from all the directions together (e.g., Jourde et al., 2016). Such a merging is done exclusively to compute R .

Seasonal variations in R , caused by the temperature changes in the atmosphere, can be treated in terms of an effective temperature (Barrett et al., 1952), T_{eff} :

$$\frac{\Delta R}{\langle R \rangle} = \alpha_T \frac{\Delta T_{\text{eff}}}{\langle T_{\text{eff}} \rangle} \quad , \quad (1)$$

where α_T is the effective temperature coefficient, $\langle R \rangle$ is the mean muon rate, and $\langle T_{\text{eff}} \rangle$ is the mean effective temperature. T_{eff} is defined as the temperature of an isothermal atmosphere that produces the same meson intensities as the actual atmosphere. Thus, it is related to the atmosphere's temperature profile, and it is associated to the altitudes where observed muons are produced. We use the parametrization given by Grashorn et al. (2010):

$$T_{\text{eff}} = \frac{\int_0^\infty W(X)T(X)dX}{\int_0^\infty W(X)dX} \quad , \quad (2)$$

where the temperature, $T(X)$, is measured as a function of atmospheric depth, X . The weights, $W(X)$, contain the contribution of each atmospheric depth to the overall muon production. These weights depend on the threshold energy E_{th} , that is, the minimum energy required for a muon to survive a particular opacity in order to reach the underground detector. Since $T(X)$ is measured at discrete levels of X , we perform a numerical integration based on a quadratic interpolation between temperature measurements to obtain T_{eff} .

The effective temperature will be different for different zenith angles. To compare T_{eff} variations to our measured muon rates, we need to account for this dependence. Following Adamson et al. (2014), we bin the zenith angle distribution and calculate a weighted effective temperature, $T_{\text{eff}}^{\text{weight}}$, as follows:

$$T_{\text{eff}}^{\text{weight}} = \sum_{i=1}^M F_i \cdot T_{\text{eff}}(\theta_i) \quad , \quad (3)$$

where M is the number of zenith angle bins, $T_{\text{eff}}(\theta_i)$ is the effective temperature in bin i , and F_i is the fraction of muons observed in that bin. The formula for $T_{\text{eff}}(\theta_i)$ is similar to equation (2), but the atmospheric depth is replaced by $X/\cos\theta$ and E_{th} is calculated for each zenith angle as well. From now on, we will refer to $T_{\text{eff}}^{\text{weight}}$ as T_{eff} . These values are calculated four times a day and then day averaged, and the resulting standard deviation is used as an uncertainty estimate of the effective temperature daily mean value. Thus, a representative value of effective temperature is calculated for each day, which fully accounts for the particular setup of our experiment.

The goodness of fit of the linear relationship in equation (1) can be quantified by the Pearson correlation coefficient r . This parameter is equal to ± 1 for a full positive/negative linear correlation, respectively, and 0 for no correlation. We perform a linear regression between the relative muon rate and effective temperature variations using Monte Carlo simulations. In this way, we can account for error bars in both variables and compute the uncertainty of the fitted parameters. Following Adamson et al. (2010), the intercept is fixed at zero and the slope of the linear fit is the effective temperature coefficient, α_T . To evaluate the effects of systematic uncertainties, we modify $\langle T_{\text{eff}} \rangle$ and the parameters involved in the computation of T_{eff} (i.e., the 12 input parameters in $W(X)$; c.f. Adamson et al., 2010) and recalculate the effective temperature coefficient, α_T . These systematic errors are added in quadrature to the statistical error obtained from the linear fit in order to obtain the experimental value of α_T .

We also use Monte Carlo simulations to determine the theoretical expected value of the effective temperature coefficient, α_T^{theory} , in order to compare it with the experimental one. Muon energy, E_μ , and zenithal angle, θ , are randomly sampled from the differential muon spectrum given by Gaisser et al. (2016) and corrected for altitude according to Hebbeker and Timmermans (2002). Then, the muon is randomly assigned an azimuthal angle, ϕ , according to a uniform probability distribution. The overburden opacity in the Mont Terri URL is determined for each combination of (ϕ, θ) from our muon data set, together with the corresponding E_{th} (Tanabashi et al., 2018). We continue the Monte Carlo sampling until we obtain 10,000 successful events that satisfy $E_\mu > E_{\text{th}}$, for which we compute the α_T^{theory} distribution using the expression derived by Grashorn et al. (2010). Next, we determine the value of α_T^{theory} and its uncertainty as the mean and standard deviation of the distribution, respectively. The systematic uncertainty is the one reported by Adamson et al. (2014).

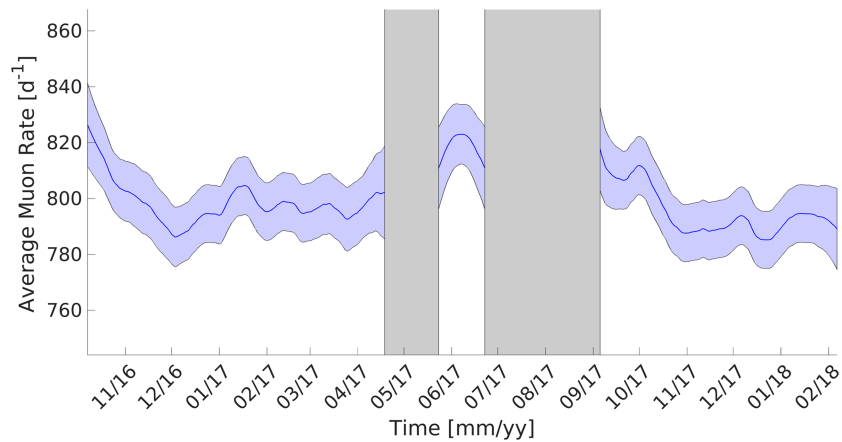


Figure 2. Average cosmic muon rate as a function of time, computed using a 30-day width Hamming moving average window. The colored surface delimits the 95% confidence interval. Gray bars indicate periods where the acquisition was interrupted for work in the Mont Terri Underground Rock Laboratory.

We look for the occurrence of SSWs during the acquisition period using the definition of a major SSW given by Charlton and Polvani (2007). A major midwinter warming is considered to occur when the zonal mean zonal wind at 60°N and 10 hPa become easterly during winter. The first day on which this condition is met is defined as the central date of the warming. The zonal mean zonal wind is the average east-west (zonal) wind speed along a latitude circle. To ensure that only major midwinter warmings are identified, cases where the zonal mean zonal wind does not reverse back to westerly for at least 2 weeks prior to their seasonal reversal to easterly in spring are assumed to be final warmings and as such are discarded. SSWs typically manifest as a displacement or a splitting of the polar vortex (Charlton & Polvani, 2007), a cyclone residing on both of the Earth's poles that goes from the midtroposphere into the stratosphere.

4. Results

Based on 382 days of data, the average daily rate of cosmic muons in the Mont Terri URL is of $(800 \pm 10) \text{ day}^{-1}$, calculated by counting all the muons detected each day no matter their direction or the altitude at which they were produced. We also compute an average muon rate for each axis of observation, which we use to estimate

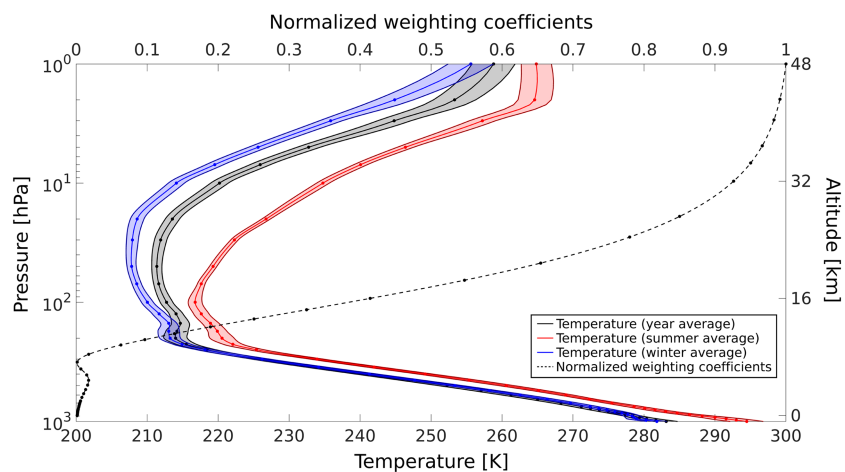


Figure 3. Atmospheric temperature profiles (solid lines) above the Mont Terri site and weighting coefficients (dashed line) used to calculate T_{eff} , as a function of pressure level and altitude. The dots represent the 37 pressure levels for which the temperature data sets are provided by the European Centre for Medium-range Weather Forecast. The right vertical axis represents approximate altitudes corresponding to the pressure levels on the left vertical axis. The summer average temperature (solid red line) and the winter average temperature (solid blue line) are computed considering a period of 1.5 months in each season during 2017. The colored surfaces represent the ± 1 standard deviation in each curve. The effective temperatures of each profile are as follows: $T_{\text{eff}}^{\text{year}} = (217 \pm 1) \text{ K}$, $T_{\text{eff}}^{\text{summer}} = (225 \pm 1) \text{ K}$, and $T_{\text{eff}}^{\text{winter}} = (214 \pm 1) \text{ K}$.

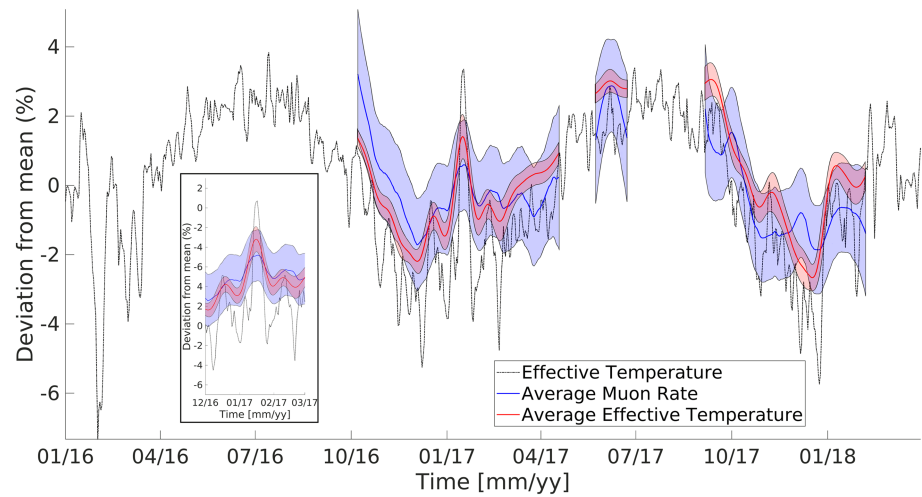


Figure 4. Daily percent deviations from the mean of the average cosmic muon rate, the daily effective temperature, and the average effective temperature computed using a 30-day width Hamming moving average window. The colored surfaces delimit the 95% confidence interval associated to each curve. The inset displays a zoom around the period of time in which a major sudden stratospheric warming is detected.

the corresponding opacity values. Minimum and maximum opacities are of approximately 500 and 1,500 mwe, respectively, while the average opacity considering all possible directions is of (700 ± 160) mwe. The cosmic muon rate presents significant variations in time (Figure 2). Maximum rate values occur close to the summer periods, while minimum rate values occur during winter times.

We use the ERA5 data set offered by the European Centre for Medium-range Weather Forecast, which is a climate reanalysis data set produced using 4D-Var data assimilation (Copernicus Climate Change Service (C3S), 2017). Temperature data consist of interpolated (0.25° by 0.25°) globally gridded data on 37 atmospheric pressure levels from 0 to 1,000 hPa, listed four times a day (00:00, 06:00, 12:00, and 18:00 hr). From this data set, we interpolate the temperature profiles at Mont Terri URL location. In Figure 3 we present the typical atmospheric temperature profiles at Mont Terri for summer, winter, and a year average over the analysis period. We also display in the same plot the corresponding normalized weighting coefficients W as a function of pressure levels, used to compute T_{eff} . The largest temperature changes occur above ~ 16 km, where the weighting coefficients are more significant. The effective temperatures corresponding to the

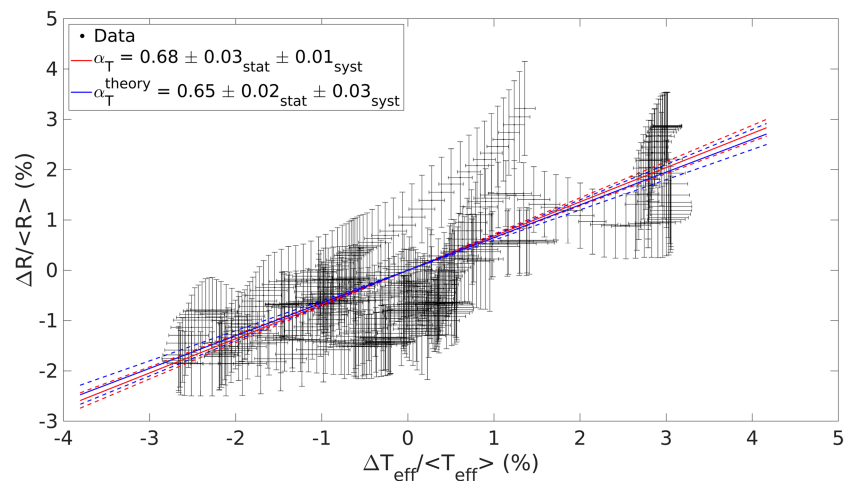


Figure 5. Average cosmic muon rate relative variation versus average effective temperature relative variation, fitted with a line with the y intercept fixed at 0. The resulting slope is $\alpha_T = 0.68 \pm 0.03_{\text{stat}} \pm 0.01_{\text{syst}}$ and is represented with a red line. The blue line represents the theoretical expected value of $\alpha_T^{\text{theory}} = 0.65 \pm 0.02_{\text{stat}} \pm 0.03_{\text{syst}}$. The dotted lines represent the uncertainty of each one of the values.

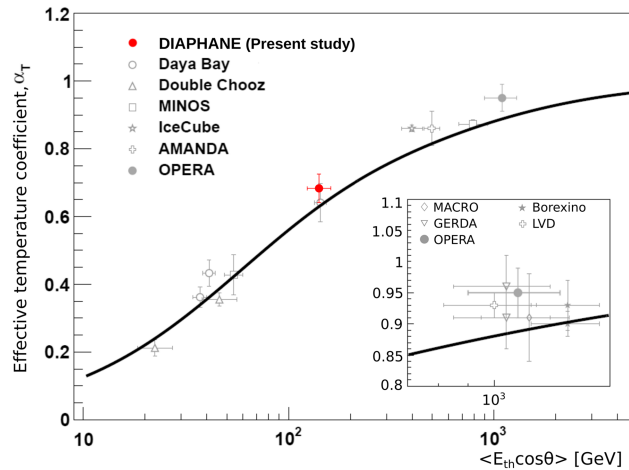


Figure 6. Experimental values of the effective temperature coefficient as a function of $\langle E_{th} \cos \theta \rangle$. The red dot represents the present study. The continuous black line represents a theoretical model. The inset plot shows the experiments performed at the underground Gran Sasso Laboratory. Figure adapted from Agafonova et al. (2018)

average curves and $\theta = 0^\circ$ are given by $T_{eff}^{year} = (217 \pm 1)$ K, $T_{eff}^{summer} = (225 \pm 1)$ K, and $T_{eff}^{winter} = (214 \pm 1)$ K. There is thus a difference of ~ 10 K between typical summer and winter conditions.

We compare the variations in the muon rate to the variations in the effective temperature in Figure 4 in terms of relative variations (see equation (1)). For consistency, we also apply a Hamming moving average window of 30 days to the T_{eff} time series. The two average curves evolve similarly in time. Indeed, the Pearson correlation coefficient between the deviation from mean of the average muon rate and that of average effective temperature yields a value of 0.81. We compute a linear fit between the two data sets (see section 3), which yields an effective temperature coefficient of $\alpha_T = 0.68 \pm 0.03_{stat} \pm 0.01_{syst}$, with $\chi^2/NDF = 414/381$ being the reduced χ^2 of the fit (Figure 5). The largest contribution to the systematic error in α_T comes from the ± 0.06 uncertainty in the meson production ratio (Barr et al., 2006), the ± 0.31 K uncertainty in the mean effective temperature (Adamson et al., 2010), and the ± 0.026 TeV uncertainty in E_{th} , which results from the distribution of opacities along the axes of observation. To discard possible systematic biases, we also performed a linear fit allowing for a nonzero y intercept. The fit resulted in an estimated value of zero within one standard deviation uncertainty for this intercept and a slightly lower value of $\alpha_T = 0.67 \pm 0.03_{stat} \pm 0.01_{syst}$ for the effective temperature coefficient.

The theoretical expected value was found to be $\alpha_T^{theory} = 0.65 \pm 0.02_{stat} \pm 0.03_{syst}$. Thus, the experimentally estimated value is consistent with the theoretical one within one standard deviation. In Figure 6 we present our

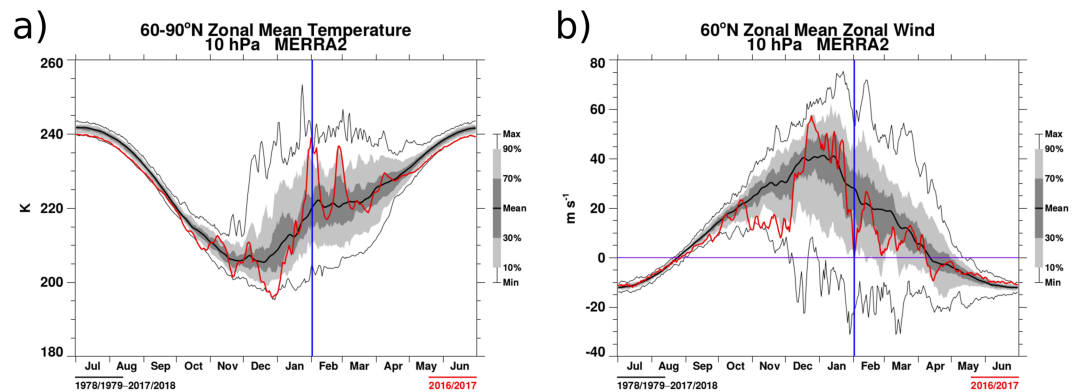


Figure 7. The Goddard Earth Observing System Data Assimilation System MERRA-2 data used to define sudden stratospheric warming events. (a) Zonal mean temperatures averaged over 60–90°N. (b) Zonal mean zonal wind at 60°N. The red curve denotes values for the 2016–2017 period, and the thick black curve corresponds to climatological values averaged from 1978 to 2018. The vertical blue lines reference a major sudden stratospheric warming for that winter. MERRA-2 = Modern-Era Retrospective analysis for Research and Applications, Version 2.

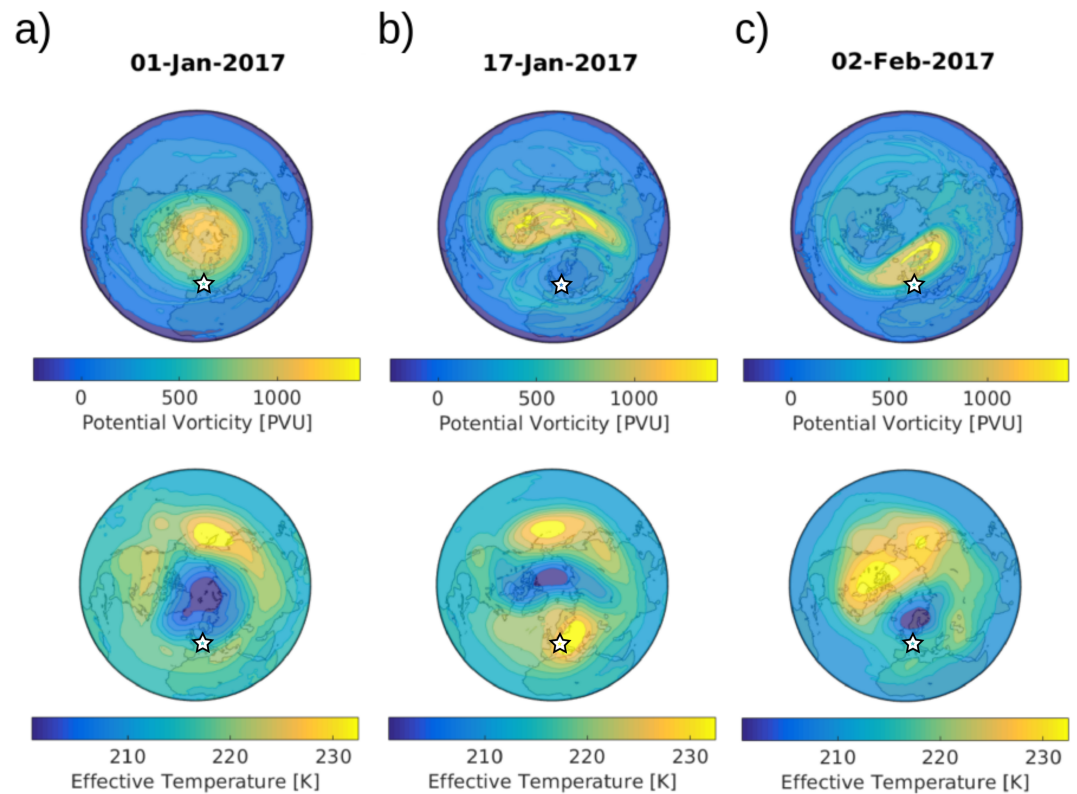


Figure 8. Potential vorticity at the 850 K potential temperature surface (top row) and effective temperature (bottom row) for (a) January 1, (b) January 17 and (c) February 2, 2017, derived from the European Centre for Medium-range Weather Forecast data set. The maps are centered on the North Pole, and the location of the Mont Terri Underground Laboratory (47.38°N, 7.17°E), close to the town of Saint-Ursanne, Switzerland, is represented with a star. $1 \text{ PVU} = 10^{-6} \text{ K}\cdot\text{m}^2\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$.

estimated value of α_T along with a theoretical model accounting for pions and kaons (Agafonova et al., 2018) and estimates from other experiments. Our estimate is consistent with the one obtained by An et al. (2018) in similar opacity conditions and with the theoretical model.

Taking a closer look at Figure 4, we can see that an anomalous increase in the effective temperature occurs between January and February 2017. The same anomalous behavior can be observed in the muon rate (see inset in Figure 4). We used the Charlton and Polvani (2007) definition and the Modern-Era Retrospective analysis for Research and Applications, Version 2, produced by the Goddard Earth Observing System Data Assimilation System (Gelaro et al., 2017) to determine if a major SSW occurred during this time period. We found that a major SSW took place during winter 2016–2017, with 1 February as the central date of the warming. In a few days, it increased the zonal mean temperature in the polar region by more than 20 K (Figure 7a).

Finally, we analyzed changes produced by the SSW using Ertel's potential vorticity (Matthewman et al., 2009). This parameter quantifies the location, size, and shape of the winter polar vortex. Figure 8 shows the spatial distribution of Ertel's potential vorticity at the 850 K potential temperature surface ($\sim 10 \text{ hPa}$, $\sim 32 \text{ km}$) for three different days, which are representative of the changes provoked. The figure also shows the effective temperature spatial distribution during these 3 days. On 1 January (Figure 8a) the vorticity and temperature exhibit “typical” winter conditions: the polar vortex is centered on the Pole, together with the minimum effective temperature. On 17 January, a reshaping on the polar vortex can be already observed. It is at this moment also that the largest effective temperature anomaly occurs in the Mont Terri region (Figure 8b). On 2 February, that is, 1 day after the event can be properly classified as a major SSW due to the reversal of the zonal mean zonal wind (see Figure 7b), the polar vortex shape is still anomalous with the “comma-shaped” maximum of potential vorticity now closer to the Mont Terri URL (Figure 8c). At the same time, the effective temperature in the Mont Terri region has decreased to values similar to those in 1 January.

5. Discussion

After a year of continuous muon measurements with a portable muon detector under relatively low-opacity conditions, we found that changes in the thermal state of the atmosphere represent the largest cause of muon rate variations. The correlation between these variables was first suggested by a simple comparison of the relative variation time series. Then, it was confirmed by the large correlation coefficient (0.81) and by the fitted effective temperature coefficient, which is in agreement with the theoretical value predicted for our particular opacity and zenith angle conditions. Furthermore, our experiment was by chance performed under similar opacity conditions to the Daya Bay detector, an established underground muon detector especially built for neutrino experiments (An et al., 2018). Its corresponding estimate of the effective temperature coefficient is also in agreement with ours (Figure 6).

Our muon detector is sensitive to both seasonal and short-term temperature variations. The regional thermal anomaly reaching its maximum around 17 January 2017 (Figure 4) is coincident with the polar vortex changing its shape from a normal pole-centered circle to a displaced “comma-shaped” one (Figure 8). This is a typical feature of a SSW (O'Neill, 2003). Furthermore, the criteria by Charlton and Polvani (2007) for declaring a major SSW are accomplished 15 days later. The time difference can be potentially explained by the zonally averaged wind criteria used to define major SSWs, against the local character of the temperature variations affecting the production of high-energy muons.

Under much higher opacity conditions (3,800 mwe, i.e., more than 5 times the Mont Terri URL opacity), the large muon detector of the Borexino experiment, Gran Sasso, Italy, also reported muon rate variations related to this SSW in 2017 (Agostini et al., 2019). Given the large opacity, most of the muons completely lose their energy before reaching the detector. Thus, only high-energy muons resulting from the decay of high-energy parent mesons are detected. As explained by Grashorn et al. (2010), high-energy mesons are most sensitive to middle-atmosphere temperature variations due to their relatively long lifetime and thus a higher probability of interacting with the atmosphere before decaying. This results in a higher sensitivity to temperature variations, which translates into a larger effective temperature coefficient (see Figure 6). Despite being in less advantageous conditions in terms of detector acceptance and tunnel depth, our portable muon detector was also able to detect these short-term effects (15 days) directly linked to middle-atmosphere dynamics (Figure 4).

Compared to lidar measurements, which can obtain temperature profiles over tens of kilometers in altitude but have very narrow global coverage (only as wide as the laser beam), muon detectors naturally provide integrated measurements in altitude and a larger horizontal coverage. Our results therefore imply that small and affordable muon detectors could be used to study middle-atmosphere temperature variations without resorting to, for example, expensive lidar systems. Besides being transportable, the advantage is that no high-opacity conditions are needed. A minimum opacity of 50 mwe would be required to filter out the temperature-dependent lowest-energy muons (Grashorn et al., 2010). Besides being temperature dependent, low-energy muons can also be influenced by other phenomena such as atmospheric pressure variations (Jourde et al., 2016), which is why we consider optimal to remove them. However, open-sky conditions may also reveal new insights into atmospheric phenomena (e.g., Hariharan et al., 2019) and more experimental studies are needed to better understand the limits of the methodology. Thus, detectors could be installed in any buried facility with access to electrical power and real-time data transmission, for example, with a Wi-Fi network, such as road tunnels. In Europe, many underground research facilities exist in this condition (e.g., Mont Terri UL in Switzerland, 47.4°N; the LSBB UL in France, 43.9°N; and Canfranc UL in Spain, 42.7°N). These experiments could be crucial to fill the current data gap related to middle-atmospheric dynamics, in particular the study of temperature anomalies associated to SSW in midlatitudes (Sox et al., 2016). Furthermore, the technique may be used to study similar phenomena in the Southern Hemisphere.

The effective atmospheric temperature to which the muon rate is sensitive is a weighted average of a temperature profile from 0 to 50 km, with increasingly significant weights at higher altitudes (Grashorn et al., 2010). Indeed, 70% of the total weights are given between 50 and 26 km, 90% between 50 and 18 km, and 95% between 50 and 15 km (see Figure 3). Thus, muon rate variations are mostly sensitive to temperature variations in the high stratosphere. Muon measurements can therefore complement lidar mesospheric studies (e.g., Sox et al., 2016; Yuan et al., 2012). In terms of the spatial support, in the configuration used

for this experiment (see section 2) the total angular aperture of the detector is of approximately $\pm 40^\circ$, but more than 95% of the muons are registered within an aperture of $\pm 30^\circ$. At 50 km, this represents a surface of $50 \times 50 \text{ km}^2$. Therefore, muon measurements may be used to sample more regional atmospheric behavior.

Besides the potential applications to atmospheric studies, portable muon detectors may be used to precisely calibrate the effective temperature curve (Figure 6). The experimental setups used to estimate these values, so far, are concentrated in either high- or low-opacity conditions, whereas with our approach we could sample the curve rather uniformly, even in the same tunnel by varying the orientation of our detector and thus the opacity and zenith angle conditions.

Our findings have direct implications for applications aiming to characterize density variations in the subsurface (e.g., Jourde et al., 2016). Indeed, synchronous tracking of the open-sky muon rate while performing a continuous imaging of a geological body (e.g., density monitoring) may not be sufficient to characterize the influence of high-atmosphere temperature variations, since the relative effect on the total amount of muons registered increases with opacity. In turn, the mentioned possibility to improve the calibration of the muon rate dependence with middle-atmosphere dynamics is crucial to safely remove this effect. The effect will be increasingly important at higher latitudes due to the increase of seasonal temperature variations and for increasing rock opacities. At Mont Terri (47.38°N), relative effective temperature variations can be as high as 4% which, given the effective temperature coefficient estimated, imply changes in muon rate as high as 3% (c.f. Figure 4). However, muon rate changes would be at maximum 1% if the opacity would be reduced by 1 order of magnitude to 70 mwe, or equivalently 26 m of standard rock, for vertical observations.

Finally, relative temperature and muon rate variations are not always coincident in Figure 4, despite using the same time-averaging window. Equivalently, deviations from the linear relationship up to 2% and mostly around 1% can be observed in Figure 5. The deviations from a perfect correspondence are presumably due to physical phenomena influencing the muon rate other than the effective atmospheric temperature. Variations arising from changes in the primary cosmic rays or changes in the geomagnetic field induced by solar wind typically have temporal scales that are much smaller (e.g., seconds to hours) or much larger (e.g., a solar cycle of ~ 11 years). Changes reported recently as induced by lower-altitude atmospheric phenomena such as thunderclouds only lasted 10 min (Hariharan et al., 2019), and the low-energy muons affected by atmospheric pressure variations (Jourde et al., 2016) get filtered in the first meters of rock in our experiment. A much more likely explanation may be given by changes in the groundwater content of the rock overlying the Mont Terri URL and will be the subject of forthcoming publications.

6. Conclusion

We report for the first time sensitivity to middle-atmosphere temperature variations using a portable muon detector. Changes detected are associated not only to seasonal variations but also to short-term (15 days) variations caused by a Sudden Stratospheric Warming. The occurrence of this event was verified by applying a standard definition of SSWs and also observed by regional temperature and polar vortex variations obtained from the European Centre for Medium-range Weather Forecast and Modern-Era Retrospective analysis for Research and Applications, Version 2 reanalysis data. Previous reports on the sensitivity of muon rate to these phenomena exist only for large, expensive, and immobile muon detectors often times associated to neutrino experiments and high-opacity conditions. Our findings imply that portable muon detectors may be used to further study short-term temperature variations and to improve the calibration curve of muon rate dependence with an effective temperature value. This, in turn, is crucial for geoscience applications aiming at studying subsurface processes by characterizing density changes with muons.

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Acknowledgments

This study is part of the DIAPHANE project and was financially supported by the ANR-14-CE 04-0001 and the MERRA experiment of the Mont Terri project (www.mont-terri.ch) funded by Swisstopo. M. R. C. thanks the AXA Research Fund for their financial support. We are grateful to Thierry Theurillat and Senecio Schefer for their technical and logistical assistance at Mont Terri URL. The MERRA data are available from the website (https://acd-ext.gsfc.nasa.gov/Data_services/met/ann_data.html) and the ECMWF data from the website (<https://www.ecmwf.int/>). Muon data used for all calculations are displayed in figures and are available online (<https://doi.org/10.23728/b2share.0e9f3f3ce91b49afb3baadd4bcebb8>). This is IGP contribution 4049. We thank the Editor and two anonymous reviewers for their constructive comments and suggestions, which helped to improve our work.

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