Study of seasonal and short-term temperature variations in the middle atmosphere using cosmic muons

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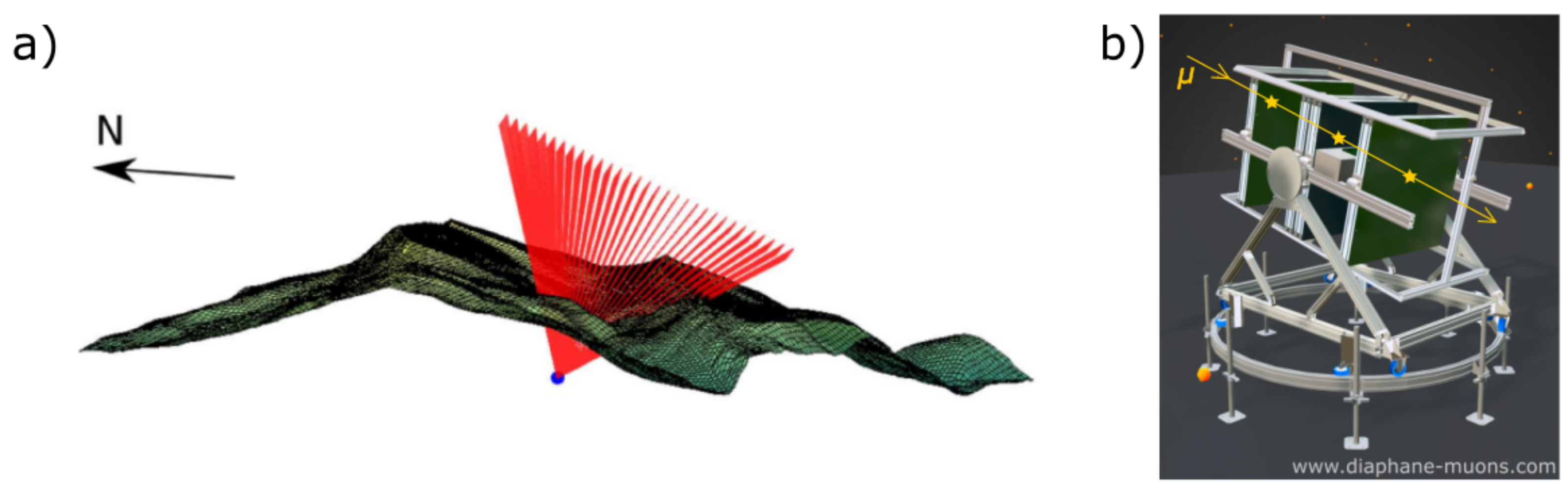
I - INTRODUCTION

- Cosmic muons are produced in air showers and they easily penetrate the Earth's atmosphere.
- Temperature changes in the atmosphere affect the production and absorption of muons along their path down their production level and may have large impacts on the muon flux measured underground.
- The atmospheric effective temperature is a weighted average of the atmosphere's temperature profile from 1000 to 1 hPa (approximately from 0 to 50 km), with increasingly significant weights at higher altitudes, and is associated to the altitudes where observed muons are produced.
- 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).
- SSWs are typically manifested as a perturbation of the polar vortex, a permanent cyclone residing on both of the Earth's poles.

Illustration of primary cosmic rays that reach Earth's atmosphere and produce air showers, in which muons are produced.

II - THE PORTABLE MUON DETECTOR

- We use a portable muon detector to study muon rate variations at the Mont Terri underground rock laboratory, Switzerland (at a depth of ~300 meters below the Earth's surface).
- The portable muon detector was conceived for muon tomography for geophysical applications by the DIAPHANE project (www.diaphane-muons.com).
- It is equipped with three plastic scintillator detection matrices of 80 cm width.
- The detection matrices are divided into pixels, which define the detector's axes of observation.
- We merge the signals from all the axes of observation together and we compute the average cosmic muon rate, R [day^{-1}], using a 30-day width Hamming moving average window [3].



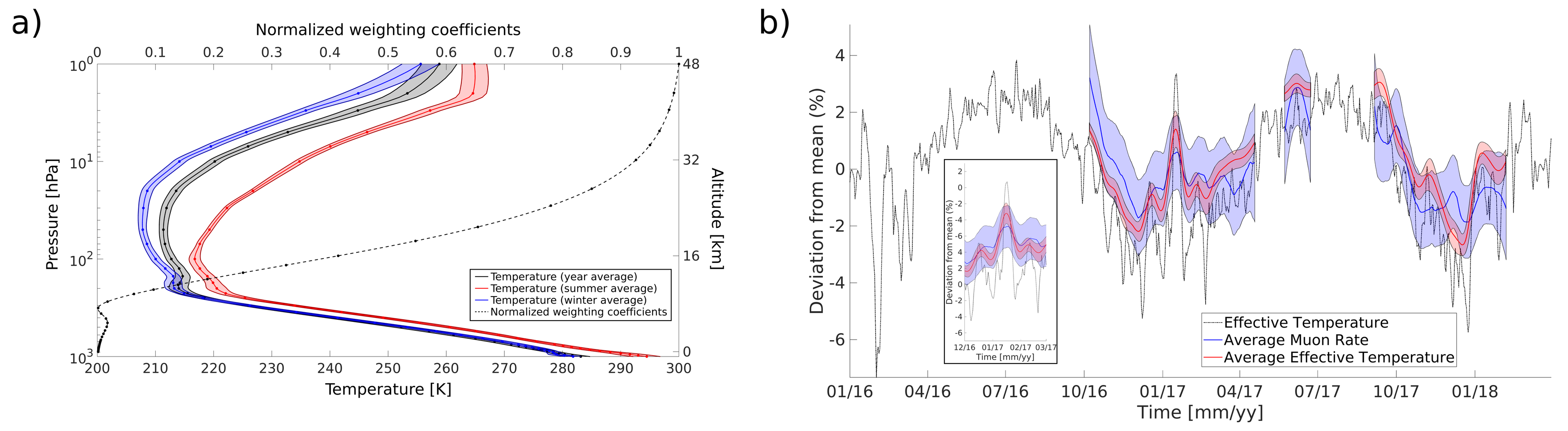
a) Detector's position (blue) and axes of observation (red), along with the topography. b) Schematic view of the muon telescope. Muon trajectories are recovered from fired pixels.

III - SEASONAL VARIATIONS IN THE MUON RATE

- Seasonal variations in R, caused by the temperature changes in the atmosphere, can be treated in terms of the atmospheric effective temperature, T_{eff} [K]:

$$\frac{\Delta R}{\langle R\rangle} = \alpha_{\mathrm{T}} \times \frac{\Delta T_{\mathrm{eff}}}{\langle T_{\mathrm{eff}}\rangle},$$

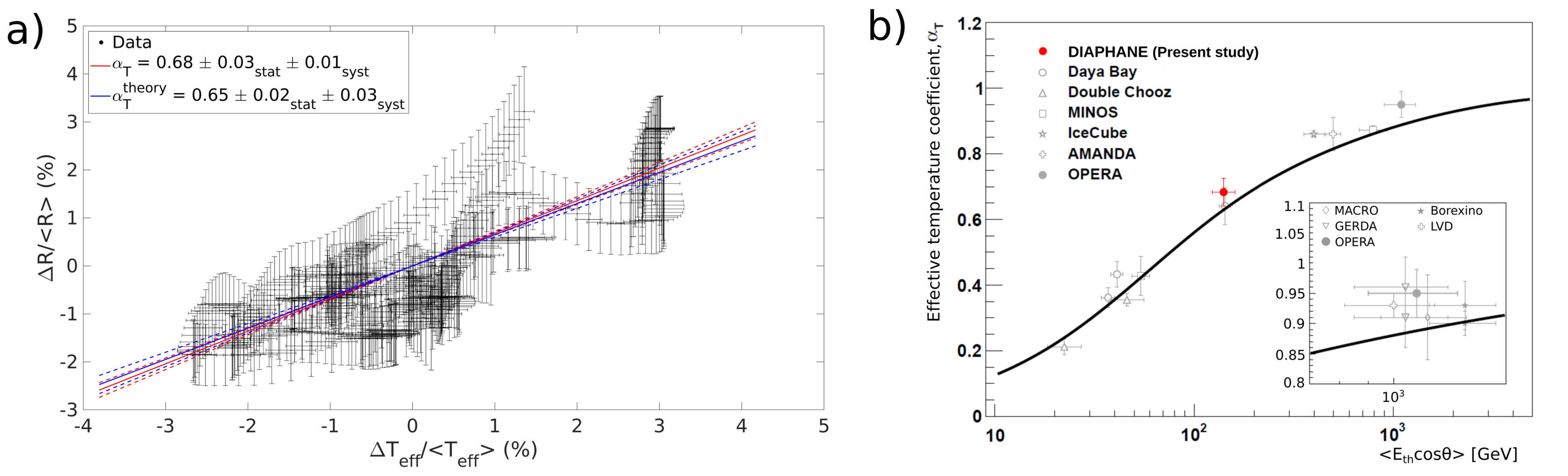
where α_{T} is the effective temperature coefficient, $\langle R\rangle$ is the mean muon rate and $\langle T_{\mathrm{eff}}\rangle$ is the mean effective temperature.



a) Atmospheric temperature profiles (solid lines) above the Mont Terri site and weighting coefficients (dashed line) used to calculate T_{eff}. $T_{\mathrm{eff}}^{year} = (217 \pm 1)$ K, $T_{\mathrm{eff}}^{summer} = (225 \pm 1)$ K and $T_{\mathrm{eff}}^{winter} = (214 \pm 1)$ K. b) Daily percent deviations from the mean computed using a 30-day width Hamming window. The transparent surfaces delimits the 95% confidence interval associated to each curve.

IV - ESTIMATION OF THE EFFECTIVE TEMPERATURE COEFFICIENT

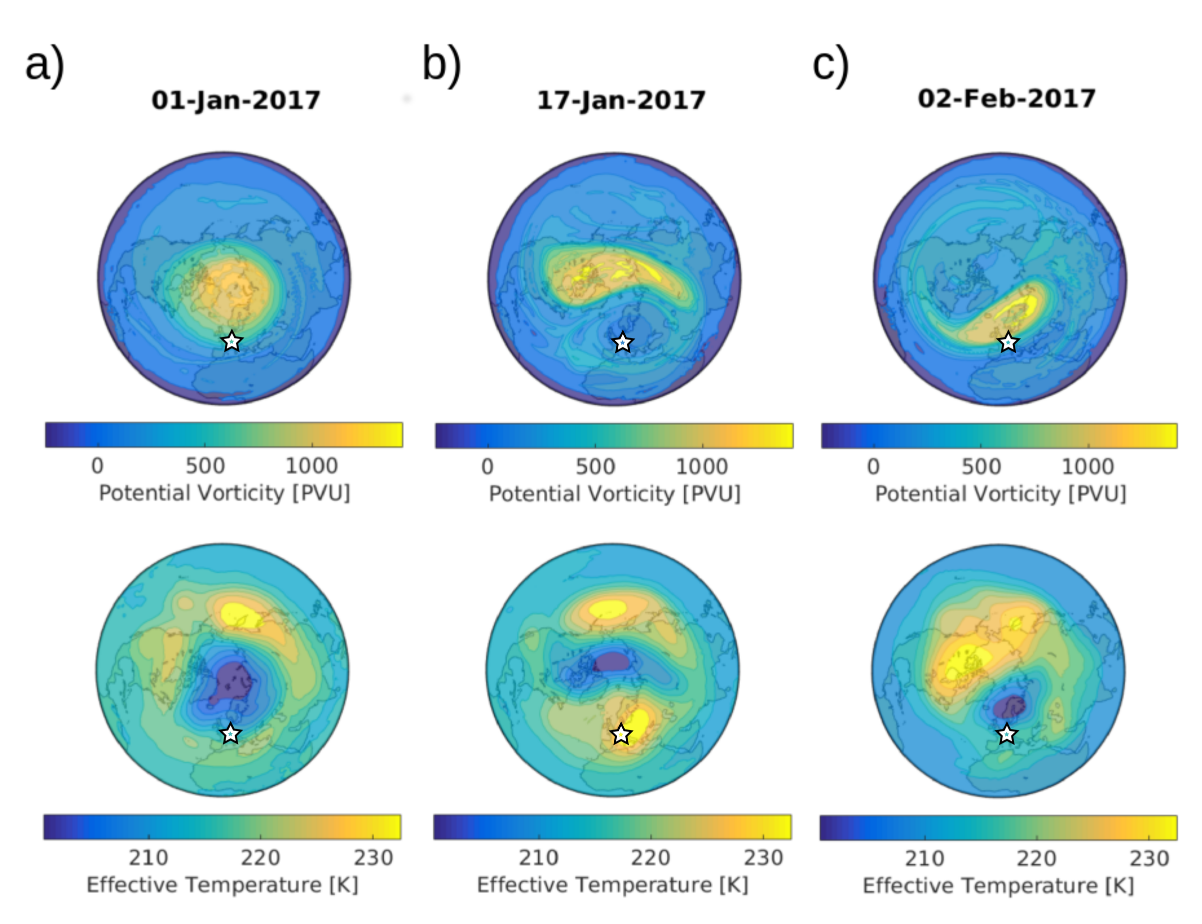
- We determined the effective temperature coefficient to be $\alpha_{\mathrm{T}} = 0.68 \pm 0.03_{stat} \pm 0.01_{syst}$. This value is consistent with previous experimental results and with the theoretical prediction value $\alpha_{\mathrm{T}}^{\mathrm{theory}} = 0.65 \pm 0.02_{stat} \pm 0.03_{syst}$.



a) $\frac{\Delta R}{\langle R\rangle}$ vs $\frac{\Delta T_{\mathrm{eff}}}{\langle T_{\mathrm{eff}}\rangle}$, fitted with a line with the y intercept fixed at 0. The resulting slope is α_T and is represented with a red line. The blue line represents the theoretical expected value $\alpha_{\mathrm{T}}^{\mathrm{theory}}$. b) Experimental values of α_T as a function of $\langle E_{th}\cos\theta\rangle$, which is associated with the overburden opacity in the detector's site. Figure adapted from [2].

V - SHORT-TERM VARIATIONS IN THE MUON RATE

- We detected short-term variations in the muon rate associated to a major Sudden Stratospheric Warming (SSW) that took place on February 1, 2017 (see inset in deviation from mean figure, bottom of the left column).



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 ECMWF data set. The location of the Mont Terri URL (47.38°N, 7.17°E) is represented with a star. The position of the polar vortex is shown using the Ertel's potential vorticity, which is a measure of the location, size and shape of the winter polar vortex.

VI - CONCLUSIONS AND FUTURE WORK

- Portable muon detectors may be used to further study short-term temperature variations in the middle atmosphere.
- In the configuration used for this experiment, more than 95% of the muons are registered within an angular aperture of approximately $\pm 30°$. At 50 km, this represents a surface of 50×50 km^2. Therefore, muon measurements may be used to sample more regional atmospheric behavior.
- Relative temperature and muon rate variations are not always coincident in our study. We think that a likely explanation may be given by changes in the groundwater content of the rock overlying the Mont Terri URL. This will be the subject of forthcoming research.

VII - REFERENCES

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