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Exploration of the stratosphere with cosmic-ray muons detected underground

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Cosmic radiation is a potential additional tool for atmospheric monitoring. High-energy cosmic rays, interacting in atmosphere, produce secondary particles, the production and propagation of which is ruled by the state of the atmosphere. In particular, atmospheric muons carry information on the stratosphere, as its temperature modulates their intensity.
We present a comprehensive investigation of the 24-years series of the muon flux recorded underground with the Large Volume Detector in the Gran Sasso Laboratory in Italy. Using advanced spectral-analysis methods, we reveal, in addition to the well-known annual cycle, two significant variations with periods of about 4 and 10 years, the former observed for the first time in a muon time series.
These two multiannual components, however, are not present in the series of the so-called effective temperature – an average parameter commonly used to describe the entire atmospheric profile in relationship to the detected muon flux –, but we find them in the series of the raw temperatures in the lower stratospheric levels. We show that the weaker multiannual cycles emerge in the temperature series thanks to the dampening of the dominant annual radiative cycle at these levels, which are affected by higher-frequency variability related to transport and wave processes.
We also show that the multiannual variations are not typical only of the Gran Sasso area but are present at large scales throughout the Northern Hemisphere. The analysis of the series of the muon flux reveals also evidence of daily- to monthly-scale variations, especially during the highly variable winter period. Although such short-term modulations are also found in the series of the effective temperature, we show that the variations of the two series are brought to better agreement when considering only specific layers of the atmosphere depending on the particular event. The amplitudes of the multiannual variations are significantly larger than those expected on the basis of the temperature modulations. Such differences may be due to acknowledged difficulties of the adopted temperature reanalysis-dataset to thoroughly represent long-term variability scales, so that long-term modulations in the raw temperature series, and, consequently, in the effective temperature record, would result artificially attenuated.
The muon flux therefore may be envisaged as a high time-resolution integrated proxy of lower stratospheric temperatures.

Primary authors: TARICCO, Carla (Dipartimento di Fisica-Torino); ARNONE, Enrico (Department of Physics, University of Turin); BIZZARRI, Ilaria; RUBINETTI, Sara (Dipartimento di Fisica - Università di Torino)

Co-author: LVD COLLABORATION

Presenter: TARICCO, Carla (Dipartimento di Fisica-Torino)

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