PROCEEDINGS OF SCIENCE

Impact of the atmospheric river occurring in March 2022 on east Antarctica on Cosmic-Rays measurements

Guillaume Hubert[a,*], **Philippe Ricaud**[b], **Vincent Favier**[c] **and Jonathan Wille**[c,d]

[a]*ONERA DPHY, University of Toulouse, 2 av. Edouard Belin, Toulouse, France*

[b]*CNRM, Meteo-France/CNRS, UMR 3589*

[c]*IGE, Institut des Géosciences de l'Environnement, France*

[d]*Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland*

E-mail: guillaume.hubert@onera.fr, philippe.ricaud@meteo.fr, vincent.favier@univ-grenoble-alpes.fr, jonathan.wille@env.ethz.ch

The primary cosmic rays (CRs) interact with atmospheric atoms, producing secondary CRs (neutron, proton, muon etc.). Meteorological conditions influence the secondary CRs properties, such as the atmospheric pressure and the hydrometric properties (snowfall, the atmospheric water vapor and liquid water, the soil moisture). The CHINSTRAP project aims at recording CR induced-neutron spectra at Concordia Antarctic station, over a wide energy range from meV up to tens of GeV with a short time resolution. At the same time, a radiometer records continuously the water vapor contents and temperatures profiles (HAMSTRAD project). In March 2022, an atmospheric river (AR) caused some of the highest temperature anomalies ever observed over Antarctica (absolute temperature record of -9.4 °C on March 18th at Concordia). The ARs transport large amounts of moisture from the mid- to high-latitudes, modifying considerably usual dry conditions observed at Concordia. This AR event attenuated CRs measurements at Concordia, something previously never observed. A first analysis shows a correlation between the CR induced neutron flux decreases (in the order of 15%) and the increases of the integrated water vapor and liquid water path (IWV and LWP, respectively). This work demonstrates the importance of CRs attenuation during particle transport mechanisms in a highly saturated atmosphere.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

[*]Speaker

1. Introduction

Primary cosmic rays (CRs) generate cascades of secondary CRs through collisions with nuclei in the atmosphere, practically classified as muons, electromagnetic particles and hadronic particles (neutrons, protons, and mesons) [1]. To study secondary CR at ground level, many detectors are distributed around the Earth, in particular in the Polar Regions. The Neutron Monitors (NMs) are used across the world to monitor CR in the vicinity of the Earth magnetosphere. Another alternative is to use directly neutron spectrometry technique which will make it possible to deduce the neutron energy spectrum. Among the most advanced systems, there are the Bonner Sphere Spectrometers (BSSs), based on spherical proportional counters.

Secondary CR-induced neutrons are influenced by environmental and systematic effect, in particular the atmospheric pressure, the hydrometric environment close to the instrument (snowfall) and the atmospheric water vapor. Another influence concerns the albedo neutron produced by the interaction of air-shower neutrons with the soil. Hydrogen in soil, air and snow determines the amount of ground albedo neutrons in the sensitive energy range from 1 eV to 10 MeV. In order to get around the influence of these parameters, the detection of high-energy neutrons is preferred because environmental effects have a less impact. The CHINSTRAP project aims at recording CR induced-neutron spectra at Concordia Antarctic station, over a wide energy range from meV up to tens of GeV with a short time resolution [2]. At the same time, the HAMSTRAD aims to operate a radiometer to records continuously the water vapor contents and temperatures profiles [3]. Therefore, CR-induced neutron spectra records in Concordia are corrected from influences of atmospheric pressure and water vapor content. Another advantage of the site is the constancy of the Albedos contribution.

In March 2022, an atmospheric river (AR) caused some of the highest temperature anomalies ever observed over Antarctica (absolute temperature record of -9.4 °C on March 18th at Concordia) [4][5]. The ARs transport large amounts of moisture from the mid- to high-latitudes, modifying considerably usual dry conditions observed at Concordia. This AR event attenuated CRs measurements at Concordia, something previously never observed. This work aims at demonstrating the importance of CRs attenuation during particle transport mechanisms in a highly saturated atmosphere.

2. Instrumentation and method

2.1 Instrumentation

The Concordia station holds great significance for the study of CR due to its unique geo-magnetic conditions (approximately 0.001 GV) and its high altitude (over 3233 meters above sea level). These factors make it an ideal location for observing solar particle events like For-bush decreases or ground level enhancements [6]. The station is involved in two separate re-search programs that, despite being developed independently, have eventually converged due to a shared interest. Both projects are based on scientific instruments installed in a shelter called the "Physics" shelter, located one kilometer away from the station.

The first program is the HAMSTRAD project, which has been investigating trends in water vapor and temperature profiles from the lower troposphere to the lower stratosphere since 2012. The radiometer uses spectral information in the microwave bands 51–59 GHz (V-band, lower frequency wing of the oxygen line) and 169–197 GHz (G-band, strong water vapor line, centered at 183.3 GHz) to derive accurate tropospheric profiles of temperature and low humidity. For temperature profiling, the pressure-broadened oxygen line shape is evaluated, while the strong water vapor line allows for the profiling of very low humidity with an IWV amount of < 2 $kg.m^{-2}$ (or < 2 mm in precipitable water units). A statistical approach is used to calculate the profiles from the brightness temperatures measured by the radiometer, which provide a set of temperature and humidity data points as a function of altitude. The second program is the CHINSTRAP project which aims to continuously measure atmospheric neutron spectra since December 2015. The neutron spectrometer records the neutron spectrum from the thermal region up to the GeV energy range, using BSS multi-sphere spherical ^3He proportional counters placed in spherical moderators with different diameters and consisting of high density polyethylene and metallic shells [2].

2.2 Data correction

Two contributions were considered to correct count rate data, the air pressure and the water vapor. Thus, corrected count rate by air pressure is given by the equation 1:

$$C_{P,\,corr} = C \times \exp[-\beta \times (P_0 - P)]$$

where β is the barometric coefficient (% hPa-1) empirically determined and C_{corr} the corrected count rates. The β factor, equals to 7.1×10-3 hPa^{-1}, was empirically determined in a previous work [7].

As described in [8], the atmospheric humidity in the count rate data is taken into account using a single scaling factor C_{WV} determined by simulations:

$$C_{WV,\,corr} = C \times (1 + 0.0143 \times \Delta IWV)$$

where ΔIWV corresponds to the difference of the integrated vapor density value with the reference value on the day of the calibration.

3. Atmospheric river occurred in March 2022

Between the March 15 and 19, 2022, East Antarctica experienced an unprecedented heatwave in terms of its magnitude and intensity. During this period, there were widespread temperature anomalies of 30-45° C, reaching their peak on March 18th. Coastal regions such as Dumont d'Urville and high-altitude areas like Dome C witnessed record-high maximum temperatures. This heatwave was triggered by an exceptionally strong and persistent AR, coupled with a robust atmospheric ridge spanning the entire troposphere. The high-pressure system was further reinforced by, and reciprocally contributed to, the transport of subtropical/mid-latitude heat and moisture towards the East Antarctic Plateau. As the heatwave event unfolded, the Plateau experienced relatively heavy snowfall, while some coastal regions encountered rain and limited surface melting.

Fig. 1 and 2 show the temporal variations of three parameters measured at the Concordia station during the AR event: (Fig. 1) the atmospheric pressure, (Fig. 2) the integrated water vapor (IWV) and the liquid water path (LWP). The LWP and IWV values are obtained from the radiometer, while the atmospheric pressure is directly extracted using a pressure detector integrated into the BSS. Fig. 1 shows the atmospheric pressure on a three-month scale between February and May and specifically for the month of March 2022 alone. The representation over three months makes it possible to confirm that there is no atypical anomaly during the AR, simply an increase in atmospheric pressure of around 6 %. The system was down from March 15 at 5 a.m. to March 16 at 8 a.m. This is due to a power-off which was not detected immediately (hence the loss of data for almost 24 hours) and which required the spectrometer to be restarted.

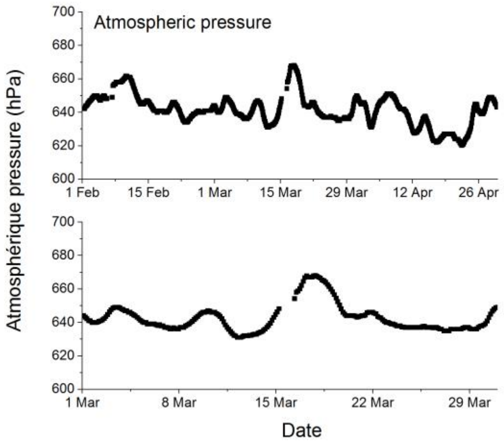

Fig. 1. Atmospheric pressure in March 2022, the detector is integrated into the neutron spectrometer system.

Fig. 2 shows the dynamic of the IWV parameter. The atmospheric water vapor dominates the ground CR variations within the first few hundred meters above the ground. Usually, the Concordia environment is well known and stable over time (low precipitation levels).

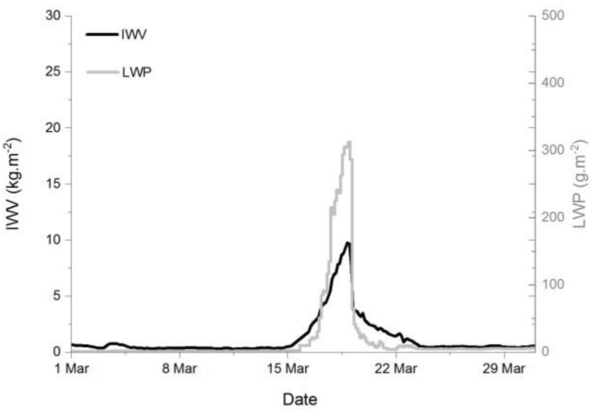

Fig. 2. Integrated water vapor and Liquid water path in March 2022, values are measured by the HAMSTRAD radiometer.

It is one of the driest and coldest places over the world with precipitable water or Integrated Water Vapor (IWV) less than 1 kg m-2 over the year reaching less than 0.1 kg m-2 in winter. The atmosphere is considered in the Dome C when the absolute humidity reaches 0.3 g.m-2, which is very low compared to values observed in typical moist conditions (i.e. 20 g.m-

2). During the AR event, the IWV parameter reaches values in the order of 10 kg.m-2. Data show that the Concordia environment is usually considered extremely dry, implying environmental or systematic effects on fast neutrons are negligible while they are significant for low-energy neutrons (epithermal and thermal). In case of the AR occurring in March 2022, the situation is fully different. Fig. 2 shows the liquid water path (LWP), defined as the weight of the liquid water droplets in the atmosphere above a unit surface area on the earth, given in units of g.m−2. Thus, LWP is important parameters to characterize clouds. LWP varies greatly from 1-2 g.m−2 before the atmospheric river event, which is usual for the dry environment characterizing Concordia, to 350 g.m−2 during the event. If we refer to the measurements recorded since 2012, the peaks observed on LWP and IWV in March 2022 are quite unique.

4. Analyses of CR-induced neutron spectra during the AR event

In addition to the measurements of the atmospheric pressure, IWV and LWP, neutron spectra and the neutron flux were recorded during the AR event. One rather unexpected observation during the AR event was the novel observation of a discernible impact of large atmospheric water content on CR measurements at Concordia Station. Fig. 3 presents the uncorrected and corrected total neutron fluxes, during the period from March 1-31, 2022.

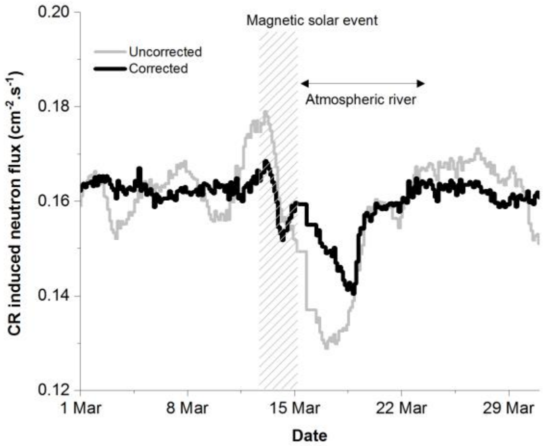

Fig.3. Uncorrected and corrected neutron flux in n/cm²/s during the period 1- 31 March 2022. Corrections applied to the uncorrected flux take into account influences of atmospheric pressure and the water vapor content.

Corrections applied to the uncorrected flux take into account influences of atmospheric pressure and the water vapor content. A magnetic solar event impacted CR data on 14-15 March, without disturbing data during the AR. The neutron flux initially decreases March 13-14th due to a solar magnetic event. Following a brief stabilization, a second decrease in CR intensity (~ 15%) was observed from 15 March, associated with the onset of the AR event, i.e. the liquid water in median/high altitude. The minimum in neutron flux was correlated with the IWV and LWP peaks. A recovery phase occurred and the neutron flux trended towards its pre-event level with the meteorological conditions returning to their baseline. Results show the importance of neutron attenuation during particle transport mechanisms in a highly saturated atmosphere.

Fig. 4 shows the neutron spectra obtained at 8 a.m. UT on March 8, 2022, which was before the occurrence of the AR event, and the spectra measured during the peak of decay at 8:30 p.m. UT on March 18, 2022. The integrated time for each spectrum is one hour. It seems that the energy domains associated with cascade and evaporation processes are more affected by the AR than the epithermal and thermal domains. Two distinct phenomena contribute to modify the neutron spectrum. Firstly, the substantial presence of liquid water in the atmosphere results in a global attenuation of neutrons, regardless of their energies. This attenuation occurs due to the scattering and absorption of neutrons by liquid water molecules, reducing the measured neutron flux. Secondly, the quantities of thermal and epithermal neutrons can be enriched as a result of the thermalization of fast neutrons during cascade and evaporation processes.

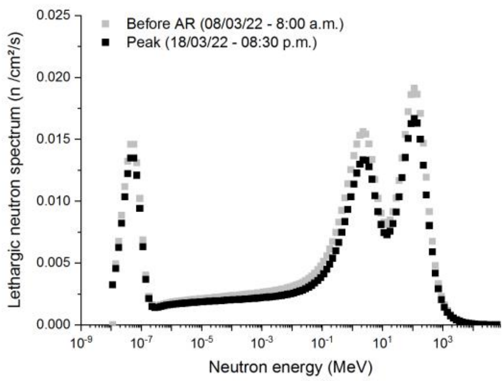

Fig.4. neutron spectra obtained at 8 a.m. UT the 8 March, 2022, i. e. before the AR event, and measured during the peak of decay (18 March 2022, 08:30 p.m. UT). The integrated time is of one hour.

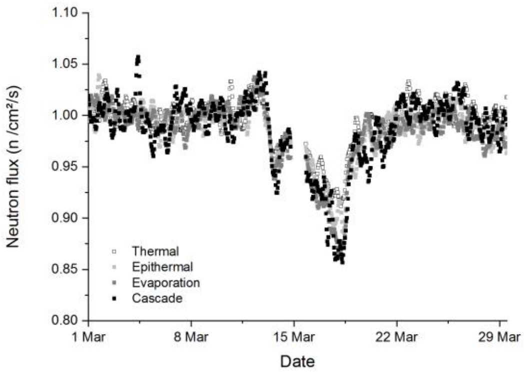

Fig.5. neutron fluxes for the thermal, epithermal, evaporation and cascade domains. The integrated time is of one hour.

To provide a comprehensive analysis, Fig. 5 presents relative variation of thermal, epithermal, evaporation, and cascade neutron fluxes throughout the month of March 2022. For each energy domain, the reference fluxes are considered as the average values of the first ten days of March. This information allows for a more detailed understanding of the variations in neutron fluxes and their respective contributions during this period, shedding light on the complex interplay between atmospheric conditions and neutron measurements. Results confirm the attenuation of neutron for each energy domain, with however a greater attenuation for the cascade and evaporation domains. There are therefore two phenomena at play: attenuation by absorption and enrichment of the thermal and epithermal domains. These findings highlight the significant impact of the AR event on neutron spectra and fluxes.

Nuclear transport simulations of CRs in the atmosphere can help a deeper understanding of the underlying physical mechanisms at play. The URANOS Monte Carlo code [9] was used to obtain preliminary analyses which will be completed in future works. This tool was designed to provide predictions of CR neutron response based on user-defined and spatially variable conditions in the soil, atmosphere, and biosphere. It primarily considers the key neutron interaction processes, which include elastic collisions, inelastic collisions, absorption, and evaporation. By incorporating these fundamental processes, URANOS enables a comprehensive understanding of how CR neutrons behave in different environmental settings.

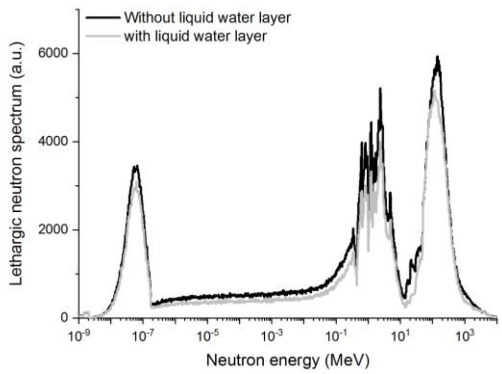

Fig.6. Neutron spectra resulting from URANOS simulations, comparing a dry atmosphere with and without the introduction of liquid water layer at an altitude of 700 m.

The scene description is based on horizontal layers. In this work, the ground is characterized by an atmospheric depth of 700 g/cm², the source layer is based on a layer 10 m thickness located 750 m above ground and characterized by a typical energy spectrum. A cutoff rigidity of 0 GV is used to be consistent with the Concordia properties. A detector layer is defined, composed of air and located 1 m above the ground. Then, the ground layer (interface between the ground and air) is defined only by water. The atmosphere is considered to be dry, i.e., without humidity. Then, a layer of liquid water located at an altitude of 700 meters and with a thickness of 20 cm was introduced. This preliminary approach does not describe the complexity of the AR event but nevertheless allows us to assess the impact of adding water at altitude. The layer of liquid water is also not realistic from the point of view of absolute density, but the intention is primarily to introduce a significant quantity of water. Fig. 6 presents neutron spectra resulting from two simulations: the first considers only a dry atmosphere, and the second considers a dry atmosphere including the liquid water layer at an altitude of 700 meters. For each simulation, 106 neutrons were considered. The amplitude ratios of the thermal, evaporation, and cascade peaks are quite similar to those experimentally observed. An overall attenuation of the neutron spectrum is observed with the introduction of the water layer at altitude. By analyzing the backscattering neutron spectrum at the surface, although not entirely obvious, a greater relative contribution can be identified in the thermal and epithermal domains.

5. Conclusion

Results and analyses based on coupled measurements of neutron spectra and meteorological parameters during the AR event demonstrated a correlation between the decrease in CR-induced neutron flux and the increase in integrated water vapor and liquid water path. The AR event occurred in March 2022 and led to attenuated CR measurements at Concordia, something that had not been previously observed. This work highlights the significance of CR attenuation during particle transport mechanisms in a highly saturated atmosphere. The energy domains related to cascade and evaporation are significantly affected by the AR, while epithermal and thermal neutrons appear to be unaffected or only mildly affected. Preliminary results from simulation-based analyses align with the observation that neutron spectra are attenuated with the introduction of a water layer, showing consistent amplitude ratios for each energy domain. Further comprehensive works will be conducted to delve into simulation analyses.

Acknowledgments

The authors thank the personnel of the Concordia station for their great help and hard work in harsh conditions. This work is supported by the IPEV (French Polar Institute, Institut Paul-Emile Victor) in the framework of the CHINSTRAP and HAMSTRAD projects.

References

1. P. K. F. Grieder, *Cosmic Rays at Earth: Researcher's Reference Manual and Data Book*. 1st ed. pp. 1093, Elsevier (2001).
2. G. Hubert, Astroparticle Physics Journal. 83, 30-39, (2016).
3. P. Ricaud, et al., Antarctic Science, 27, 598-616, (2015).
4. J. Wille et al., *The extraordinary March 2022 East Antarctica "heat" wave. Part I: observations and meteorological drivers.* Submitted to journal of climate, (2023).
5. J. Wille al., *The extraordinary March 2022 East Antarctica "heat" wave. Part II: impacts on the Antarctic ice sheet*, submitted to journal of climate, (2023).
6. G. Hubert et al., Journal of Geophysical Research: Space Physics, 124(2), (2019).
7. G. Leuthold et al., *Long-term measurements of cosmic ray neutrons by means of a Bonner Spectrometer at Mountain altitudes – First results.* Radiation Protection Dosimetry, 126(1-4), (2007).
8. R. Rosolem, et al., *The effect of atmospheric water vapor on neutron count in the cosmic-ray soil moisture observing system.* Journal of Hydro-meteorology, 14, 1659–1671, (2013).
9. M. Köhli at al., *URANOS v1.0 – the Ultra Rapid Adaptable Neutron-Only Simulation for Environmental Research.* Geosci. Model Dev., 16, 449–477, (2023).