Analysis of thunderstorms based on the data obtained by MH URAGAN and DMRL-C

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Abstract. Muon snapshots (muonographs) obtained by means of muon hodoscope URAGAN and meteorological maps from the Doppler weather radar DMRL-C during a thunderstorm event occurred in Moscow on August 30, 2018 are compared with each other in detail. Wavelet analysis of obtained muon data is performed. Search for possible predictors of a thunderstorm event is conducted.

1. Introduction
About 30 thunderstorms occur in Moscow (Russia) annually, usually from April to September. For example, about 27 thunderstorms were observed during spring and summer of 2018. One of the possible ways in which thunderstorms can be studied is muon diagnostics of the atmosphere [1]. It is a direction of meteorological observations based on surface measurements of cosmic ray muons.

Muons are formed in the atmosphere at altitude of 10 to 20 km as a result of interactions between primary cosmic ray particles and atomic nuclei of air. Those muons are constantly bombarding the Earth's surface. Their flux is changing due to various factors, such as atmospheric (for example pressure at the observation level and the vertical temperature profile of the atmosphere) and geomagnetic conditions.

In this paper, 10-minute muonographs obtained by muon hodoscope (MH) URAGAN are compared with weather maps from the Doppler weather radar DMRL-C. Results of wavelet analysis of the counting rate and characteristics of zenith-angle distributions obtained by MH URAGAN are presented.

1.1. Muon hodoscope URAGAN
Muon hodoscope is a wide-aperture tracking detector used for simultaneous detection of muons arriving from various directions. MH is capable of obtaining spatial and time parameters of the muon flux with a high precision. By using the data obtained by MH it is possible to separate the heliospheric and magnetospheric effects, which change the muon flux in a wide spatial region and for a long period of time, from the effects of the atmosphere factors, which are usually shorter and spatially localized [2].

This work uses the data obtained by MH URAGAN located inside the campus of National Research Nuclear University MEPhI (55.7° N, 37.7° E, 173 m a.s.l.). It is capable of real-time
reconstruction of a track of each muon arriving from any directions of the upper celestial hemisphere. MH URAGAN provides simultaneous registration of muons in a wide range of zenith angles (from 0° to 80°) and high spatial and angular resolution (1 cm and 0.8°, respectively). The parameters of each particle tracks (two projection angles) are restored in real time and accumulated in a two-dimensional matrix during a minute interval. Muonographs are graphical representations of that matrix summarized over the last 5 or 10 minutes with respect to the normalization matrix of the preceding 24 hours in statistical error units [3].

To accomplish visual comparison with weather maps the muonographs can be projected onto a map of the Moscow region [4]. This process results with a map on which the position of the angular cell is a projection of the spatial region in which registered muons were generated. Resulting “view range” of MH URAGAN is about 60 km.

To analyze the angular distribution of the muon flux local, the anisotropy vector $\mathbf{A}$ is used. $\mathbf{A}$ is the sum of the unit vectors of the muon tracks, normalized to the number of tracks. $\mathbf{A}$ indicates the average direction of the arrival of muons. It is possible to gather additional information from it by using the difference of the current anisotropy vector $\mathbf{A}$ and some average value $\mathbf{A}_N$ obtained during a long period of time. The difference of these vectors $\mathbf{r}$ (relative anisotropy vector) and its horizontal projection $r_{\text{hor}}$ are calculated by the formula (1). They show direction and extent of the deformation of the angular muon flux distribution.

$$\mathbf{r} = \mathbf{A} - \mathbf{A}_N, \quad r_{\text{hor}} = \sqrt{r_{\text{south}}^2 + r_{\text{east}}^2}.$$  \hspace{1cm} (1)

To analyze various periodic signals occurring in the time series of the counting rate and the characteristics of zenith-angle distributions, wavelet processing with a modified Morlet wavelet [3] is performed. This method of processing is used to select the frequencies of the most significant periodic processes observed in the characteristics of the muon flux.

1.2. Doppler weather radar DMRL-C

Doppler weather radars (DMRL) are means of meteorological observations capable of providing real-time weather data. Modern DMRL has a view range about 250 km and a maximum detection height of about 20 km. It provides cyclic monitoring at intervals about 10 minutes and obtains data with a high spatial resolution (1 km × 1 km) [5]. Such radar operates by conducting a survey sequence of circular azimuthal scans of the upper celestial hemisphere at several different angles. By doing so it collects data on cloudiness and precipitation on several conical sections of the atmosphere.

DMRL-C Doppler Meteorological Radar is intended for displaying distribution of various meteorological data, calculation and displaying vertical profile of speed, wind direction up to the height of upper limit of detection of meteorological objects, calculation and displaying of precipitation intensity within any given time interval, detection of dangerous weather phenomena and displaying velocity and direction of movement of cloud systems.

This work uses data obtained by DMRL-C located in Vnukovo International Airport. An option of dangerous weather phenomena detection is used. Its results are presented as meteorological maps of Moscow region and its surroundings with weather conditions such as clouds, rain and thunderstorm marked on those maps. Meteorological maps are provided with 10-min time resolution. DMRL-C provides information about thunderstorm activity at the moment its region enters DMRL-C view range or at the moment such region forms. In the text this moment is called a “start of the thunderstorm activity”, and the moment such activity ends is called an “end of the thunderstorm activity”.

2. Thunderstorm event analysis

Thunderstorm event analysis procedure, developed in [4], consists of following steps: heliospheric and magnetospheric situation is analyzed to exclude possible non-atmospheric effects; meteorological situation is analyzed, start and end of the thunderstorm activity are identified; visual comparison of meteorological maps and muonographs is conducted; study of various muon flux characteristics is conducted. In this work, wavelet analysis of obtained muon data and search for possible thunderstorm
predictors were added to the procedure. Thunderstorm activity was considered on a larger time and spatial scale, weather conditions not observed directly over MH URAGAN are taken into account. Detailed analysis of a thunderstorm event occurred in Moscow on August 30, 2018 is given below.

2.1. Meteorological and geomagnetic situation
This event was a severe and long thunderstorm with multiple cells; it occurred against the background of a cold atmospheric front. According to DMRL-C weather maps, the thunderstorm activity over the surroundings of the Moscow region started at 00:40 UTC 30.08.2018 and ended approximately at 15:20 UTC 31.08.2018. Thunderstorm activity area stayed over Moscow from 20:00 UTC 30.08.2018 to 06:00 UTC 31.08.2018 and was observed at weather stations in this period of time. It peaked around 00:00 UTC 31.08.2018.

It is important to notice that not long before the thunderstorm event a strong geomagnetic disturbance was observed. G3-class geomagnetic storm occurred on August 26, caused by a coronal mass ejection occurred on August 20 [6]. While effects of this storm can be visible on a large time scale when analyzing thunderstorm event of August 30, overall geomagnetic situation stabilized on August 28, more than 24 hours before the start of the thunderstorm activity.

2.2. Visual comparison of meteorological maps and muonographs
To assist with comparison of weather maps and muonographs, a program was developed especially for this work. It allows to create a new image that will contain a weather map cropped to match muonograph’s size and view range at the left side and corresponding muonograph at the right. An image will also contain current direction and speed of movement of the cloud system, weather map legend and a time stamp joint for both of its parts. Combined image can be created for any date and time if both corresponding DMRL-C and MH URAGAN data are present. Image examples are shown in figures 1 to 3. Outer black circle on the weather map replicates muonograph’s view range.

Figure 1. Visual comparison of a meteorological map and a muonograph for 30.08.2018 22:50.
Figure 2. Visual comparison of a meteorological map and a muonograph for 31.08.2018 00:00.

Figure 3. Visual comparison of a meteorological map and a muonograph for 31.08.2018 05:00.

Figure 1 shows thunderstorm cells approaching MH URAGAN. Areas corresponding to the thunderstorm cell (on the weather map) and to the area of significant lack of muons (on the muonograph) are heavily shaded. It can be seen that shape and position of those dark areas are similar to each other. Figure 2 shows multiple thunderstorm cells near the MH URAGAN and a large area of significant decrease of the muon flux corresponding to them. Finally, figure 3 shows thunderstorm activity moving away from Moscow and MH URAGAN. Dark areas are however still visible on the muonograph part, assumable marking a thunderstorm cells closest to MH URAGAN.

Such areas of significant lack of muons are present during all of the peak period of the considered thunderstorm. This is the case for a large amount of studied thunderstorms, especially for ones that were observed in a close proximity of MH URAGAN. The effect of this sharp decrease of the muon flux may be explained in different ways, most commonly as occurring due to presence of a high pressure area during the thunderstorm, i.e. pressure effect. Other possible explanation is that the effect
happens due to presence of a huge water mass in non-stationary state inside the thunderstorm cell increasing muon absorption.

2.3. Wavelet analysis
Figures 4 and 5 represent results of the wavelet analysis of the muon flux characteristics before and during the thunderstorm event of August 30. The tone gradation (from dark to light) shows the changes in the values of the wavelet coefficients (from minimum to maximum). The procedure of the image formation is described in [3]. Wavelet analysis of the muon flux data is required because the evolution of a thunderstorm cell causes turbulent and convective atmospheric processes which in turn cause different wave effects in the time series of muon flux characteristics.

Figure 4. Wavelet analysis of the MH URAGAN counting rate.

Figure 4 is a visual representation of wavelet coefficients’ powers for the waves with periods from 20 to 120 minutes for 5-min time series of the MH URAGAN counting rate. It shows that before the start of the thunderstorm activity of the considered event (marked with a vertical white line) there was an increase in wavelet coefficient power of a wave with a period of 75 minutes in the MH URAGAN counting rate. This increase (marked by a black oval) is presumably linked to the short thunderstorm activity on the periphery of the DMRL-C view range. This activity occurred from 14:00 to 20:00 August 29 completely outside the Moscow region. Still, the effect is clearly visible and goes on until the start of the thunderstorm activity of August 30.

Figure 5. Wavelet analysis of the relative anisotropy vector horizontal projection.

Figure 5 is a visual representation of wavelet coefficients’ powers for the waves with periods from 20 to 120 minutes for 5-min time series of the relative anisotropy vector horizontal projection. Black ovals mark increases in wavelet coefficient powers of 40- and 60-min waves. While 40-min wave is presumably linked to the short peripheral thunderstorm activity mentioned above, an increase in 60-min wave coefficient power occurs around the start of the thunderstorm activity of the considered event. Detailed plot of the 60-min wave wavelet coefficient power dynamics can be seen in figure 6.
Figure 6. Time series of 60-min wave coefficient power.

Arrows in figure 6 mark start and end of the thunderstorm activity. Event’s peak period is clearly visible as a large increase in wavelet coefficient power after 31.08.2018 00:00. Smaller increase around 30.08.2018 00:00 corresponds to the start of the thunderstorm activity. It is important to notice that this increase occurs slightly before to the start of the thunderstorm activity. Slight increase near the end of 28.08.2018 corresponds to peripheral thunderstorm activity that did not reach Moscow region.

3. Conclusions
A thunderstorm event occurred in Moscow on August 30, 2018 was analyzed. An ancillary program for spatially consistent visual comparison of muonographs and weather maps has been developed. It has been shown that characteristics of the muon flux provide a good and stable reaction to the passage of a thunderstorm in a proximity of muon detector. Wavelet analysis of different time series showed that before and during the passage of a thunderstorm there were periodic disturbances in the characteristics of the muon flux. It has been shown that those disturbances may occur not only before the moment of a thunderstorm passing over the MH URAGAN as it was earlier shown in [1], but at the moment or slightly before DMRL-C registration of an actual start of thunderstorm activity, including thunderstorm activity happening about 200 km away from the MH URAGAN. This proves the potential use of muon data wavelet analysis as a thunderstorm detection or prediction tool.

References
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