Muon hodoscope as a new meteorological tool

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Outline

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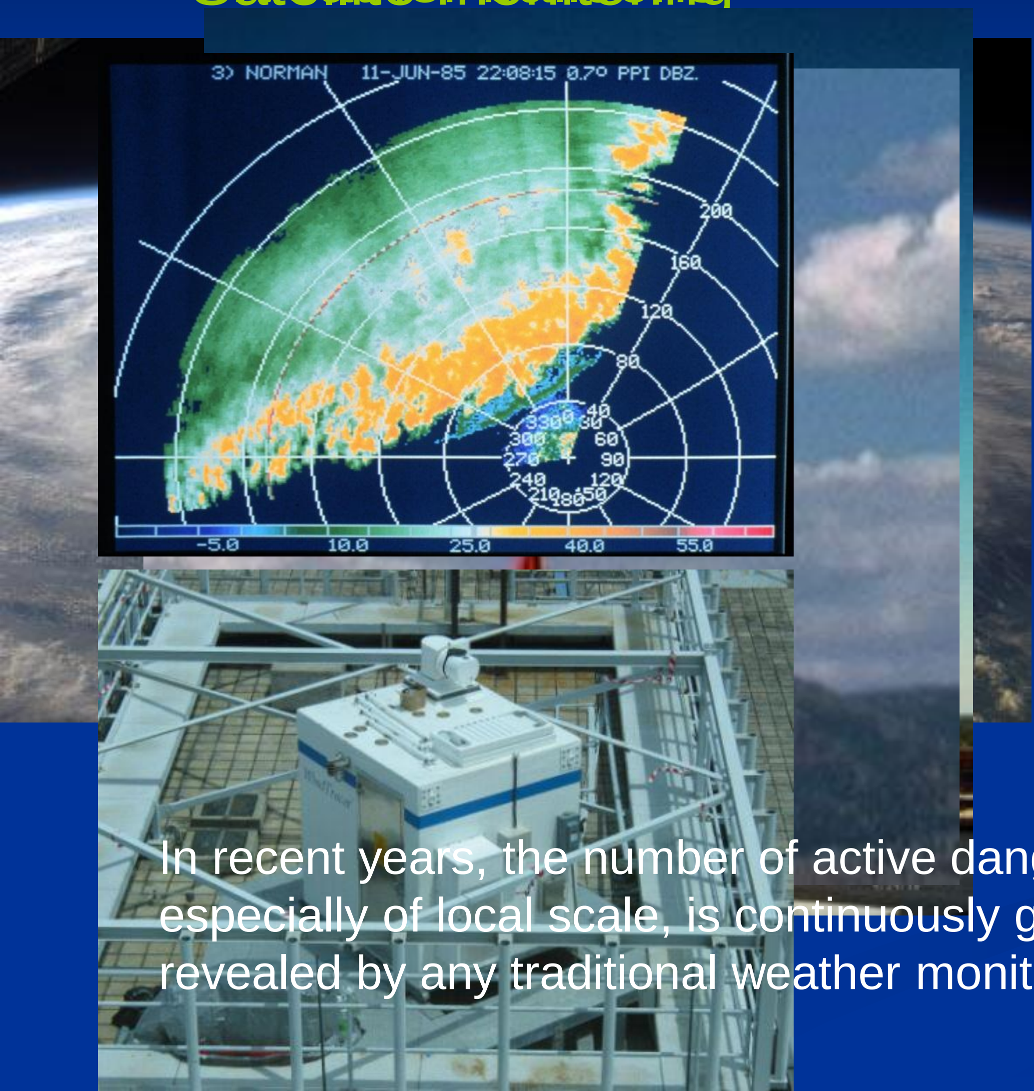
Do We Observe Weather Well?

Radar observations
Satellite monitoring
Weather Stations



- possibility of monitoring of local atmospheric disturbances
- possibility to measure vertical profile of the atmosphere
- real-time observations

BUT

- measurements only at one point
- only few launches during 24 hours
- irregularity

point (because of orbital motion)
- problems of data validation

In recent years, the number of active dangerous atmospheric processes, especially of local scale, is continuously growing. Very often they were not revealed by any traditional weather monitoring systems.

Which tool for the study of weather we would like to have?

It is necessary to develop new approaches to monitoring of the atmosphere which will be:

- able to reveal dangerous local atmospheric disturbances
- all-weather
- able to monitor large areas
- continuous and work in real time

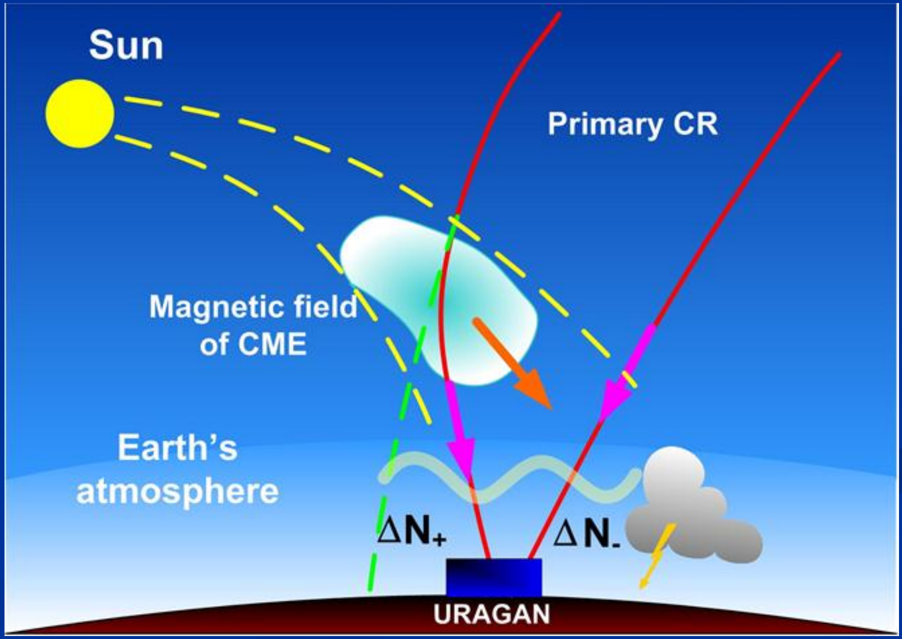
For these purposes is possible to use cosmic radiation – continuous, isotropic and permanent flux of charged high energy particles which arrive to the Earth from the Space

Muon diagnostics

- Variations of the cosmic ray muon flux at the ground level are sensitive to both atmospheric and extra-atmospheric phenomena.

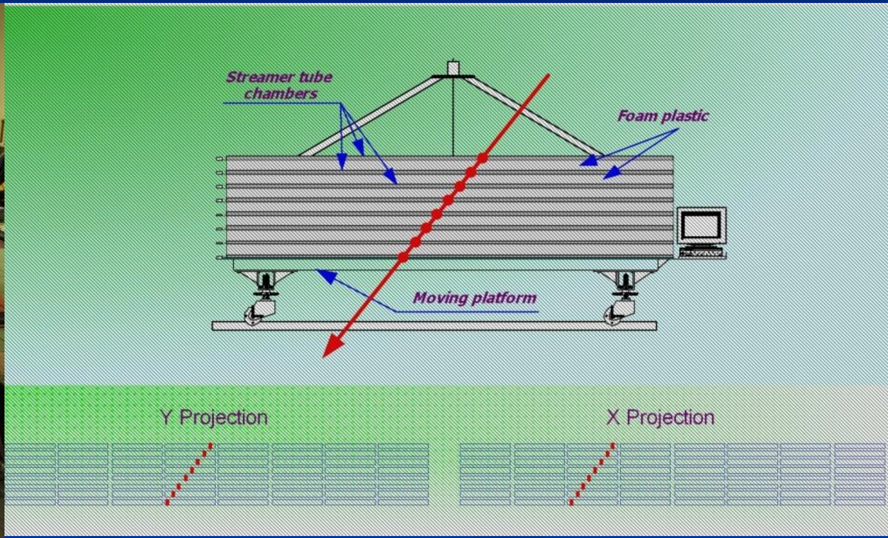
- The use of cosmic rays as a tool for research makes it possible to investigate those processes which modulate cosmic ray flux.

- The new experimental approach – **muon diagnostics:** a technique of remote monitoring of various dynamic processes in the heliosphere, magnetosphere and atmosphere of the Earth based on the analysis of spatial-angular and temporal variations of muon flux simultaneously detected from all directions of the upper hemisphere.



Muon hodoscope URAGAN

(55.7° N, 37.7° E, 173 m a.s.l.)



- 4 independent supermodules (SM)
- SM - 8 planes of streamer tube chambers with external two-coordinate strip read-out ($8 \times$ [320-*X* & 288-*Y*] chann.)
- SM area ~11 m^2.
- SM trigger: coincidence of signals from 4 or more *X*-planes within time gate 250 ns.

Total area – 45 m^2 . Counting rate ~ 6000 μ / s.
Resolution: spatial – 1 cm, angular – 1º.

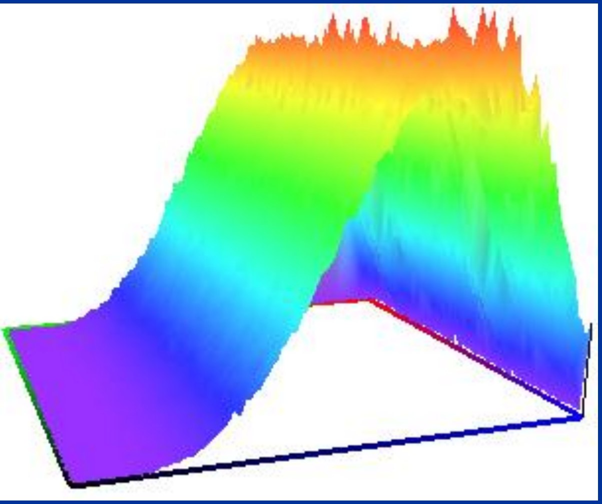
Data format

- Data of each SM – sequence of 2D-muon intensity matrices (frames) collected during one minute intervals all tracks of muons arriving from any direction of upper hemisphere, detected and reconstructed in real time mode.

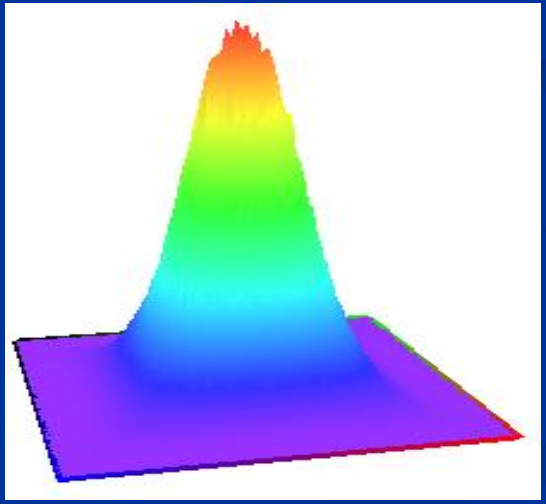
- Three type of matrices – one-minute exposure muon flux angular distributions:

Number of angular sells: *91 × 91*

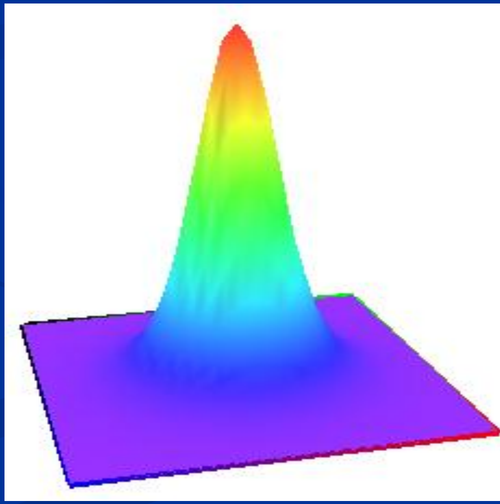
$M(\theta, \varphi) \rightarrow \Delta\theta=1°, \Delta\varphi=4°$



$M(tg\theta_Y, tg\theta_X) \rightarrow \Delta tg\theta_{XY}=(tg80°)/45.5$



$M(\theta_Y, \theta_X) \rightarrow \Delta\theta_{XY}=2°$



$M^{cor}(t,\Delta t) = M(t,\Delta t) + \Delta M^{P}(t,\Delta t) + \Delta M^{T}(t,\Delta t),$

$M^{cor}(t,\Delta t) = M(t,\Delta t) + \Delta M^{P}(t,\Delta t) + \Delta M^{T}(t,\Delta t),$

Real-time data proceeding

- one-minute and 60-minute time series of P, I_{rec} and t_{live};
- time series of characteristics of zenith-angular distributions for 5- and 60-minute matrices $M(\theta, \varphi)$;
- time series of characteristics of the angular distributions and Fourier analysis of 5-minute matrices $M(tg\theta_Y, tg\theta_X)$;
- time series of characteristics of the angular distributions of 60-minute matrices $M(tg\theta_Y, tg\theta_X)$;
- time series of results of wavelet analysis of 5-, 10- and 60-minute counting rates and characteristics of zenith-angular distributions;
- 5- and 60-minute muonographies $M(tg\theta_Y, tg\theta_X)$ of variations in the angular distributions in the East-North (Local Geographic) and GSE (Geocentric Solar Ecliptic) coordinate systems;
- image files of obtained time-series graphs.

http://nevod.mephi.ru/uragan_data.htm

Corrections related with changes of the atmosphere

$$M^{cor}(t,\Delta t) = M(t,\Delta t) + \Delta M^P(t,\Delta t) + \Delta M^T(t,\Delta t),$$

ΔM_T and ΔM_P are corrections on temperature and barometric effects for all cells of matrix M.

- Barometric coefficient ***B*** for the integral counting rate:

$$I(t) = I_0(t) + B \cdot (P(t) - P_0)$$

$I(t)$ – measured counting rate ($I(t) = N(t)/T(t)$); $P(t)$ – average atmospheric pressure; P_0 – long-time period average atmospheric pressure (~ 993 mbar); $I_0(t)$ – counting rate at P_0.

Estimation of barometric coefficients B (three versions):

- B for total counting rate $I(t)$;
- $B(\theta)$ as a function of the zenith angle in the range from 0° to 75°;
- $B(tg\theta_Y, tg\theta_X)$: for each cell of the angular distribution matrix.

Corrections $\boldsymbol{M_P}$ are calculated by the formula:

$$\Delta M^P(tg\theta_Y, tg\theta_X) = B(tg\theta_Y, tg\theta_X) \cdot (P_0 - P(t)) \cdot \Delta t$$

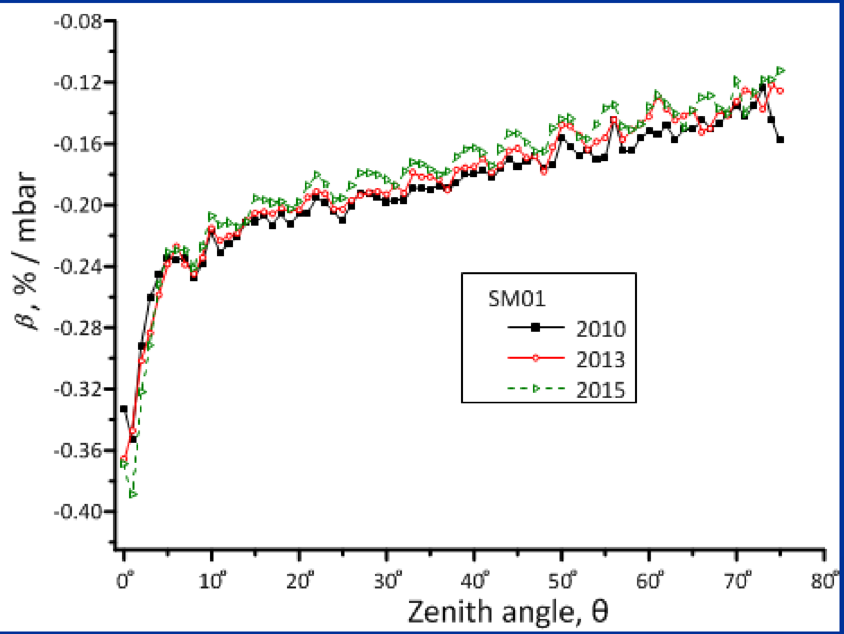
For the integral counting rate of URAGAN SM the barometric coefficient is about ~ 0.18%/mbar.

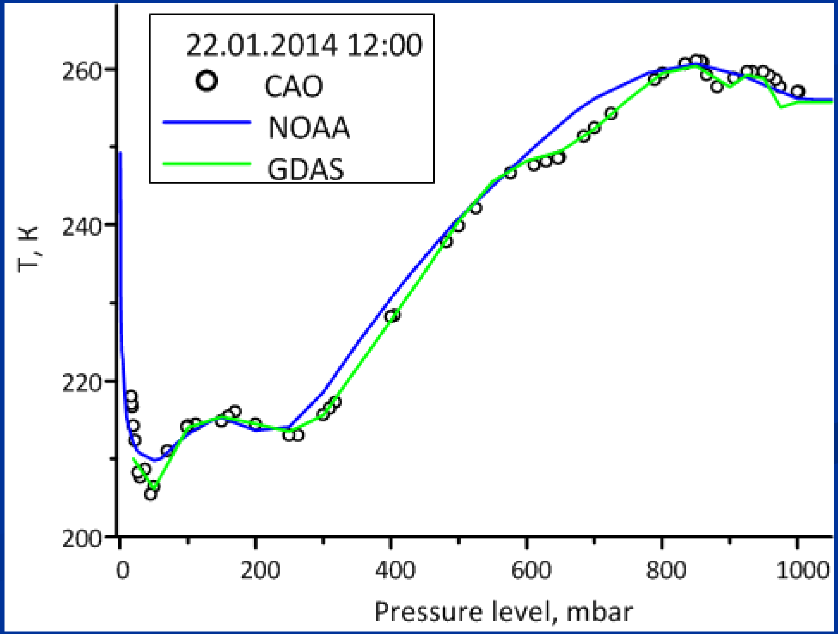
Corrections related with changes of the atmosphere

Correction for the temperature effect is calculated taking into account the temperature profile of the atmosphere:

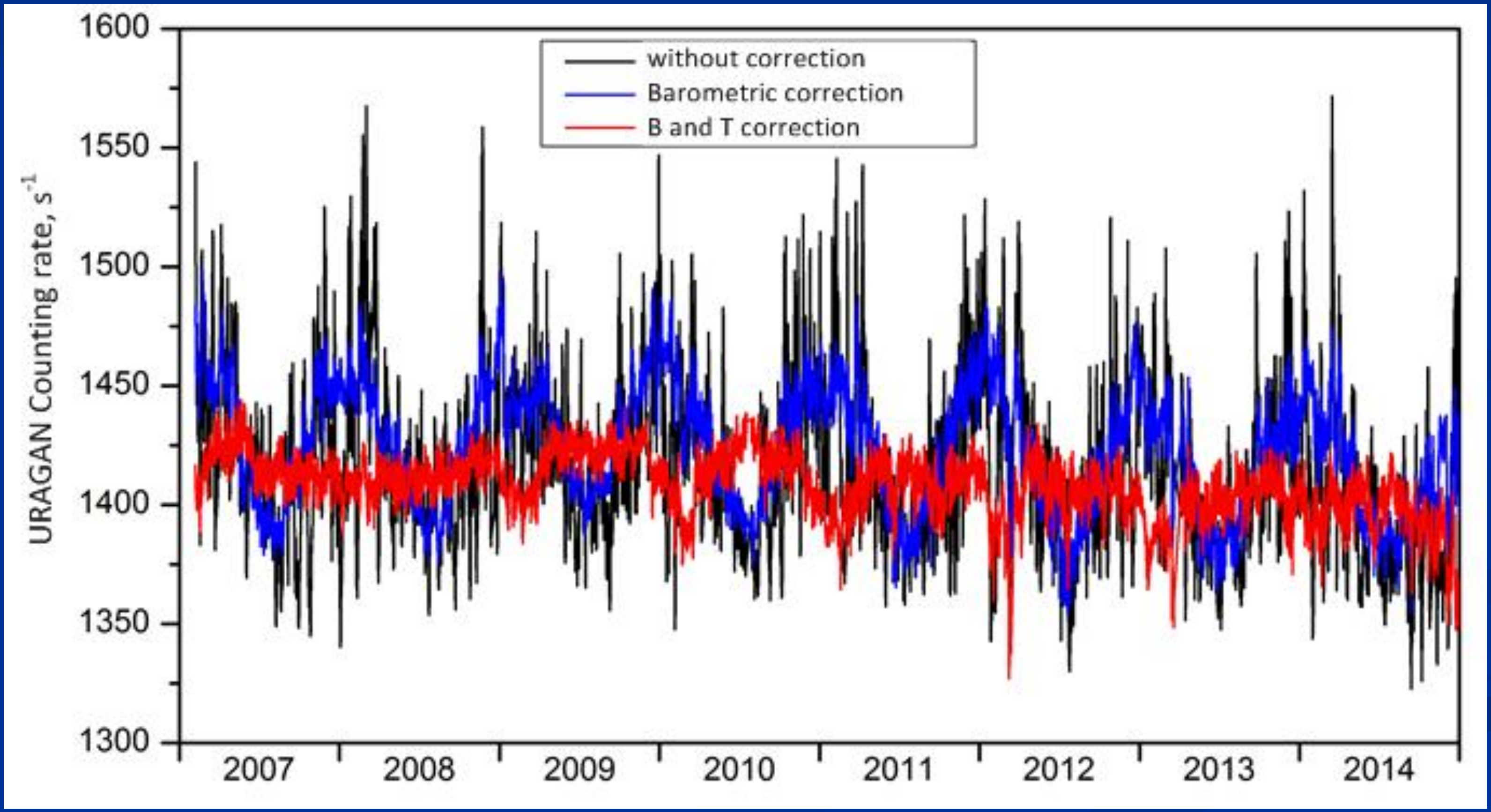
$$\Delta M^T(\theta) = M_0(\theta) \cdot \sum_i W_T(h_i, \theta) \Delta T(h_i) \Delta h_i \, / 100\%$$

$W_T(h_i, \theta)$ are differential in altitude temperature coefficients (DTC), h – depth of the atmosphere, $\Delta h = 0.05$ atm, $\Delta T(h) = T_{SMA}(h) - T(h)$ – changes in altitude behavior of the temperature, $T(h)$ – the temperature at a depth h, $T_{SMA}(h)$ is the temperature of the standard atmosphere model on the altitude.





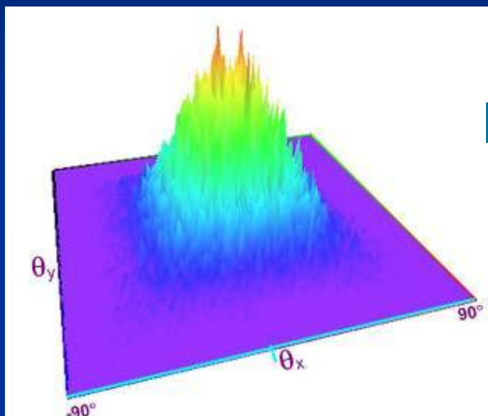
Corrections related with changes of the atmosphere

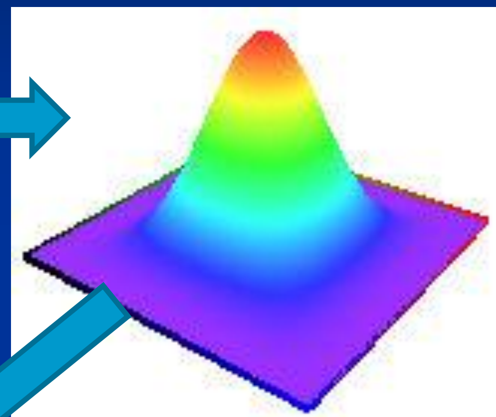


2*D* matrix and its transformation

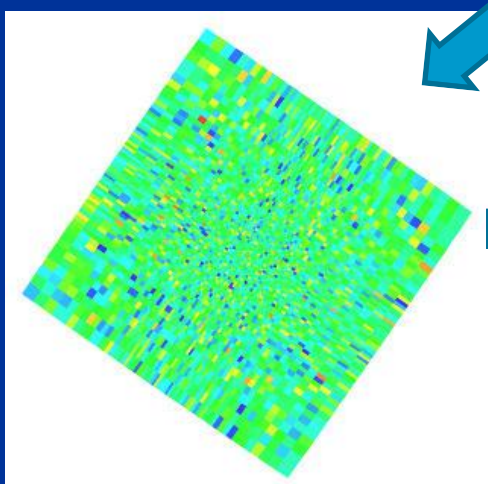
2*D*-muon intensity matrix:

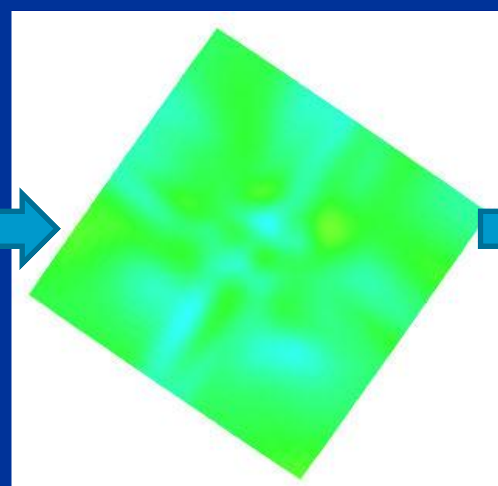
- 1-minute exposure
- angular matrix 91°x91° cells
- Average counting rate ~1700 μ/s ($7 \div 8 \times 10^4$ μ /min)
- statistical errors ~0.1 % (for 10-minute bin)

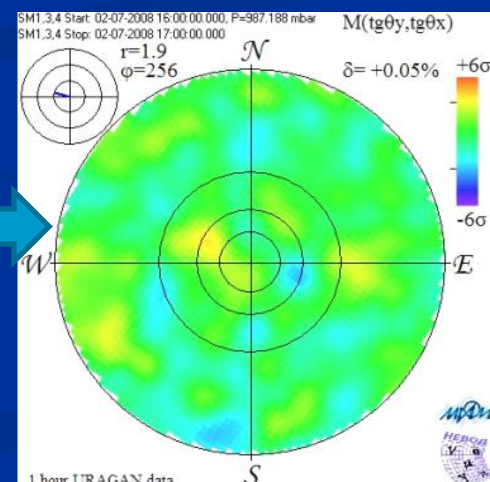




Sequence of such matrices represents the filming of the upper hemisphere in "muon light".

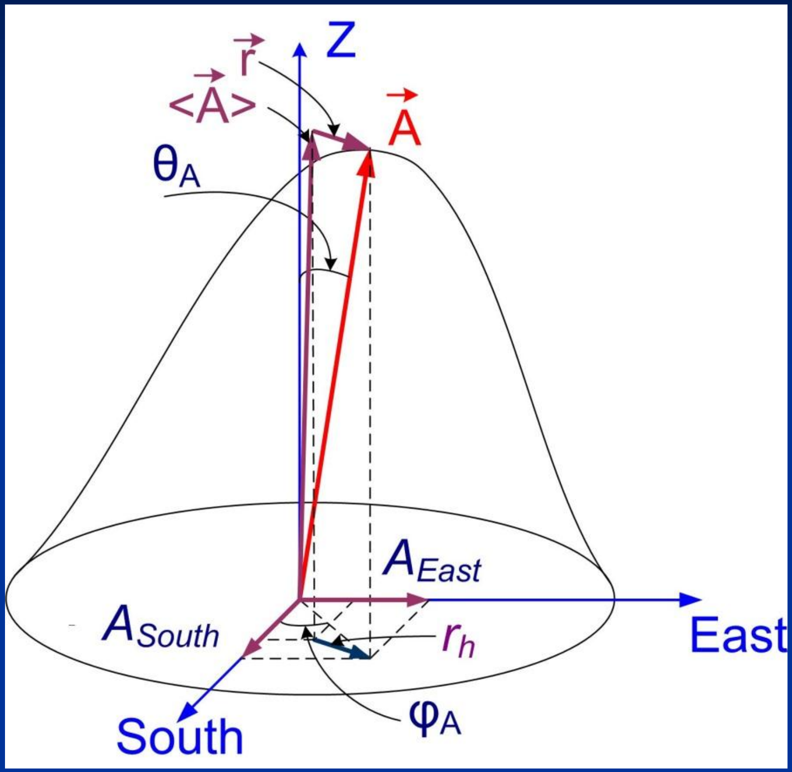






$$\delta_\sigma(\mathrm{tg}\theta_Y, \mathrm{tg}\theta_X) = \frac{M(\mathrm{tg}\theta_Y, \mathrm{tg}\theta_X) - M_N(\mathrm{tg}\theta_Y, \mathrm{tg}\theta_X) \cdot T / T_N}{\sqrt{M_N(\mathrm{tg}\theta_Y, \mathrm{tg}\theta_X) \cdot T / T_N}}.$$

Vector of the relative anisotropy



$$A_X(t) = \frac{1}{N}\sum_{\theta}\sum_{\varphi} N(\theta,\varphi,t,\Delta t)\cos\varphi\sin\theta\,;$$

$$A_Y(t) = \frac{1}{N}\sum_{\theta}\sum_{\varphi} N(\theta,\varphi)\sin\varphi\sin\theta;$$

$$A_Z(t) = \frac{1}{N}\sum_{\theta}\sum_{\varphi} N(\theta,\varphi,t,\Delta t)\cos\theta\,;$$

$$N_0(t,\Delta t) = \sum_{\theta}\sum_{\varphi} N_0(\theta,\varphi,t,\Delta t)\,;$$

$$N(t,\Delta t) = \sum_{\theta}\sum_{\varphi} N(\theta,\varphi,t,\Delta t)\,,$$

- Vector ***A*** is the sum of unit vectors with directions of reconstructed tracks in individual events normalized to the total number of muons.
- The local anisotropy vector ***A*** indicates the average arrival direction of muons.

- Relative anisotropy vector $\vec{r} = \vec{A} - <\vec{A}>$: deviations from the average direction.
- Length of the horizontal projection of vector ***r*** **:** $r_h = \sqrt{r_x^2 + r_y^2}$ - "side impact" on the angular distribution of the muon flux.

Integral intensity mode

http://nevod.mephi.ru/uragan_data.htm/

Real-time URAGAN data

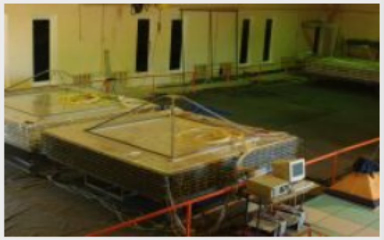
Unique Scientific Facility
Experimental Complex
NEVOD

Geographic coordinates: 37°40'E, 55°39'N

Vertical cut-off rigidity: 2.4 GV

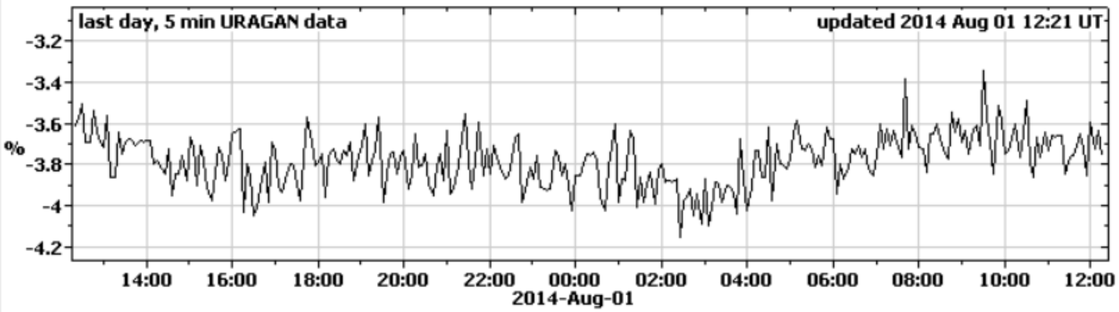
Counting rate: ~ 3 x 10^5 particle/min

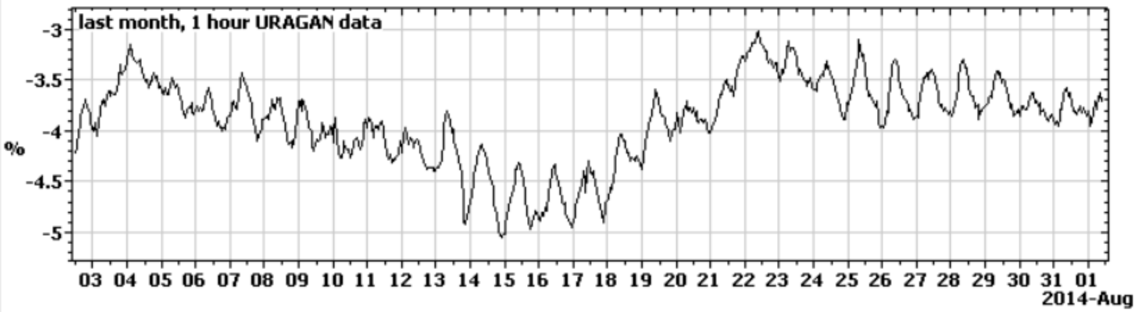
Setup threshold energy: ~ 300 MeV



Integral intensity mode

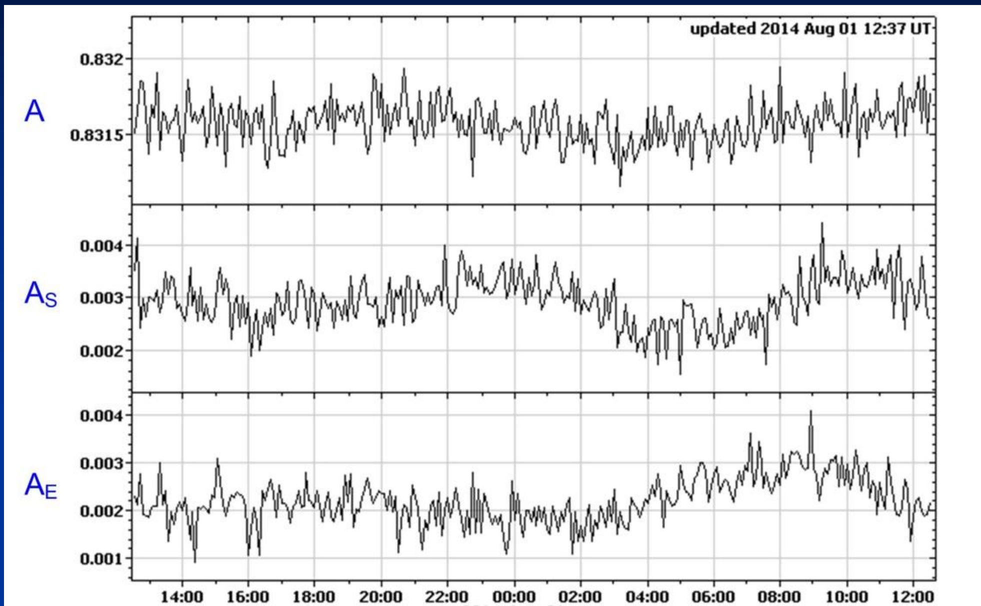
Average of URAGAN supermodules' data, corrected for pressure and normalized.

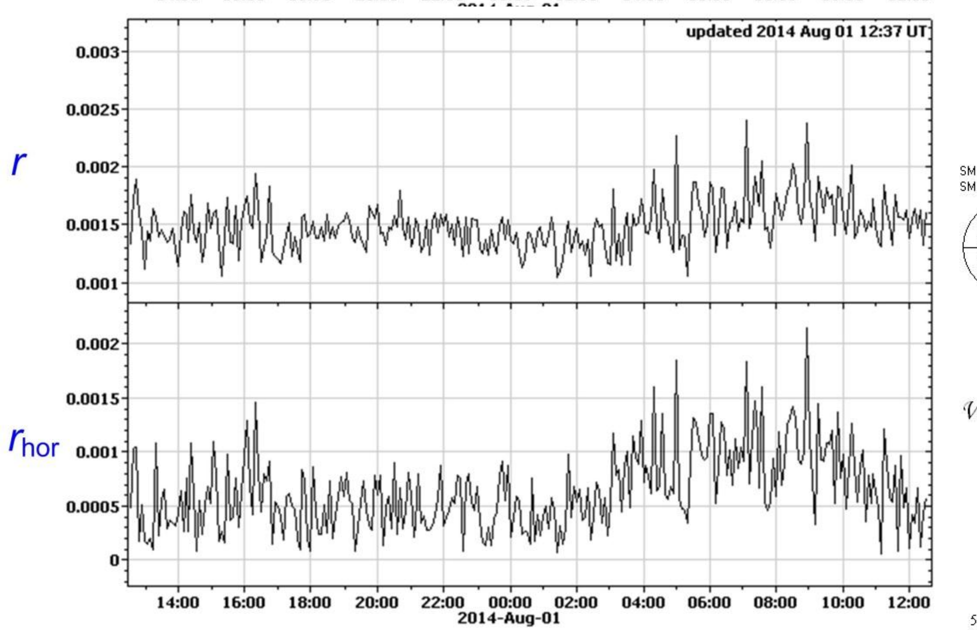


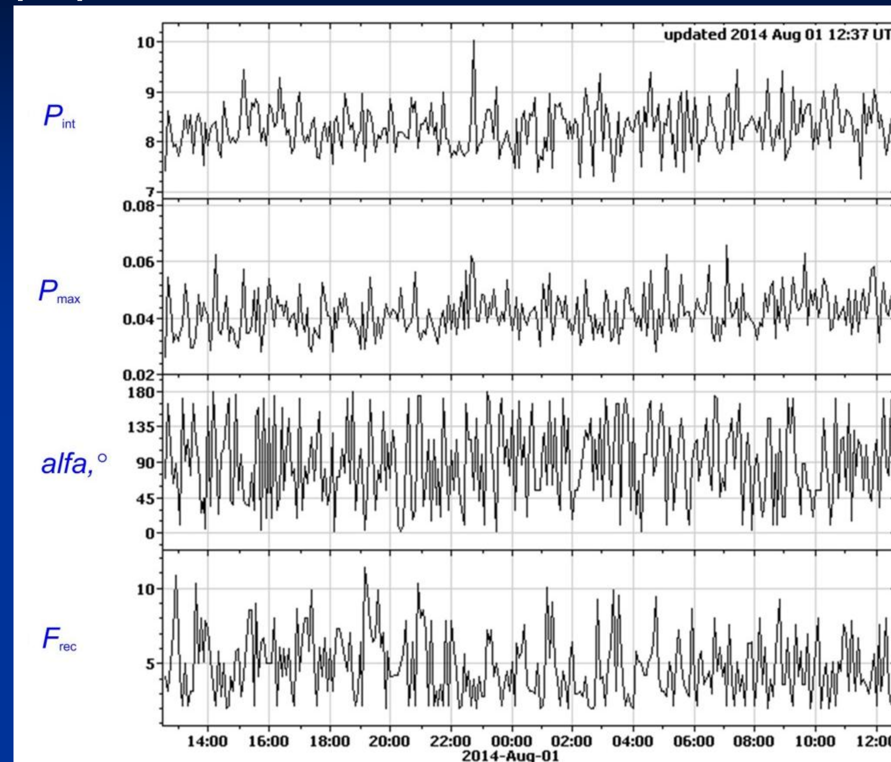


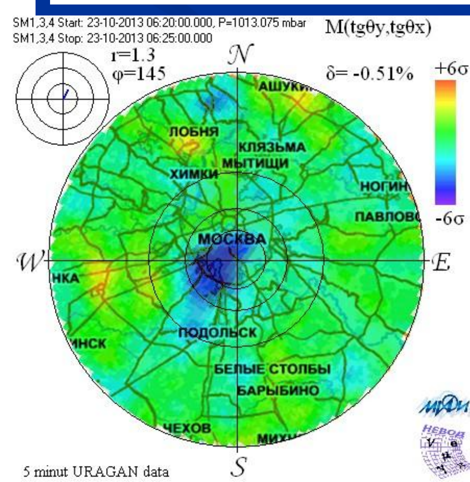
5-minute local anisotropy

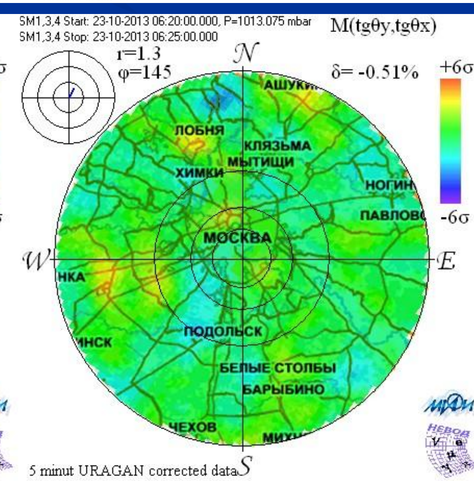
http://nevod.mephi.ru/English/atmosphere.php







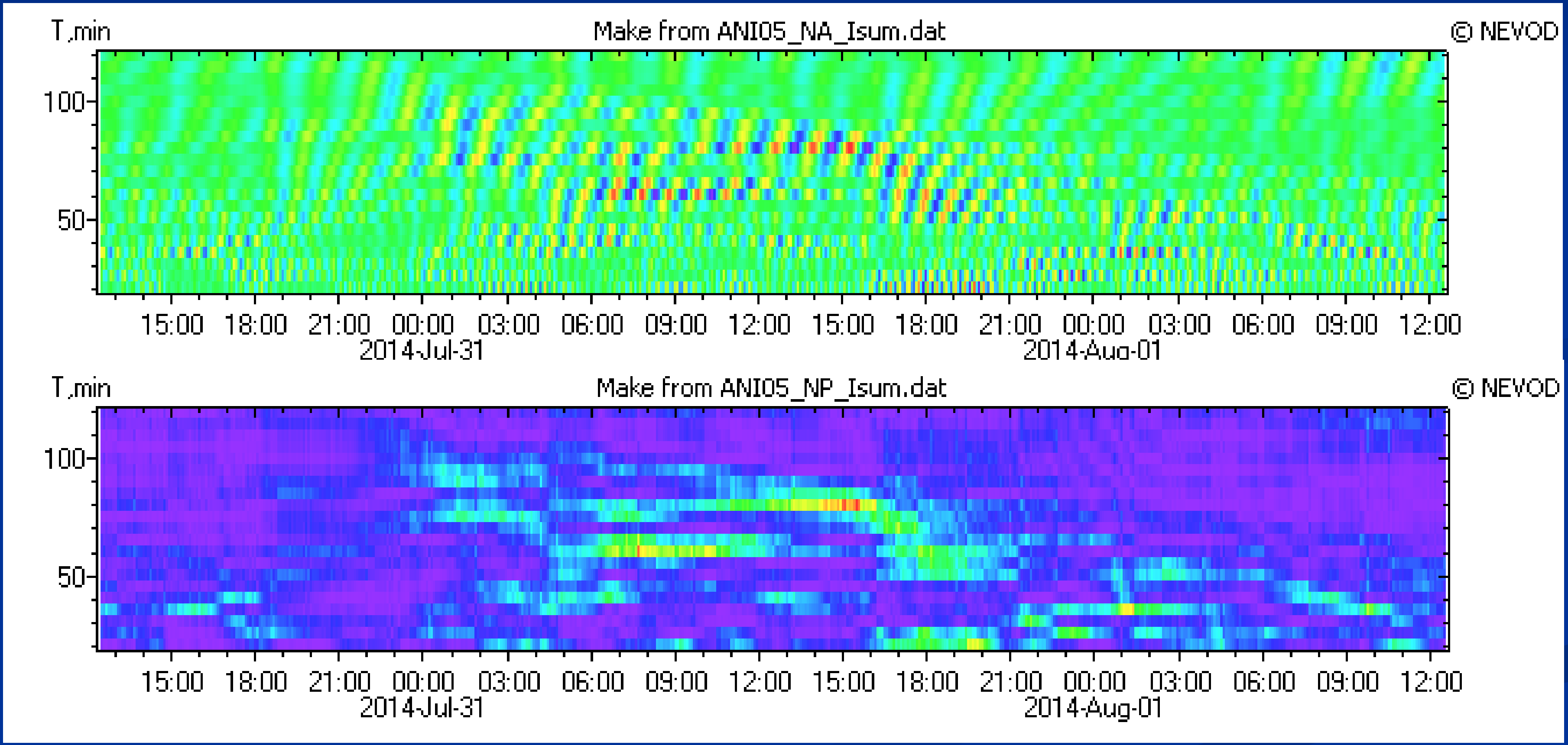




Wavelet URAGAN data processing (5 min)

http://nevod.mephi.ru/English/wavurg1.htm

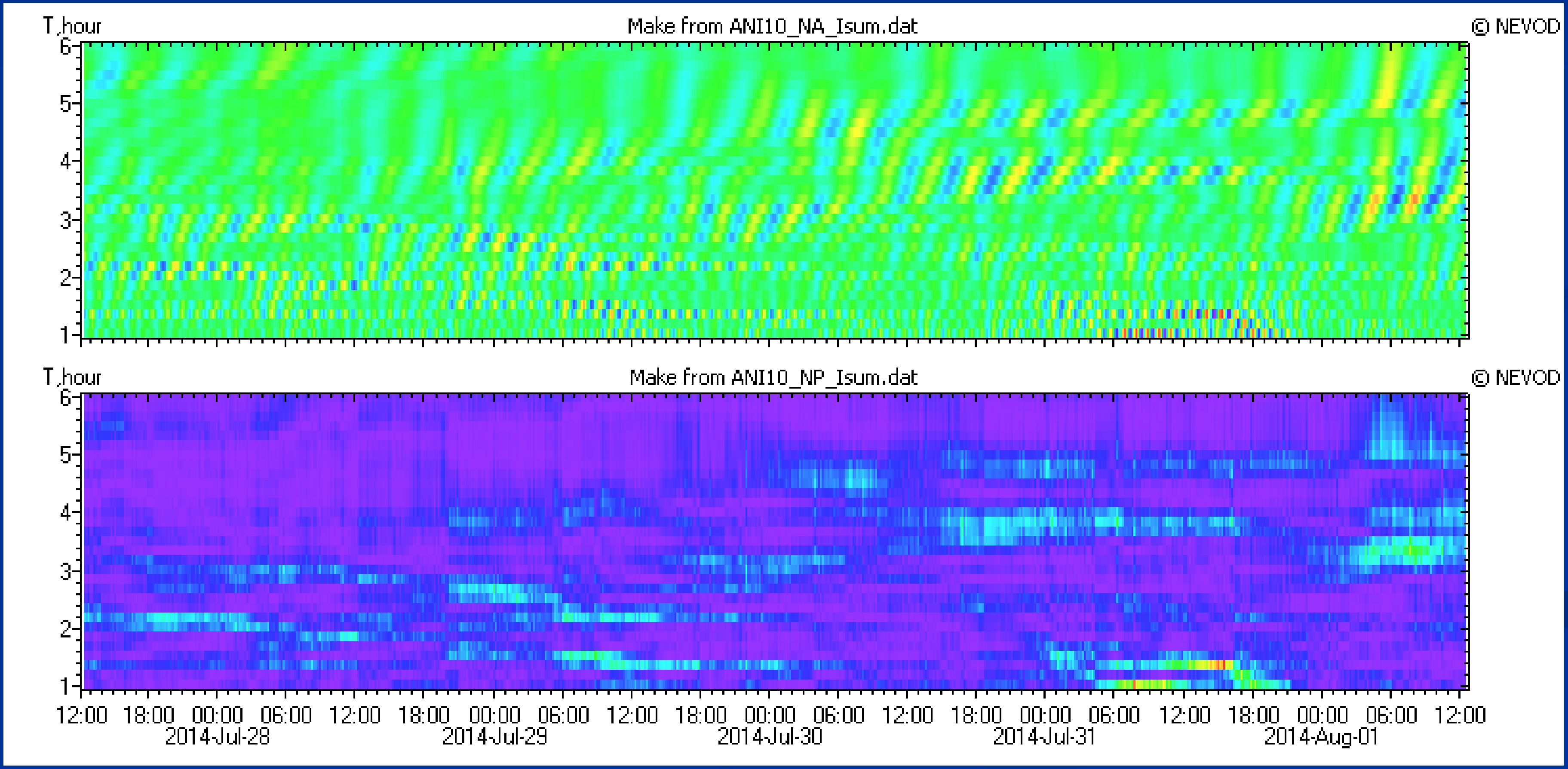
I_{sum}, A, $r_{hor.}$ Periods: 20 - 120 min



Wavelet URAGAN data processing (10 min)

http://nevod.mephi.ru/English/wavurg1.htm

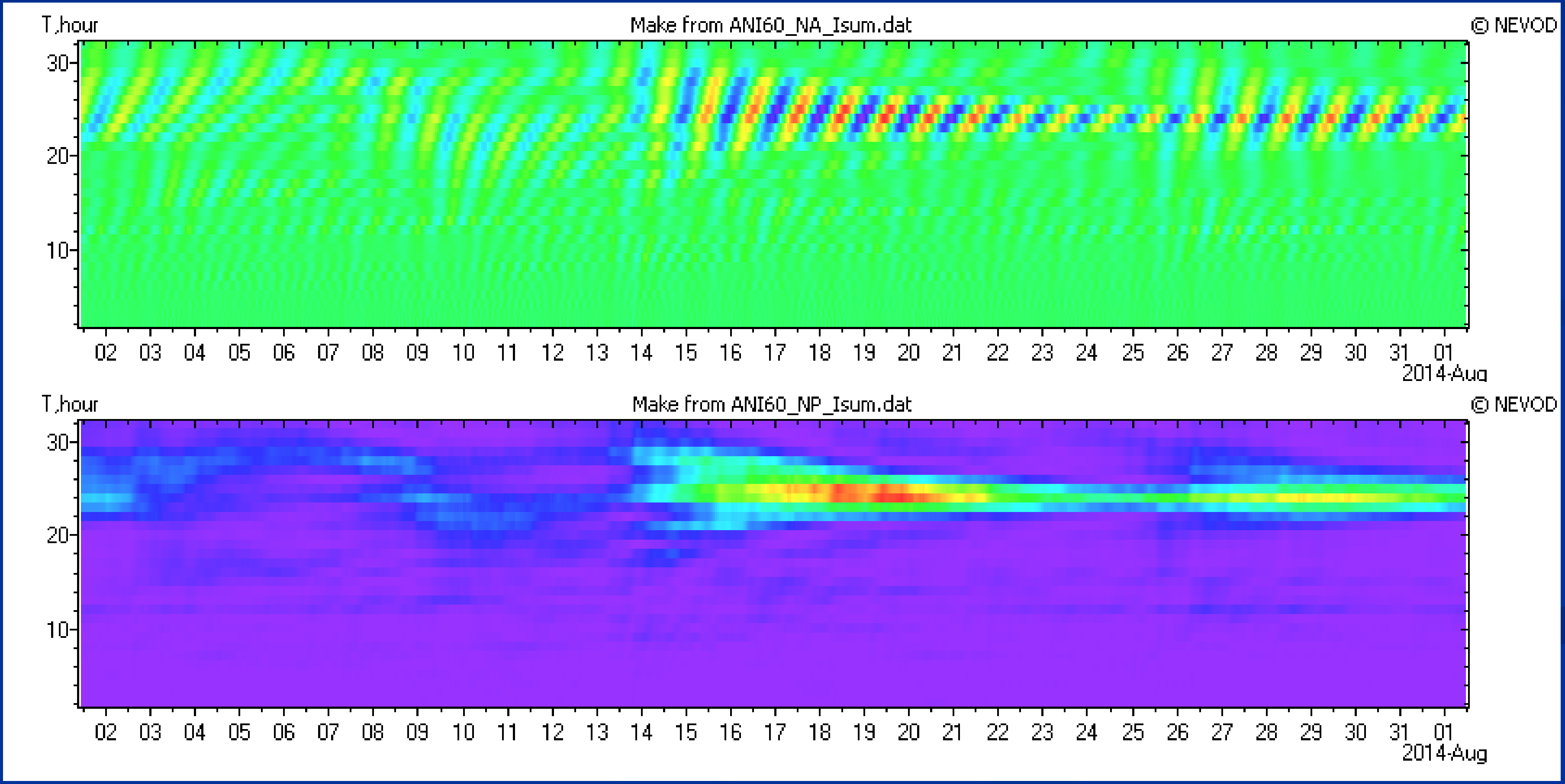
I_{sum}, A, $r_{hor.}$ Periods: 1 – 6 hours



Wavelet URAGAN data processing (60 min)

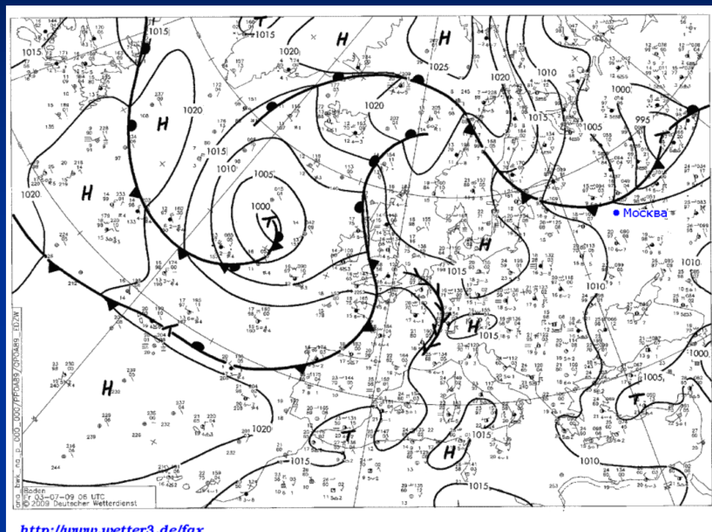
http://nevod.mephi.ru/English/wavurg1.htm

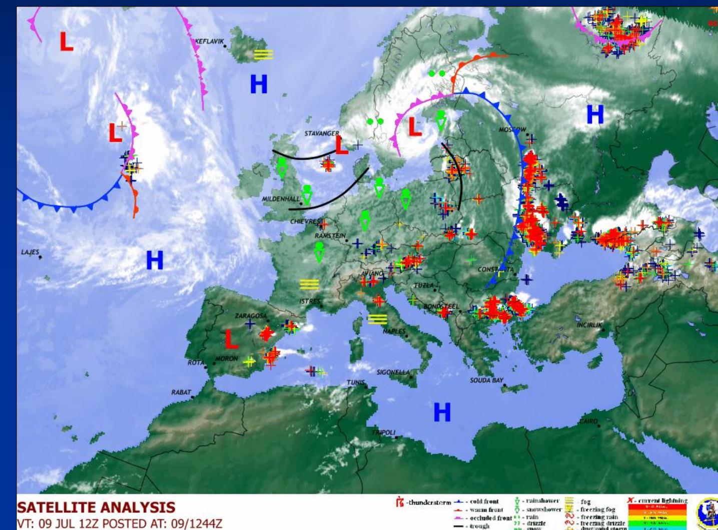
I_{sum}, A, $r_{hor.}$ Periods: 2 – 32 hours

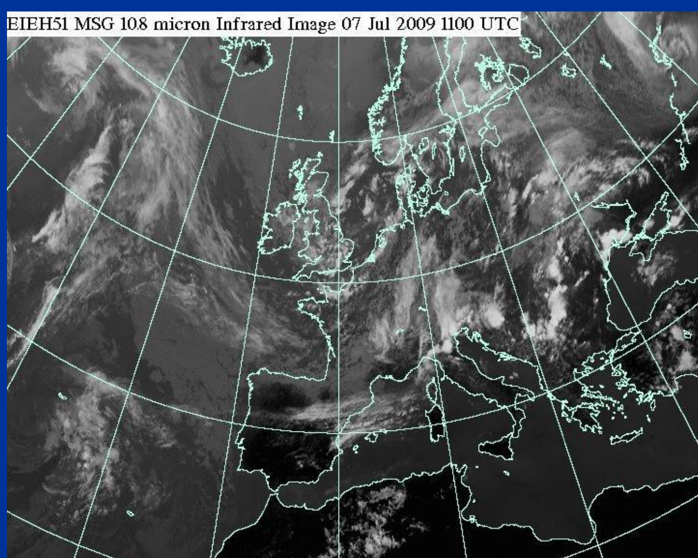


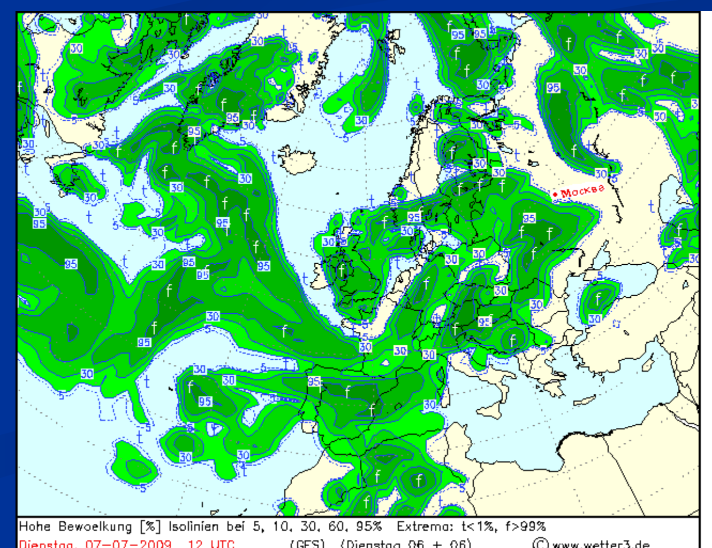
Synoptic maps

Meteomaps of atmospheric fronts and active baric system





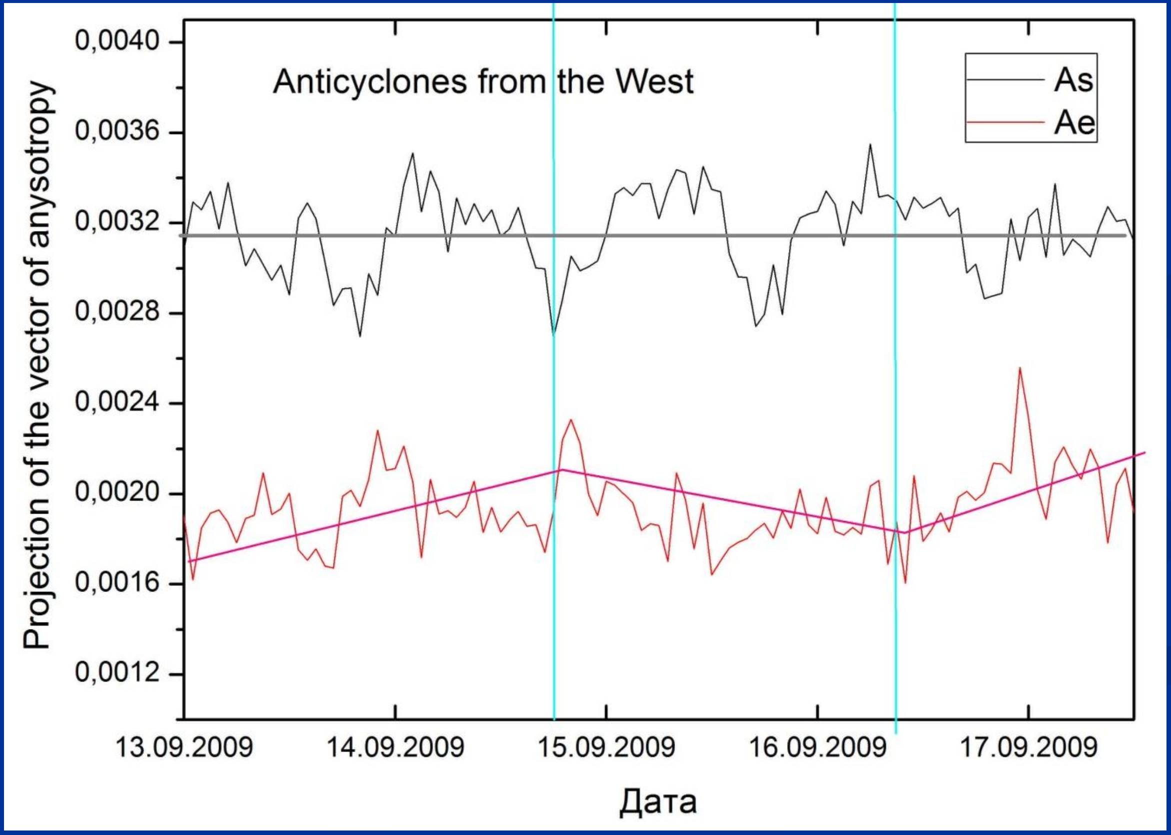




Cyclones (anticyclones) (2009 -2011)

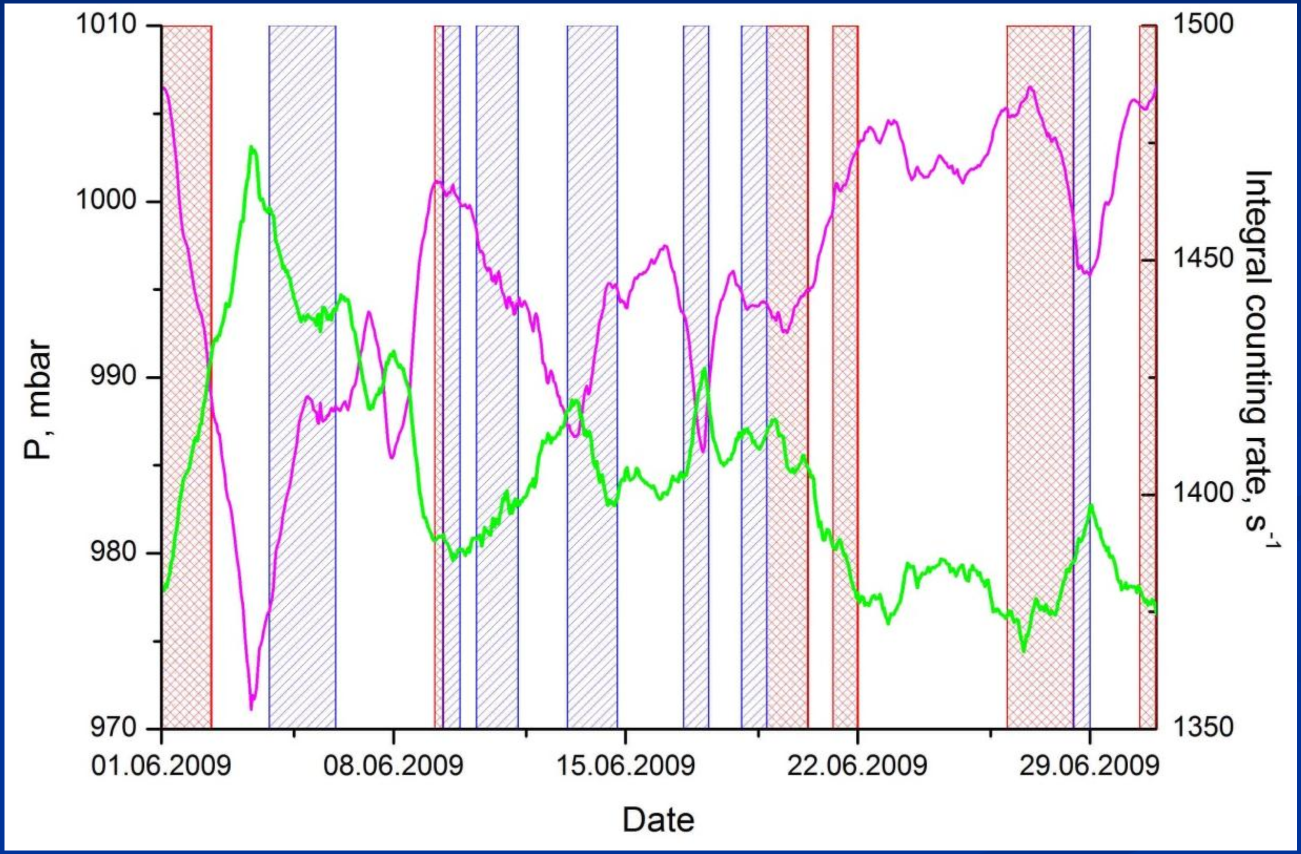
The task: study of the relations between the parameters of cyclones and anticyclones and characteristics of muon flux variations at the Earth surface.

Variations of integral counting rate: a comparison of the period of large-scale atmospheric processes over the URAGAN location and variations of muon flux at the Earth's surface.



Cyclones (anticyclones) (2009 -2011)

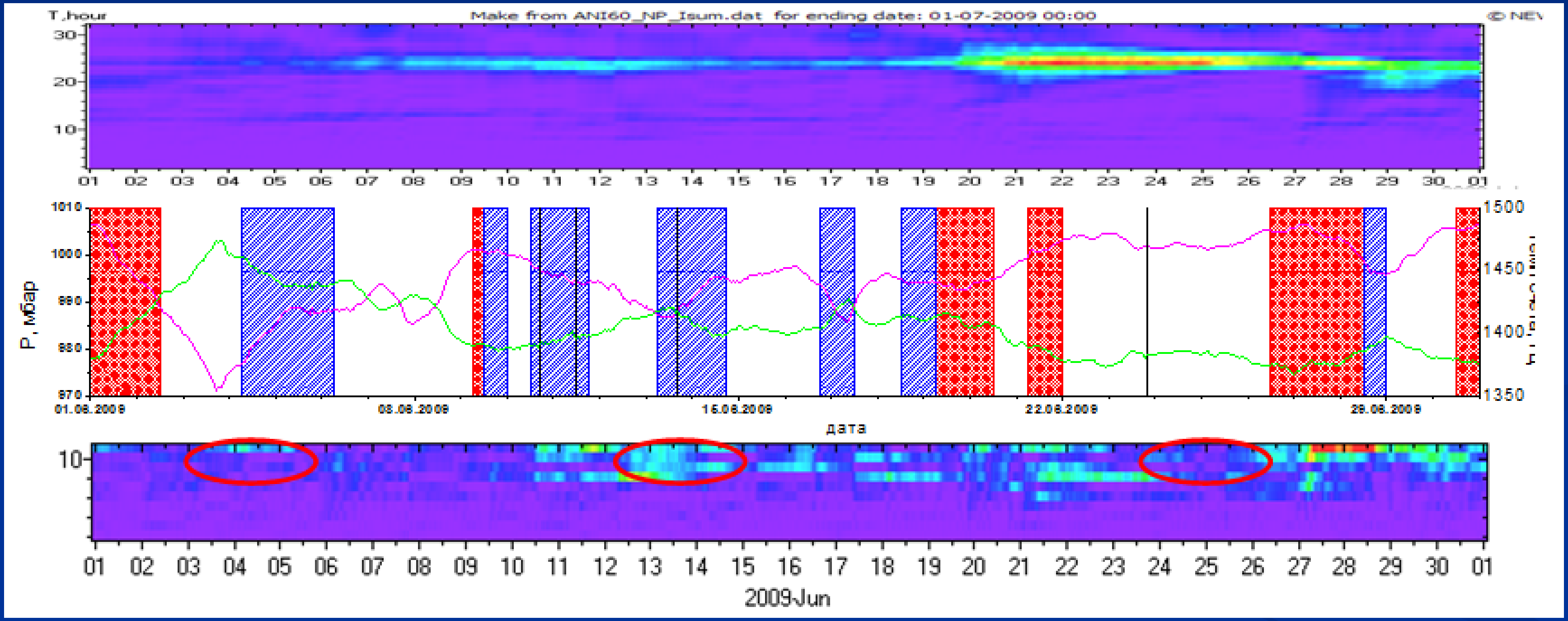
Blue areas: periods of the passage of cyclones
Red areas: periods of the passage of anticyclones



- At the arrival of the cyclone the muon counting rate increases due to the pressure drop. When a cyclone begins to move away - the pressure begins to rise and the counting rate of the muons falls down.
- In the case of the anticyclone there is the reverse process.

Monitoring cyclones passed over the Moscow

Variation of wave characteristics of muon flus during large scale atmospheric processes

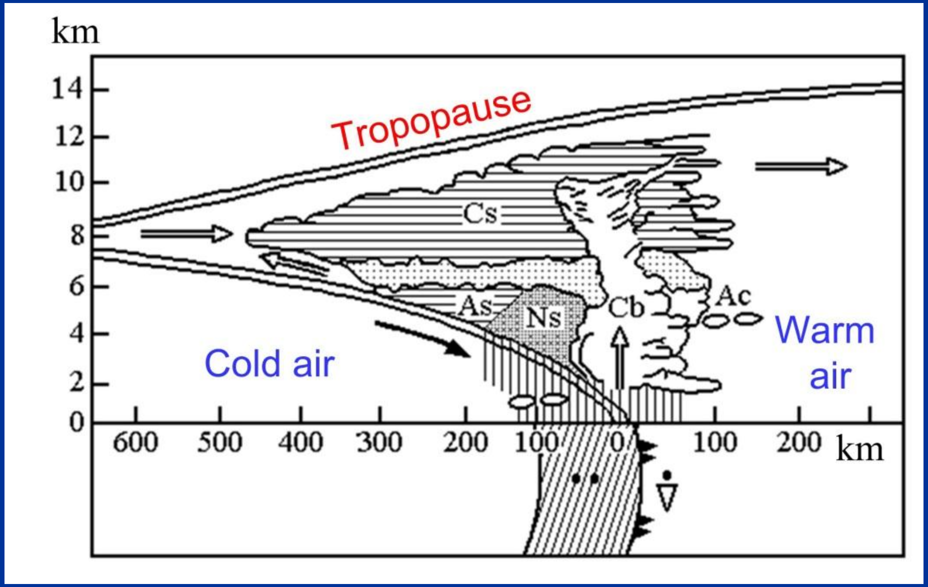


- It is clear seen the 24-hour wave associated with the daily cycle. The 12 hours second harmonic is seen too.
- In the interval of periods 2 - 12 hours is well manifested waves modulated by different processes of an atmospheric and extraterrestrial origin.
- Red ellipses are marked waves appeared during Forbush decreases.

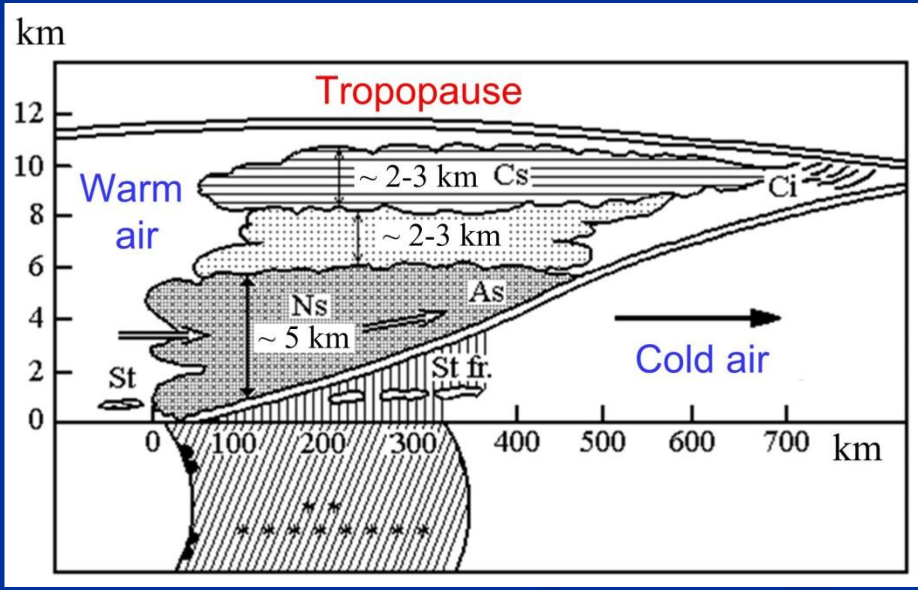
Atmospheric fronts around the Moscow

The task: study the relations between the parameters of cold and warm fronts and characteristics of the muon flux variations at ground level.

Cold atmospheric front

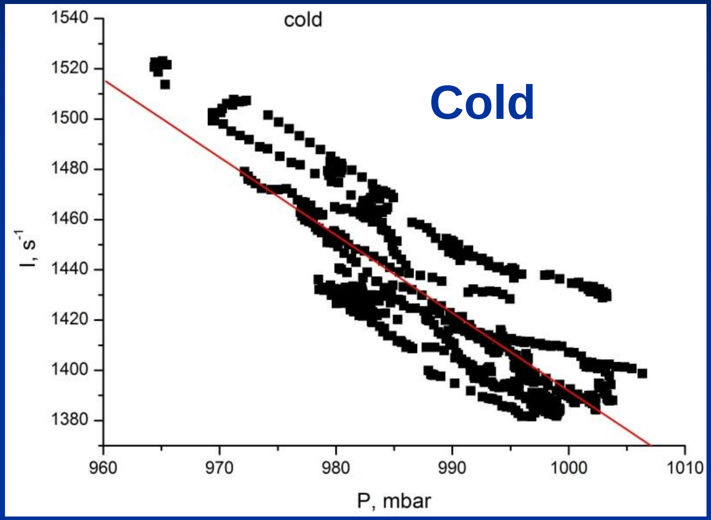


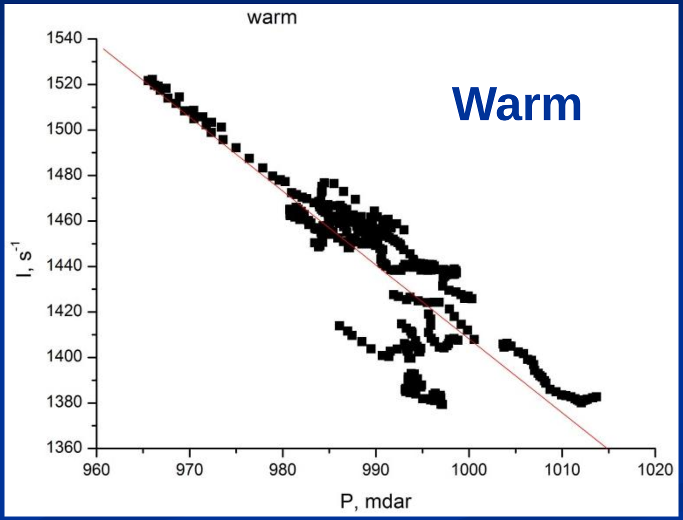
Warm atmospheric front

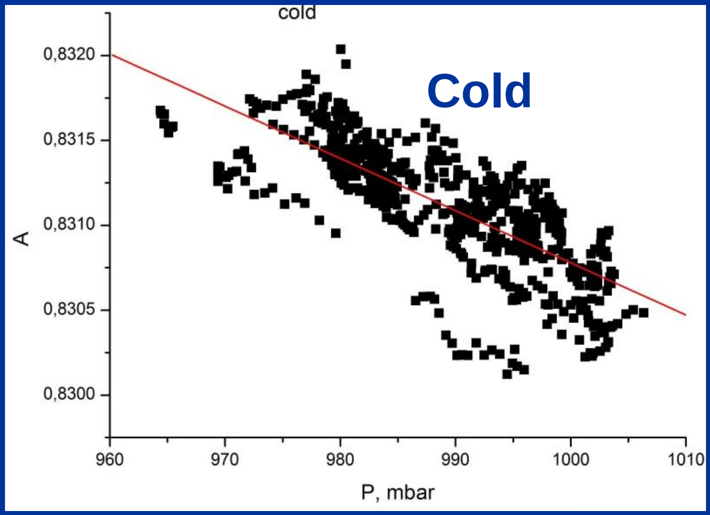


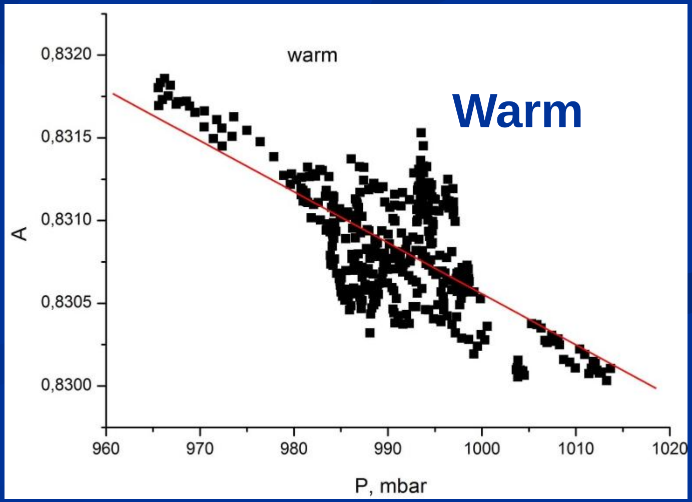
Atmospheric fronts around the Moscow

The task: study the relations between the parameters of cold and warm fronts and characteristics of the muon flux variations on the surface of the Earth.



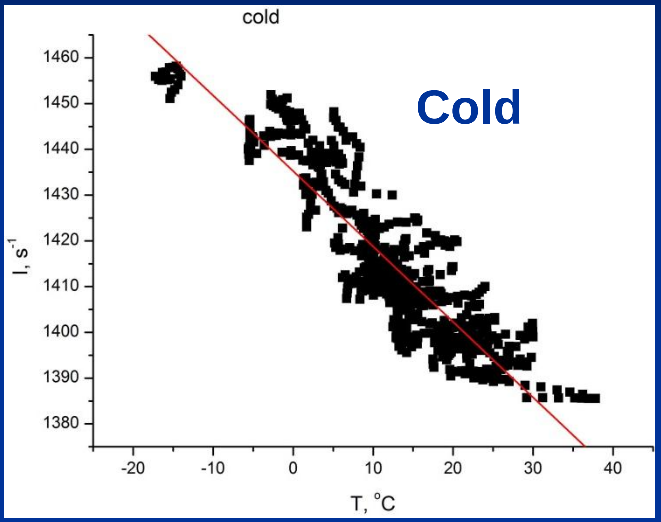


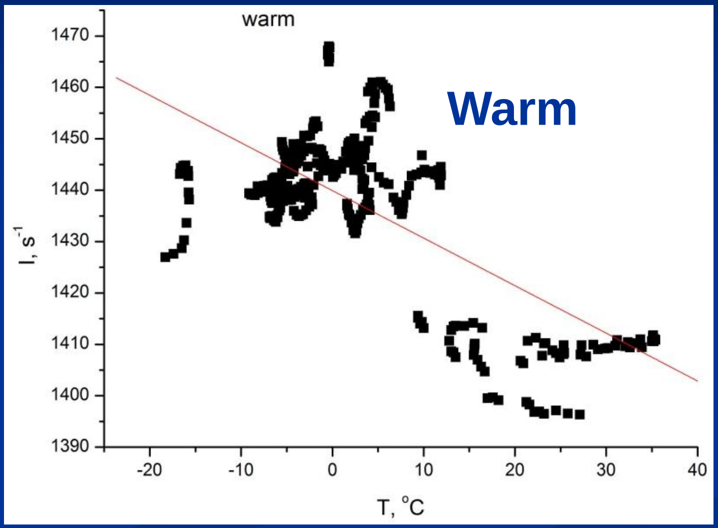


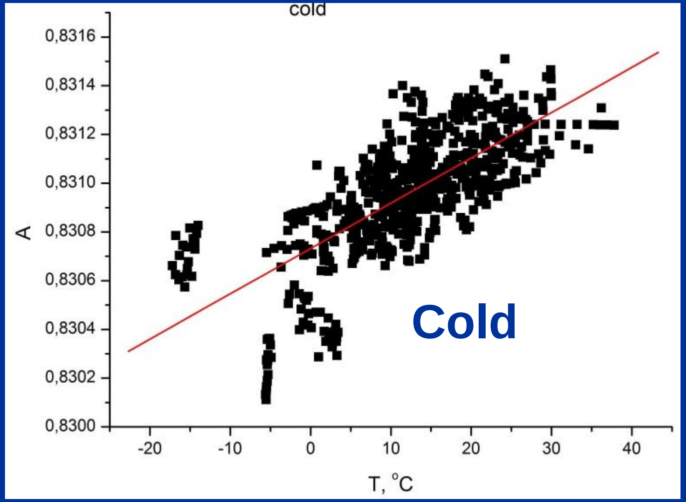


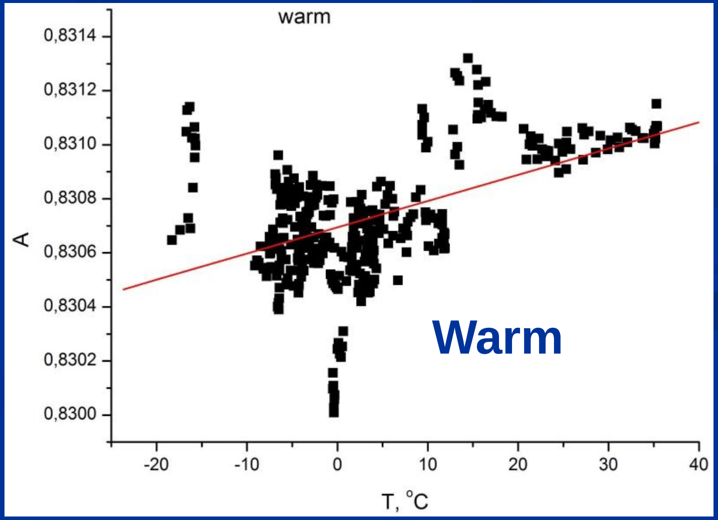
Atmospheric fronts around the Moscow

The task: study the relations between the parameters of cold and warm fronts and characteristics of the muon flux variations on the surface of the Earth.









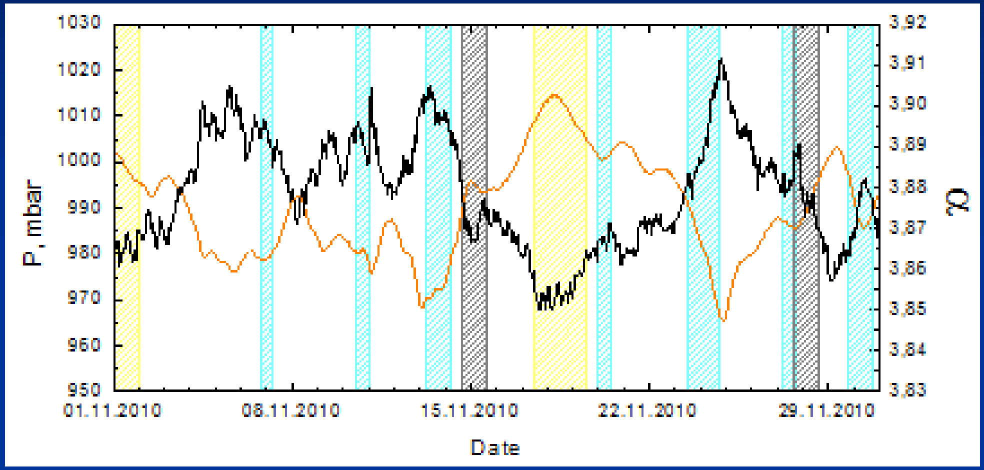
Atmospheric fronts around the Moscow

Muon flux dependence on the zenith angle is determined by fitting of the zenith-angular distribution of the matrix M (θ, φ, t) at the assumption that it has the shape of the power low of cosine of the angle, which is measured from the axis of a anisotropy vector:

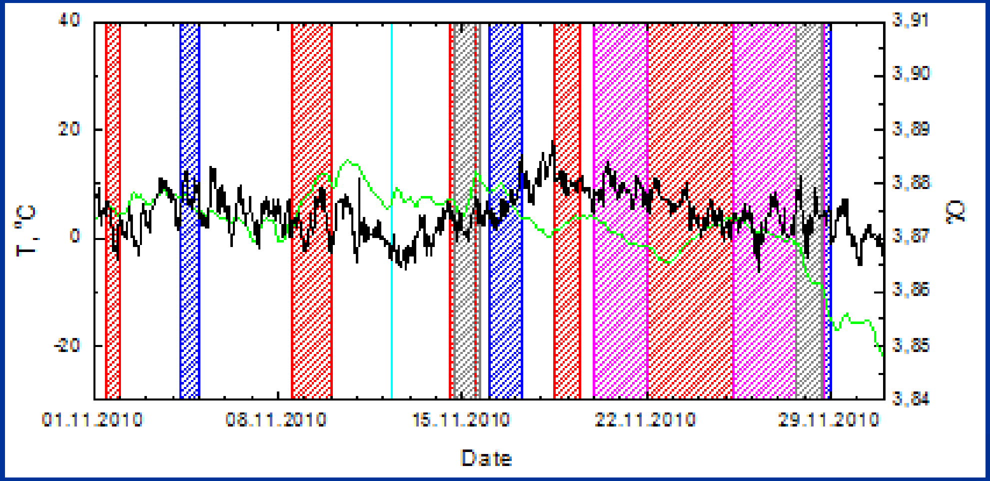
$$\frac{N(\theta,\varphi,t)}{\mathrm{T}} = C \cdot \cos^{\alpha}\theta' \cdot d\Omega \quad ,$$

$$\cos\theta' = \cos\varphi_A \sin\theta_A \cos\varphi \sin\theta + \sin\varphi_A \sin\theta_A \sin\varphi \sin\theta + \\ + \cos\theta_A \cos\theta$$

Atmospheric fronts around the Moscow



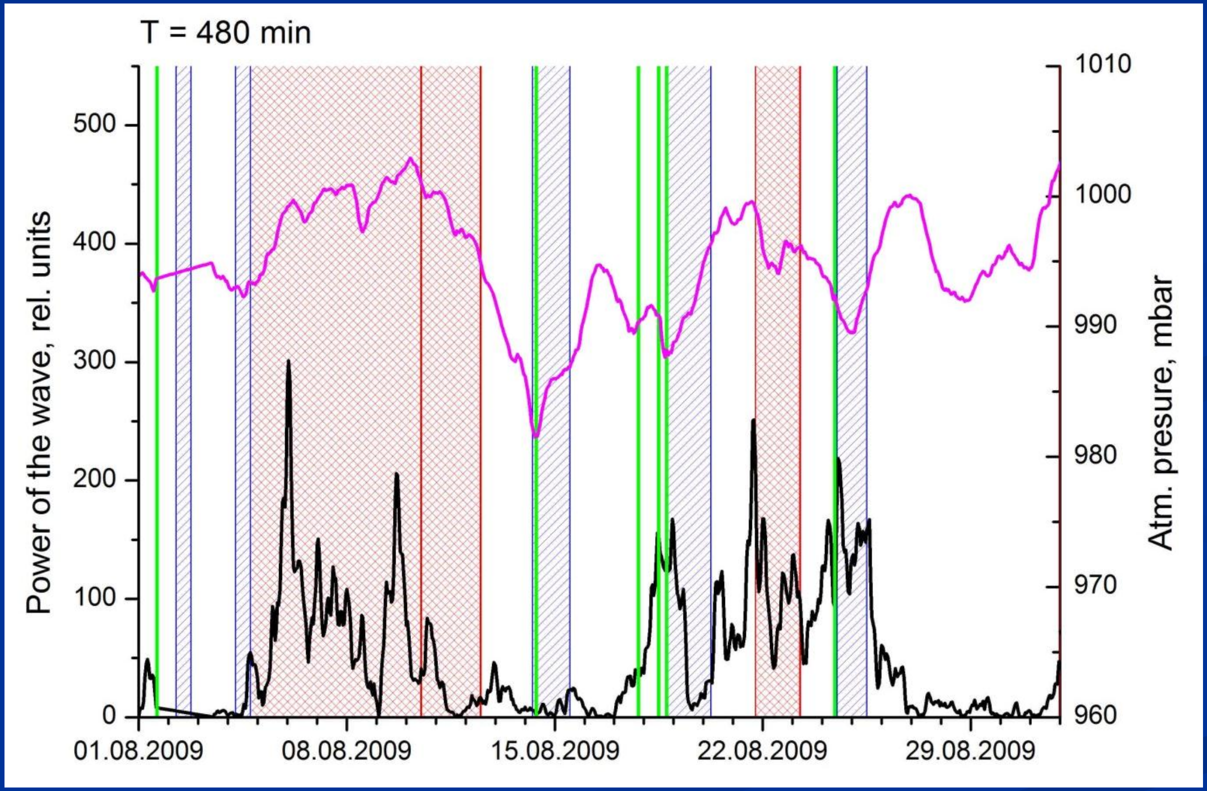
Baric systems cause the clear identifying reaction of a flux of cosmic-ray muons in the integral intensity as well as and in the zenith-azimuthal distribution.



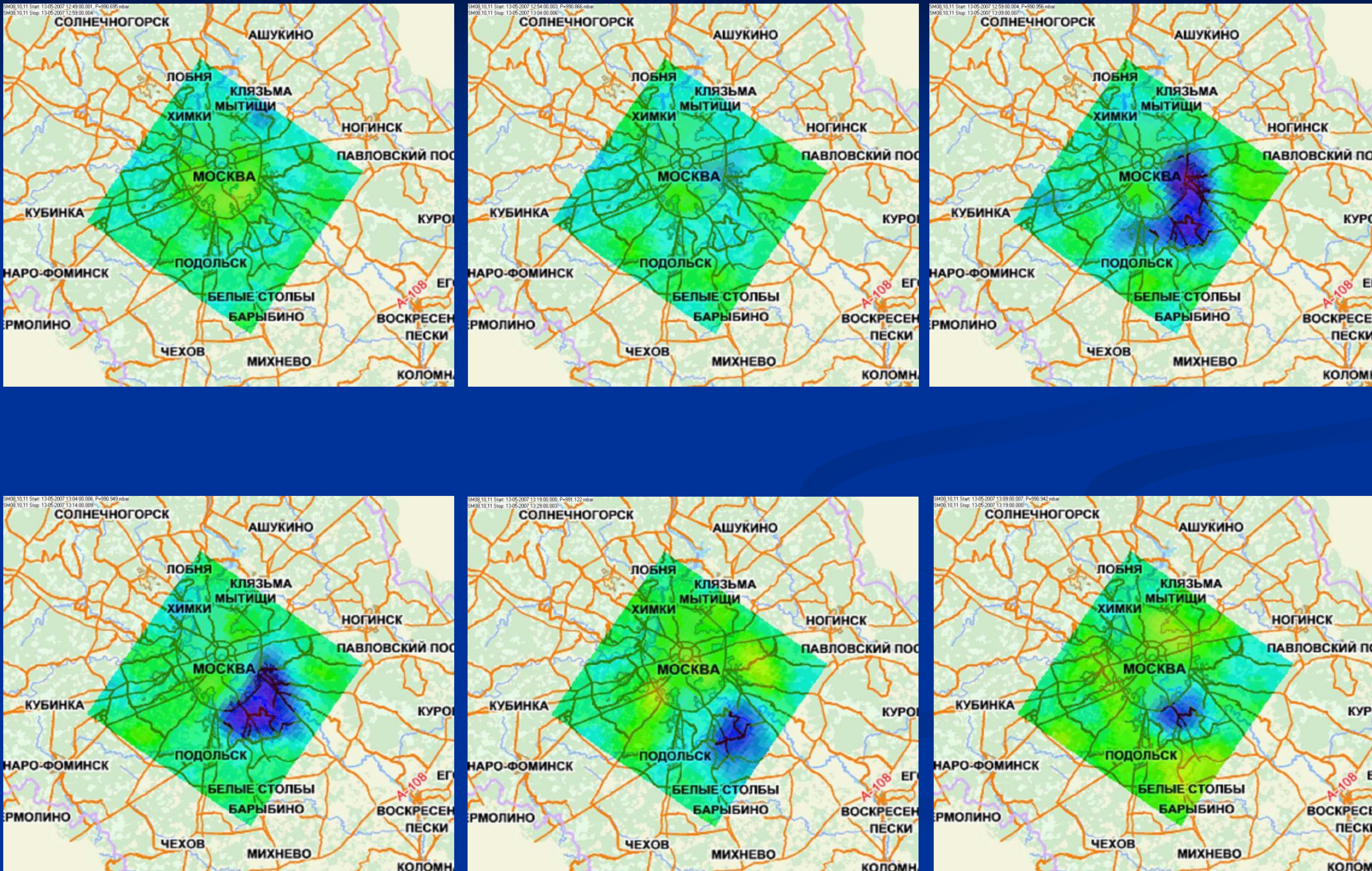
The influence of atmospheric fronts has a more complex character and at the analysis of variation of muon flux related with atmospheric fronts it is necessary take into account additional meteorological information.

Atmospheric fronts around the Moscow

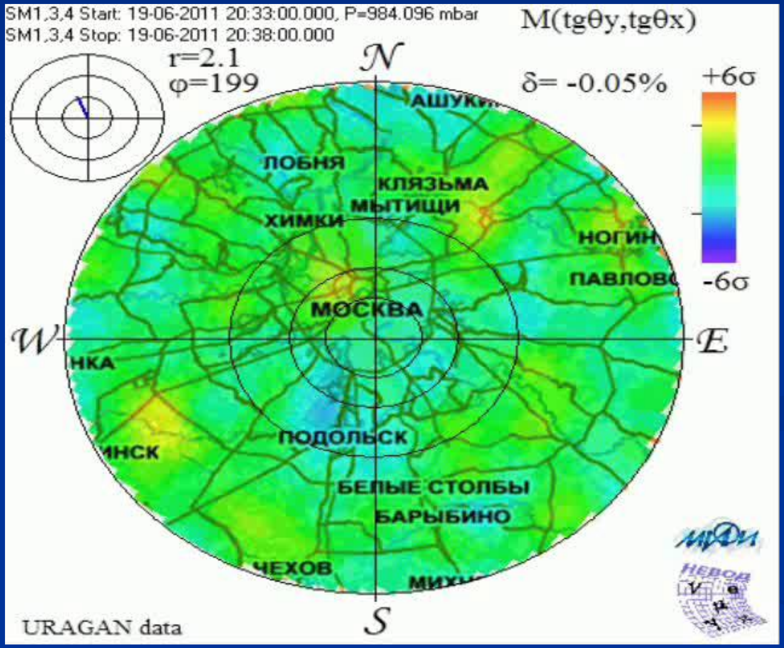
Wavelet analysis: the time dependence of the power of the wave with a period of 8 hours (green lines show the thunderstorm that passed over the Moscow):



Monitoring of the thunderstorm over Moscow



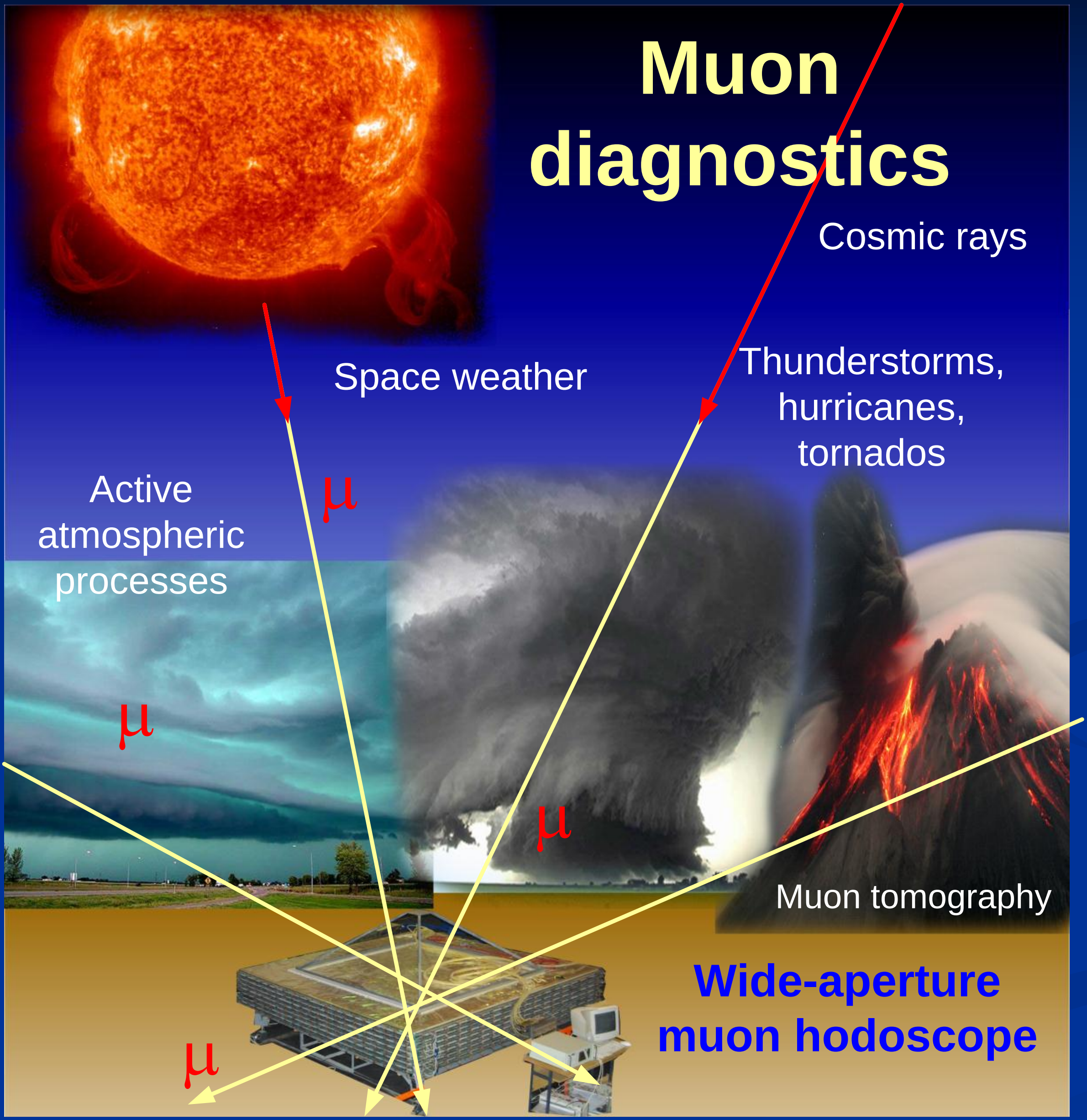
Monitoring of the thunderstorm over the Moscow



Conclusion

- Muon hodoscope URAGAN make it possible to reveal on the basis of the analysis of variation of different characteristics of muon flux (integral counting rate, zenith-angular anisotropy, wave parameters) active atmospheric phenomena.
- Variations in the characteristics of the muon flux, represented by 5-minute data, are mainly due to the atmospheric causes.
- Cyclones (anticyclones) cause the clear identifying reaction of a flux of cosmic-ray muons in the integral intensity as well as and in the zenith-azimuthal distribution.
- The influence of atmospheric fronts has a more complex character and the analysis of variations of muon flux related with atmospheric fronts requires taking into account additional meteorological information.
- However, to obtain quantitative evaluations about large scale atmospheric processes it should be carefully study each case of passing of the pressure atmospheric system through the Moscow region with the involvement of additional meteorological information.
- Muon diagnostics is a new promising approach for monitoring of local atmospheric processes, such as powerful thunderstorms.

http://nevod.mephi.ru/uragan_data.htm



Thank you for attention!