

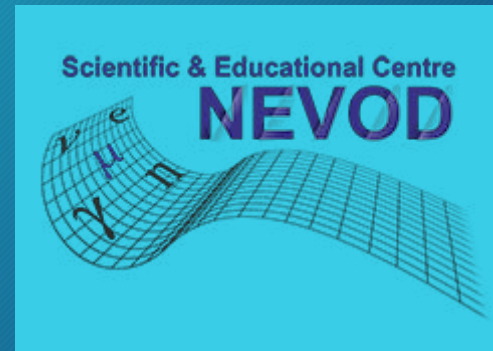


Thunderstorms and Elementary Particle Acceleration
(TEPA-2019)

October 17 2019

Nor Amberd International Conference Centre of the Yerevan Physics
Institute, Byurakan, Aragatsotn District, Armenia

Thundercloud imaging by means of muon hodoscope URAGAN and Doppler weather radar DMRL-C



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N.I. Serebryannik², V.V. Shutenko¹*

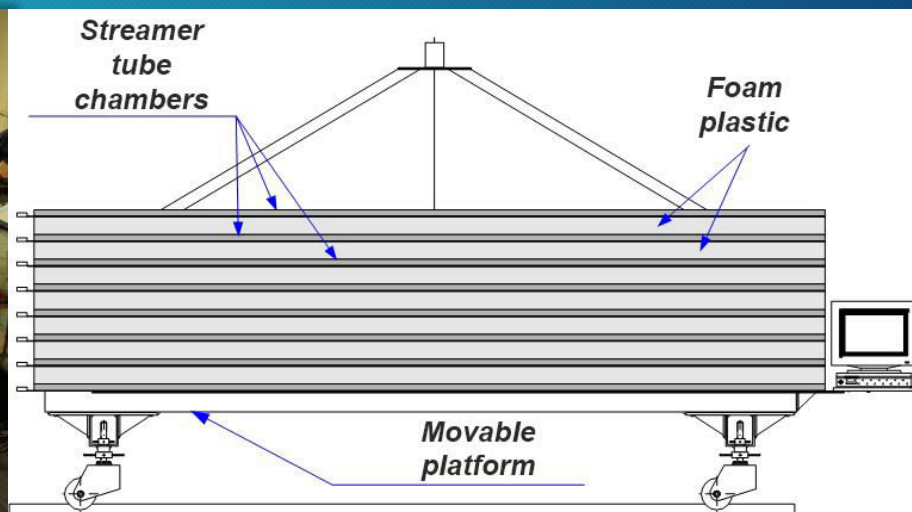
¹National Research Nuclear University MEPhI

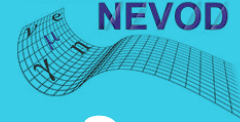
²Central Aerological Observatory



Muon hodoscope URAGAN

- provides registration of muons with a high spatial and angular resolution (about 1 cm and 0.8° , respectively) in a wide range of zenith angles (from 0° to 84°)
- track parameters are reconstructed in real time and accumulated in a two-dimensional angular matrix for one minute interval. Such a matrix is a "muon picture" of the upper hemisphere





Characteristics reflecting distortions of the muon flux

Characteristics reflecting distortions of the muon flux:

- vector of local anisotropy (\vec{A}) which indicates the average direction of muon arrival. This value is calculated as the sum of unit vectors, each of which has a reconstructed direction of a single muon track, normalized by the total number of muons
- vector of relative anisotropy (\vec{r}) which is the difference between the local anisotropy vector in the current time and anisotropy vector averaged over a long period
- \vec{r} 's projection on the horizontal plane (r_{hor}) and other projections

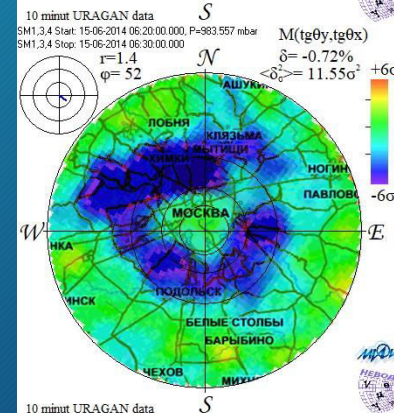
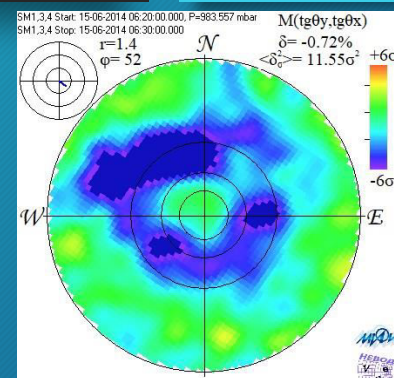
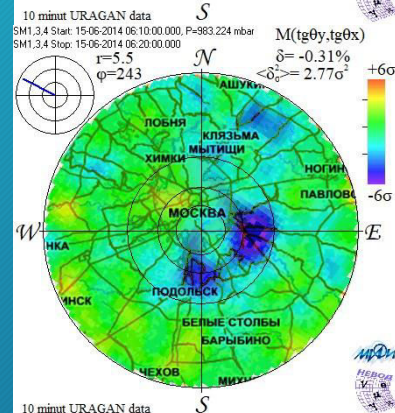
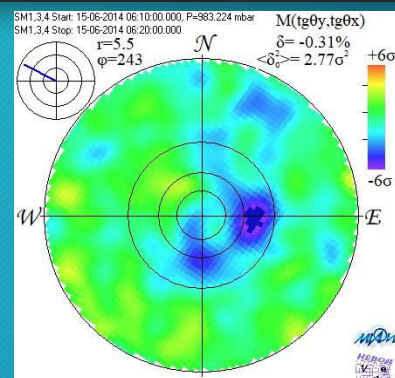
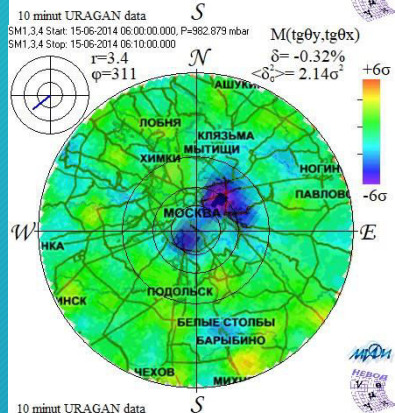
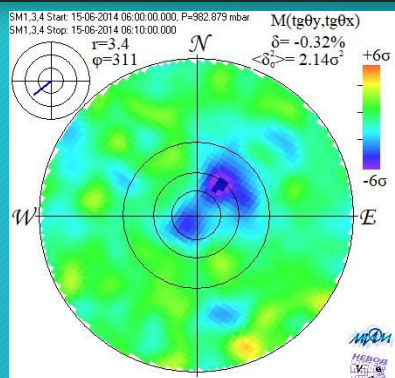
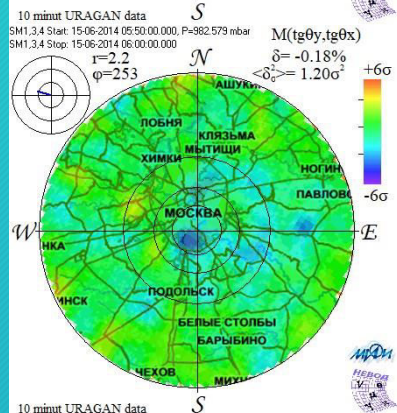
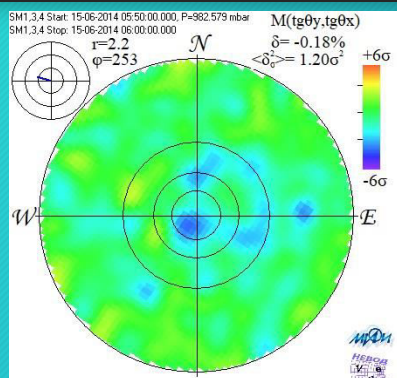
$$\vec{R} = \vec{A} - \vec{A}_N, \quad R_{hor} = \sqrt{R_{South}^2 + R_{East}^2}$$



Muon pictures (muonographs)

15.06.2014

Thunderstorm event



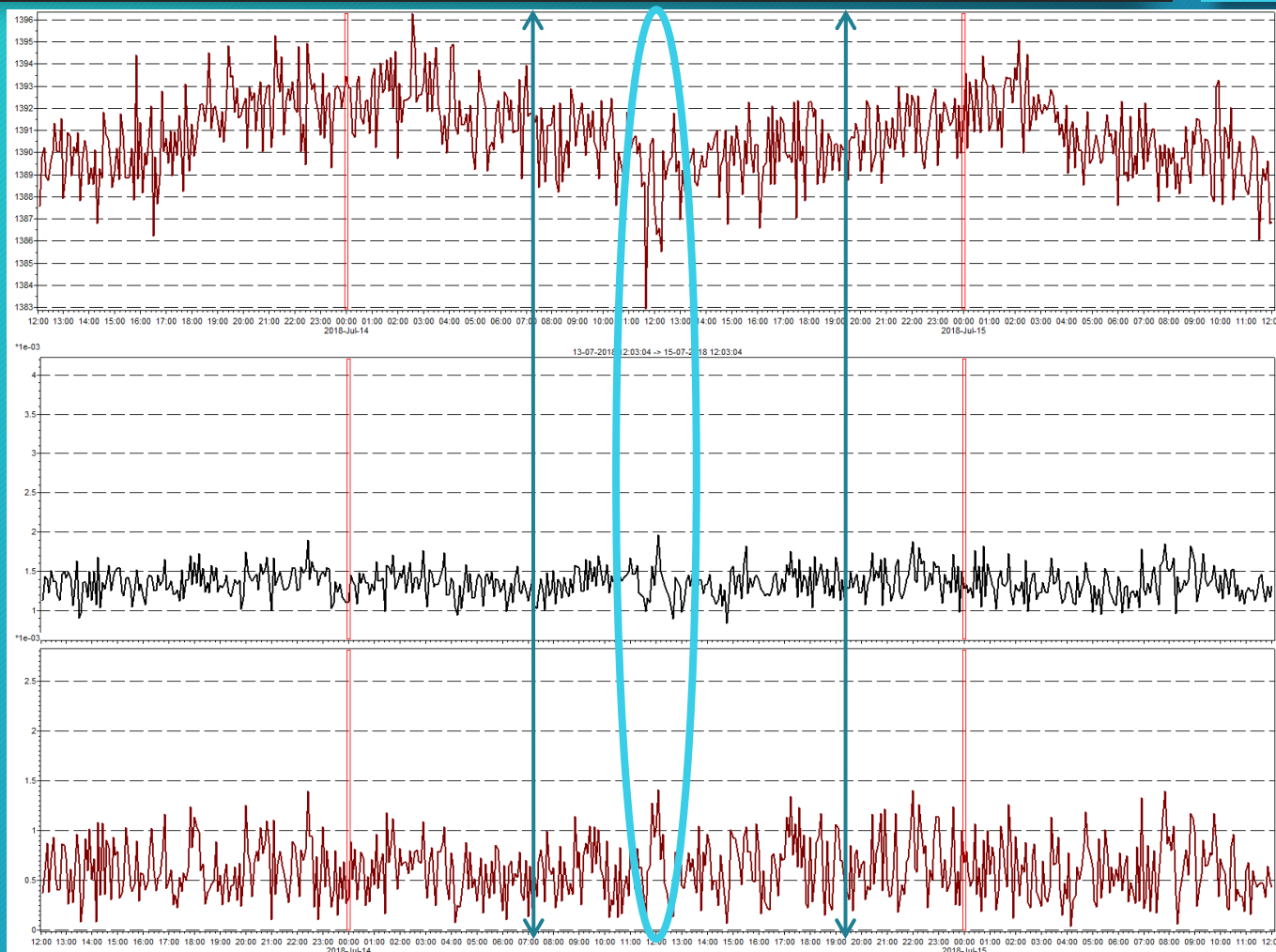
Muonograph is a graphical representation of the variations matrix of counting rate angular distribution over the last 10 minutes with respect to the normalization matrix of the preceding 24 hours in statistical error units

Muon flux characteristics during a thunderstorm (13.07.2018)

I_{sum}

r

r_{hor}



Search for thunderstorm-caused disturbances of the muon flux registered by the MH URAGAN

Открыть файл данных

Выбор параметра

- Isum
- Ax
- Ay
- Az
- PhiA
- ThetaA
- A
- Rx
- Ry
- Rz
- PhiR
- ThetaR
- R
- Rhor
- Asouth
- Aeast
- Rsouth
- Reast
- C
- Alpha

Выбор размера окна

- 1 час
- 6 часов
- 12 часов

Начало интервала

30.08.2018

Конец интервала

01.09.2018

Усреднение по

- предшествующим данным
- "окружающим" данным

Фоновый уровень

- 3 sigma
- 4 sigma
- 5 sigma

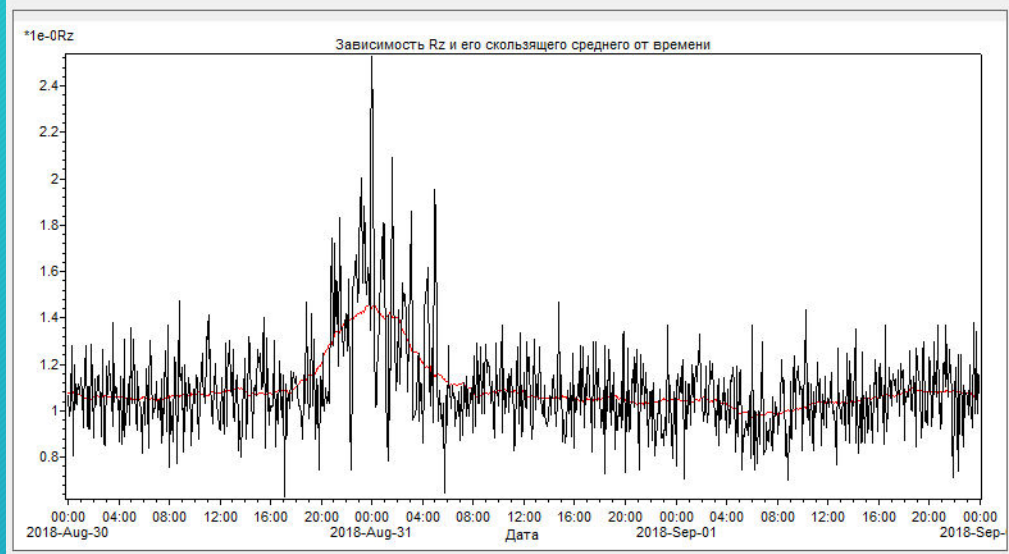
Считать данные

sig и скользящее среднее в заданном интервале

график скользящего среднего для заданного интервала

выбросы больше выбранного уровня в заданном интервале

Сигма = 0.000141487234012697

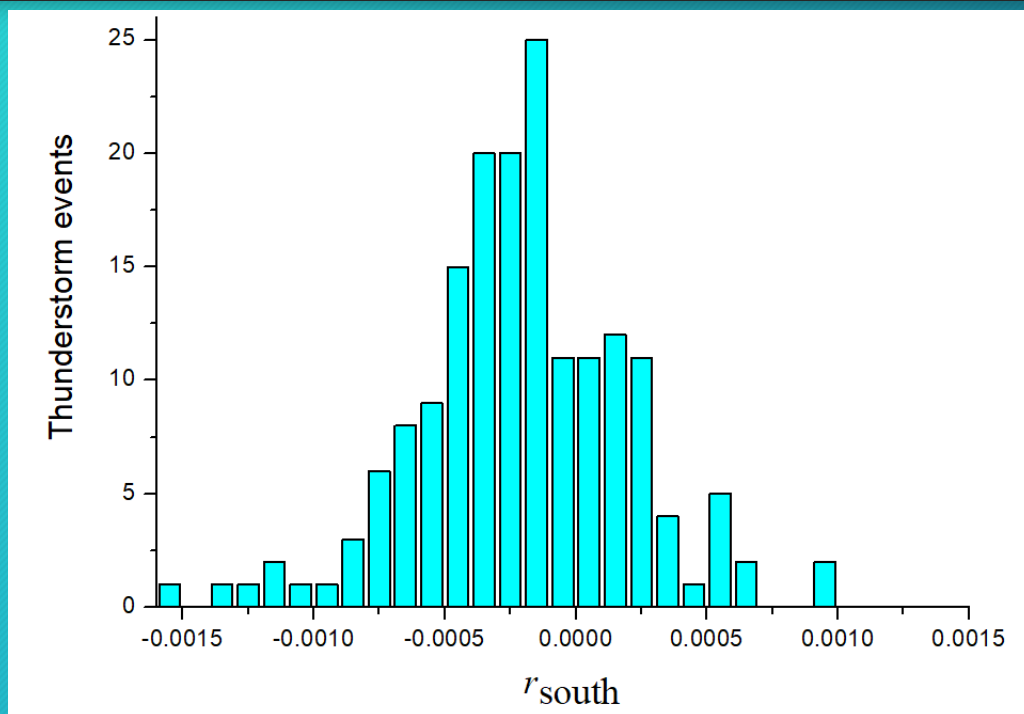


After analyzing the data for the spring-summer periods of 2014 - 2018, 173 thunderstorm events were found. It is 102 thunderstorm days vs. 135 (75%) thunderstorm days registered by 3 Moscow meteorological stations

The percentage of detection without any weather registered by weather stations: 5% (8 of 173)



Thunderstorm events that caused most significant response in the muon flux characteristics



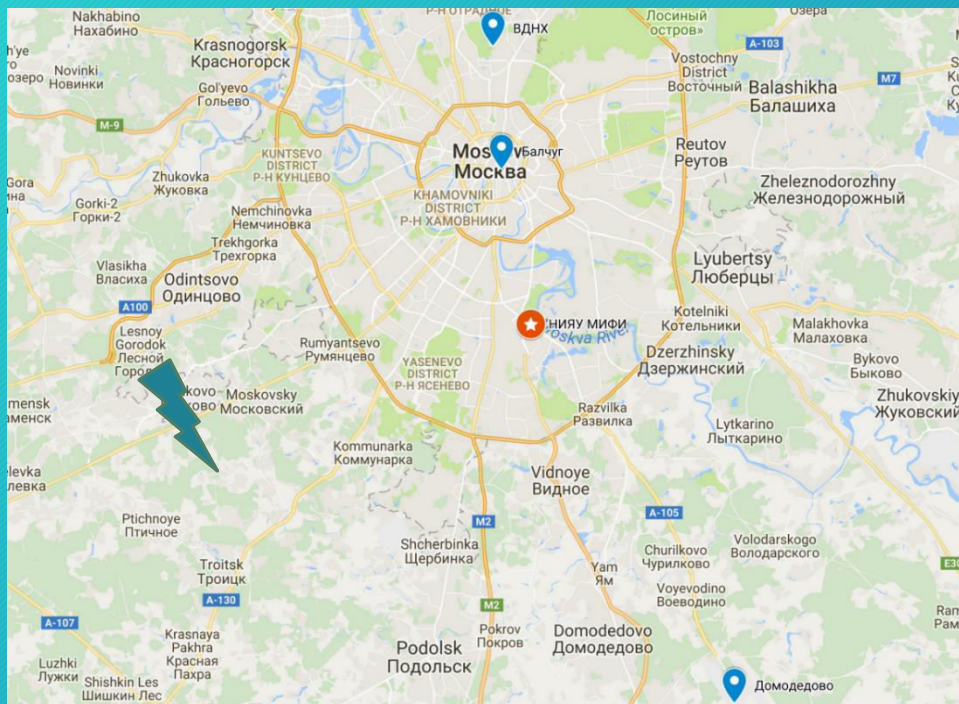
From 173 thunderstorm events selected by the thunderstorm event search program based on MH URAGAN data 17 events caused most significant response in the muon flux characteristics (10%)

1	07.06.2014 20:00
2	07.06.2014 21:30
3	09.06.2014 11:30
4	15.06.2014 06:30
5	15.06.2014 11:00
6	13.09.2014 05:00
7	23.04.2015 06:00
8	27.06.2015 00:00
9	27.06.2015 01:00
10	27.06.2015 02:00
11	27.06.2015 03:00
12	13.07.2015 13:00
13	02.03.2016 15:30
14	17.09.2016 02:30
15	29.03.2017 00:30
16	14.08.2017 21:00
17	21.09.2018 04:00

Condition of selection: deviation from the average by more than 3σ by at least one of the characteristics considered.

Sources of meteorological information

Moscow weather stations

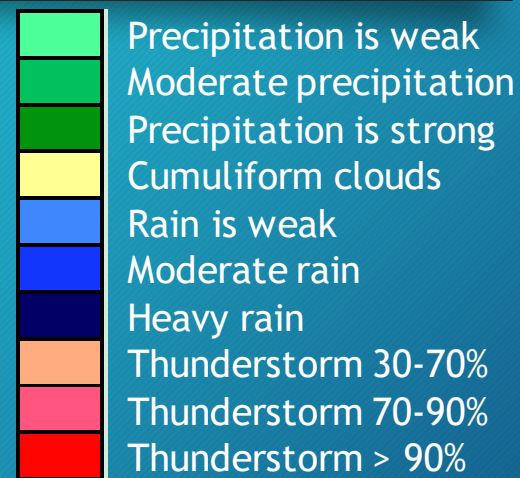
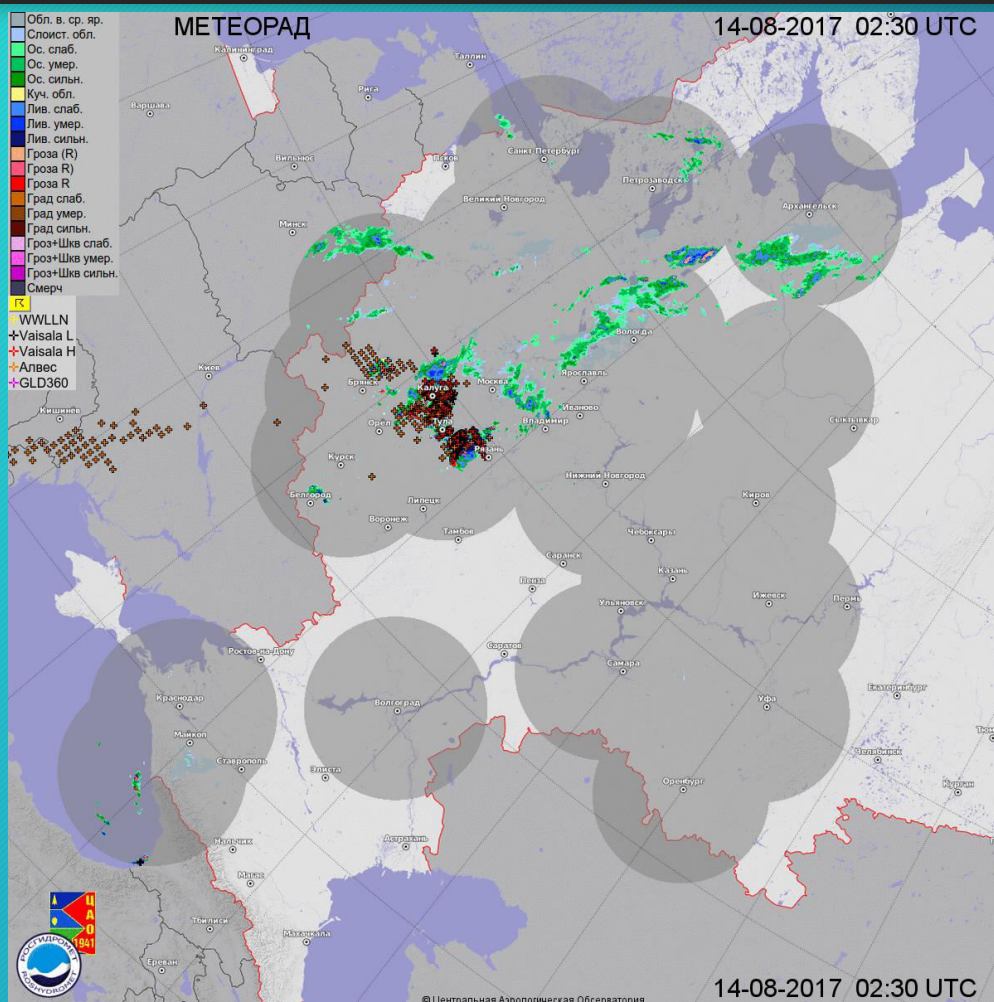


Doppler meteorological radar DMRL-C



- Weather archives available
- The most significant weather events are noted
- a view range of 250 km
- a maximum detection height of about 20 km
- a high spatial resolution (0.5 - 1 km)

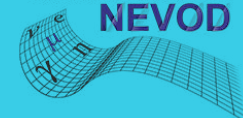
Meteorological radar network



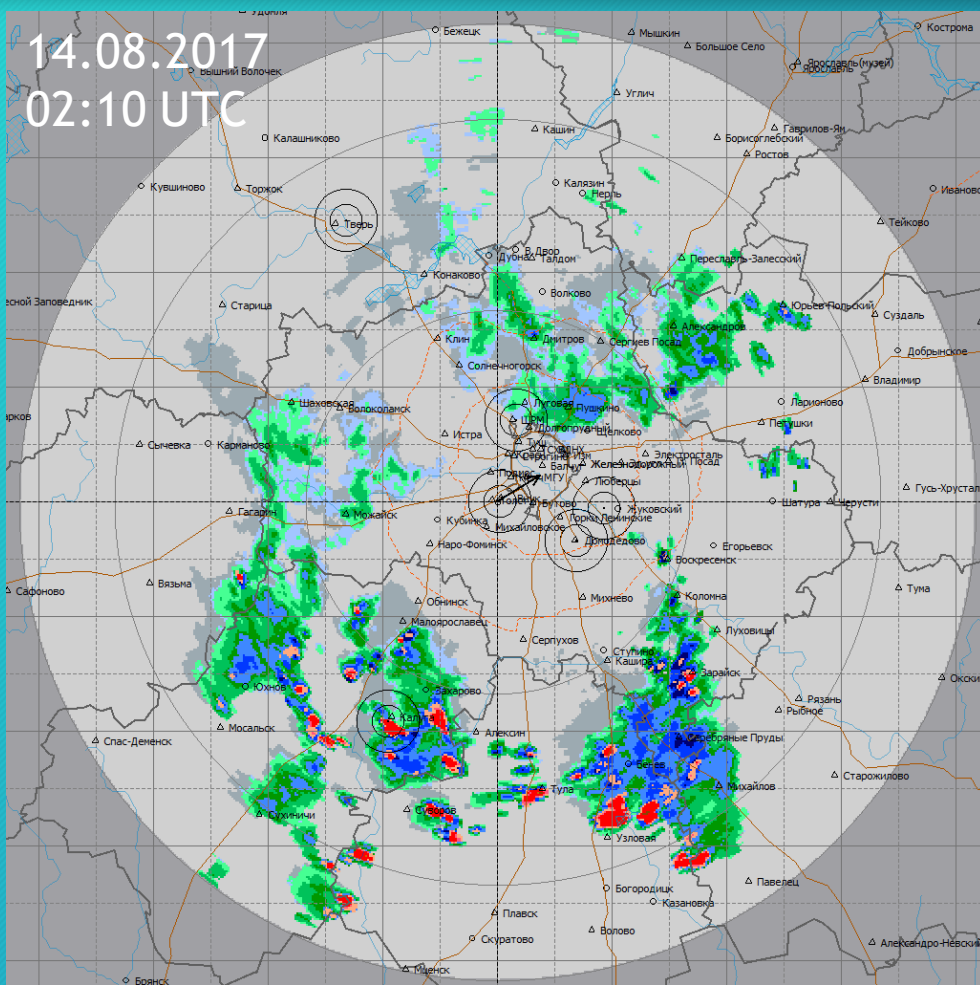
Displays distribution of various meteorological data such as precipitation intensity and velocity and direction of movement of cloud systems

Detects dangerous weather phenomena such as thunderstorms

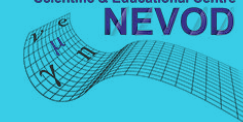
Data from DMRL-C located in Vnukovo airport is used



DMRL-C (Vnukovo airport)

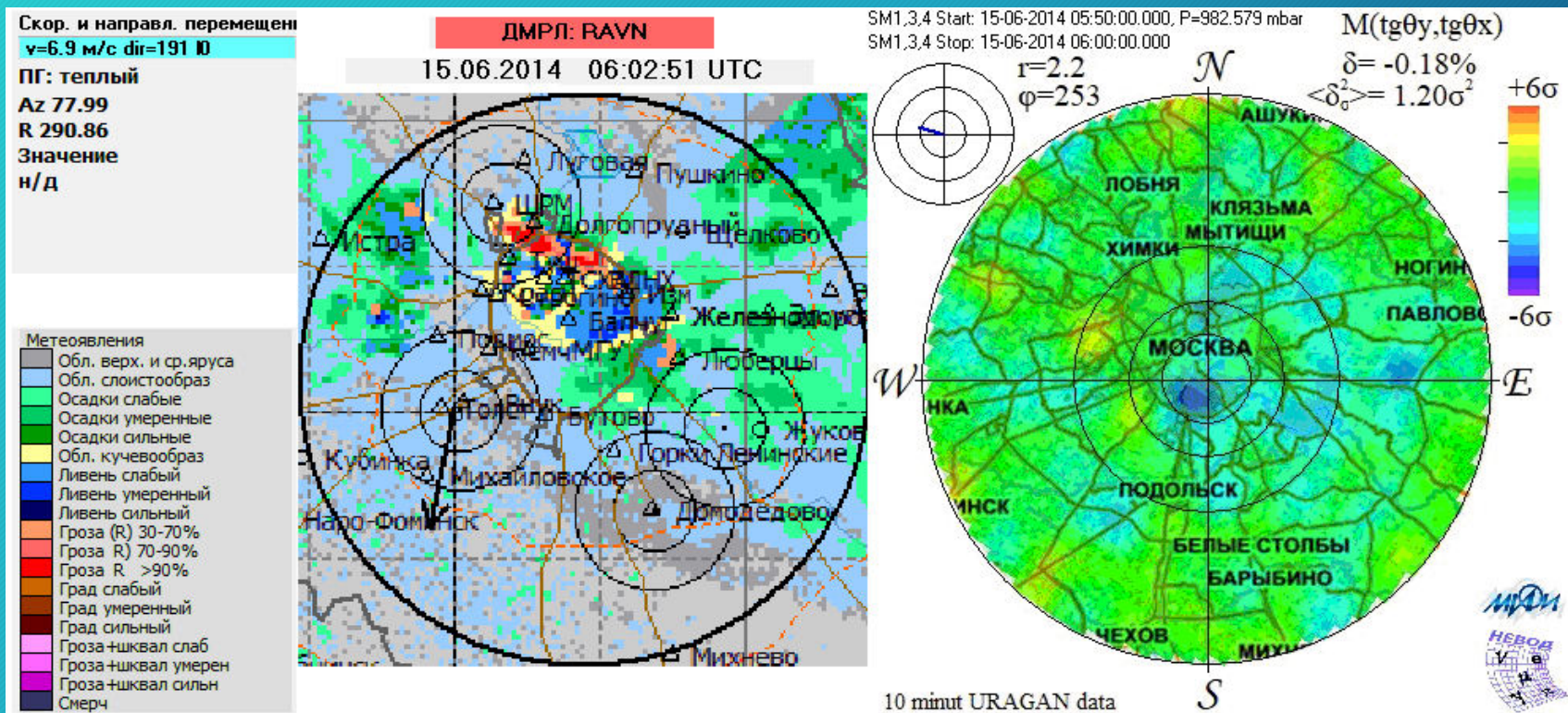


DMRL provides cyclic monitoring at 10 minutes intervals and obtains data with a high spatial resolution (1 km × 1 km). Radar operates by conducting a survey sequence of circular azimuthal scans of the upper celestial hemisphere at several different angles. By doing so it collects data on cloudiness and precipitation on several conical sections of the atmosphere.



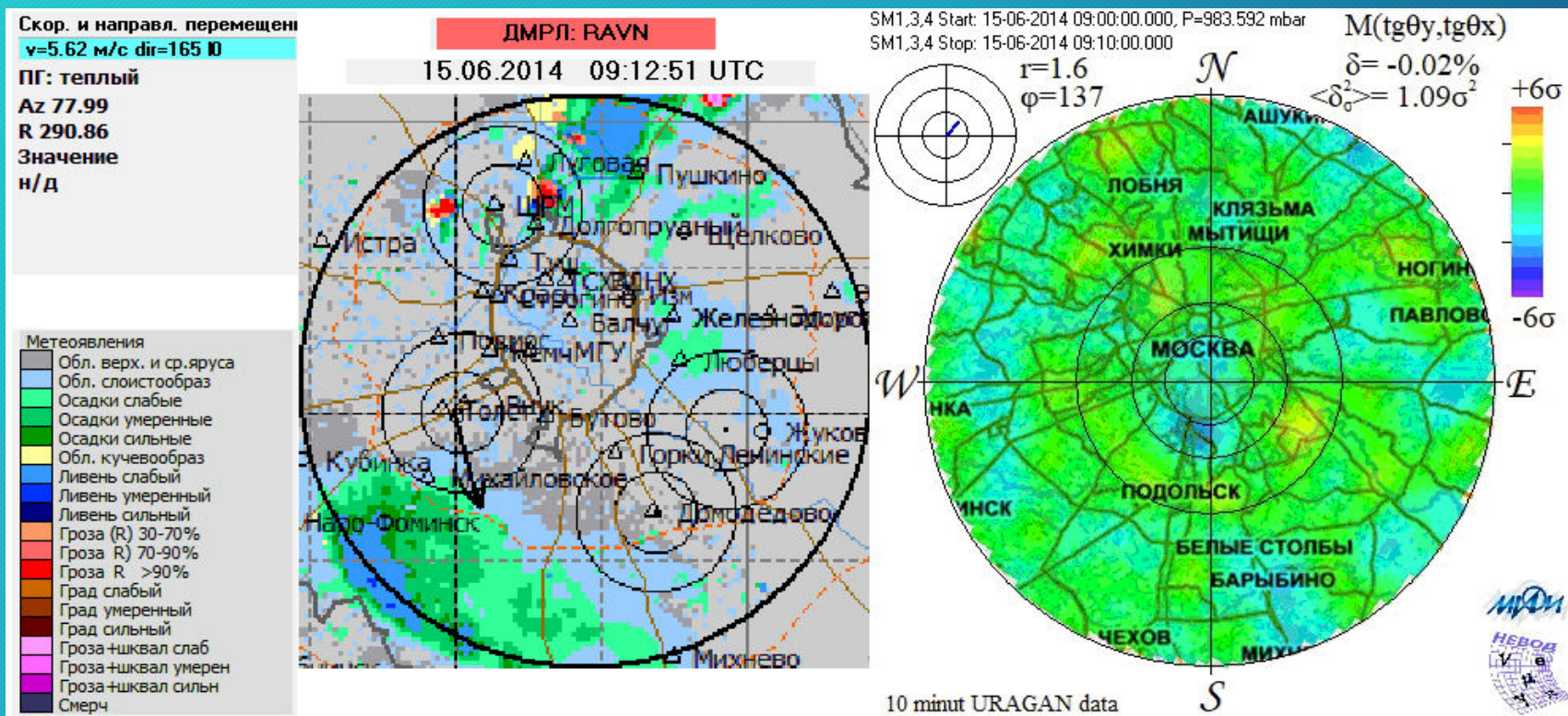
Visual comparison of muonographs and meteorological maps

15.06.2014 06:00 UTC - 09:00 UTC



Visual comparison of muonographs and meteorological maps

15.06.2014 09:00 UTC - 13:00 UTC



Visual comparison of muonographs and meteorological maps

27.06.2015 00:20 UTC - 07:00 UTC

Скор. и направл. перемещен

$v=13.5$ м/с $dir=5$ С

ПГ: теплый

Az 106.91

R 261.30

Значение

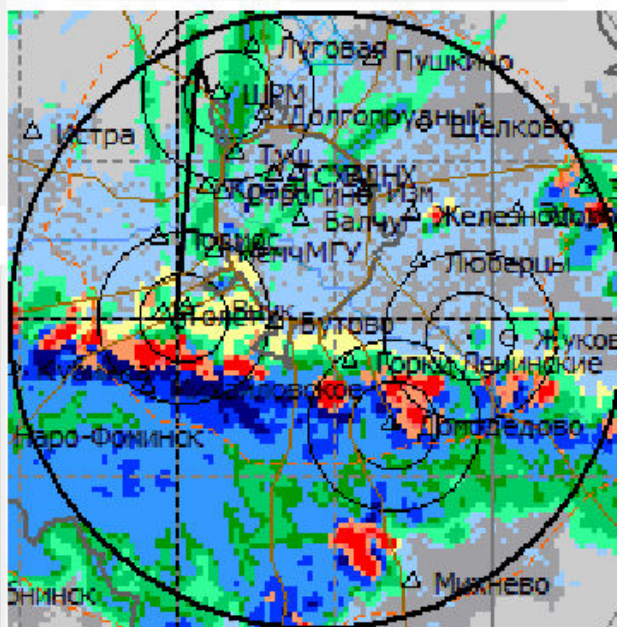
н/э

Метеоявления

- Обл. верх. и ср. яруса
- Обл. слоистообраз
- Осадки слабые
- Осадки умеренные
- Осадки сильные
- Обл. кучевообраз
- Ливень слабый
- Ливень умеренный
- Ливень сильный
- Гроза (R) 30-70%
- Гроза (R) 70-90%
- Гроза (R) >90%
- Град слабый
- Град умеренный
- Град сильный
- Гроза+шквал слаб
- Гроза+шквал умерен
- Гроза+шквал сильн
- Смерч

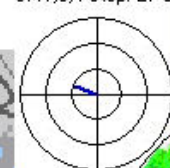
ДМРЛ: RAVN

27.06.2015 00:19:50 UTC



SM1,3,4 Start: 27-06-2015 00:10:00.000, P=985.534 mbar

SM1,3,4 Stop: 27-06-2015 00:20:00.000

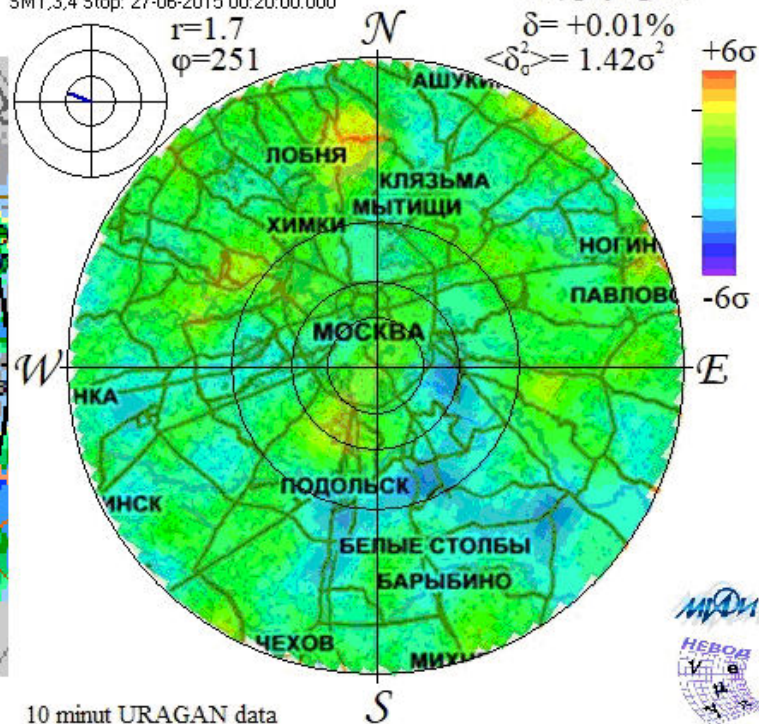


$r=1.7$
 $\phi=251$

$M(\text{tg}\theta_y, \text{tg}\theta_x)$

$\delta = +0.01\%$

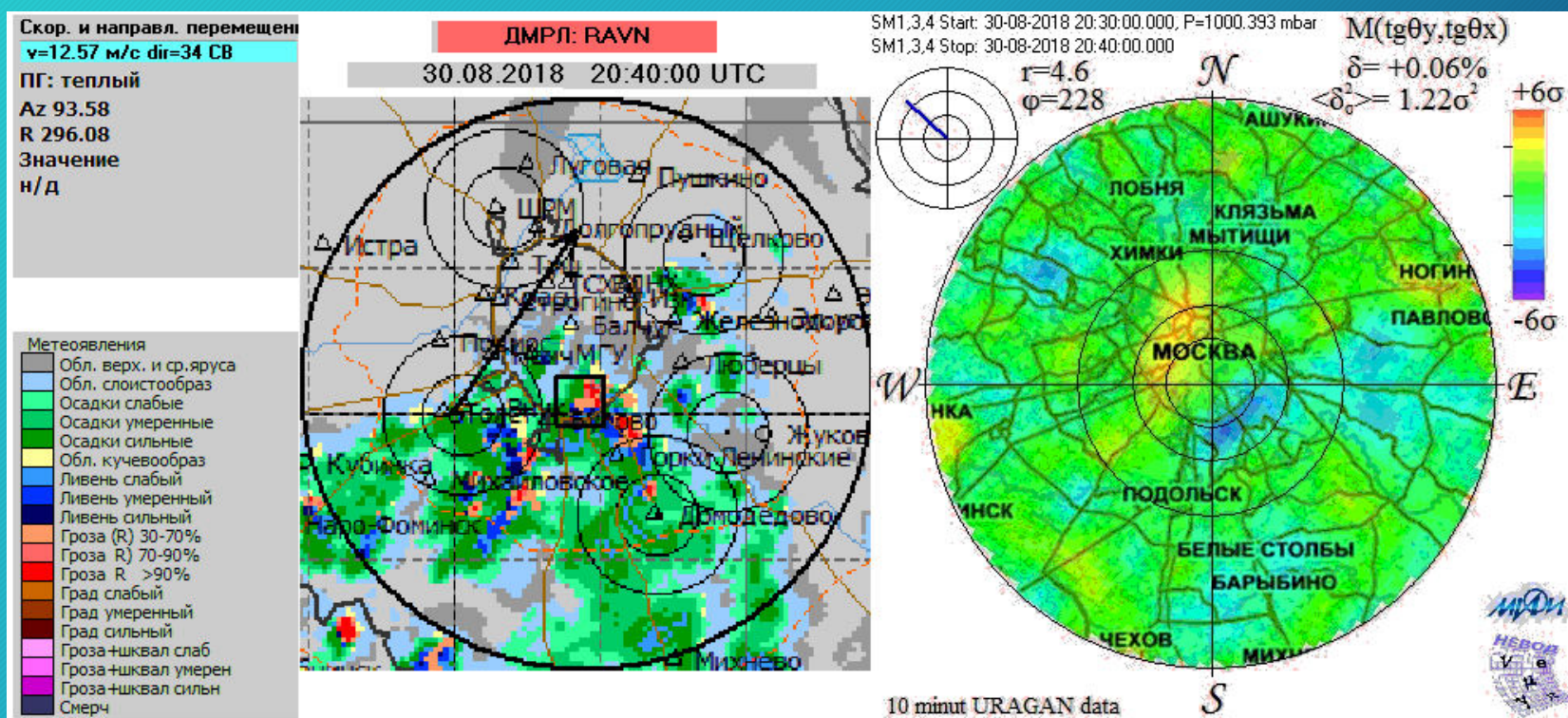
$\langle \delta^2 \rangle = 1.42\sigma^2$

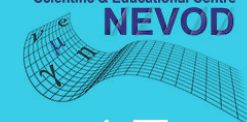


10 minut URAGAN data

Visual comparison of muonographs and meteorological maps

30.08.2018 20:10 UTC - 31.08.2019 05:10 UTC





Detailed visual comparison

30.08.2018 22:50

Скор. и направл. перемещен
 $v=13.04$ м/с dir=38 СВ
 ПГ: теплый
 Az 93.58
 R 296.08
 Значение
 н/д

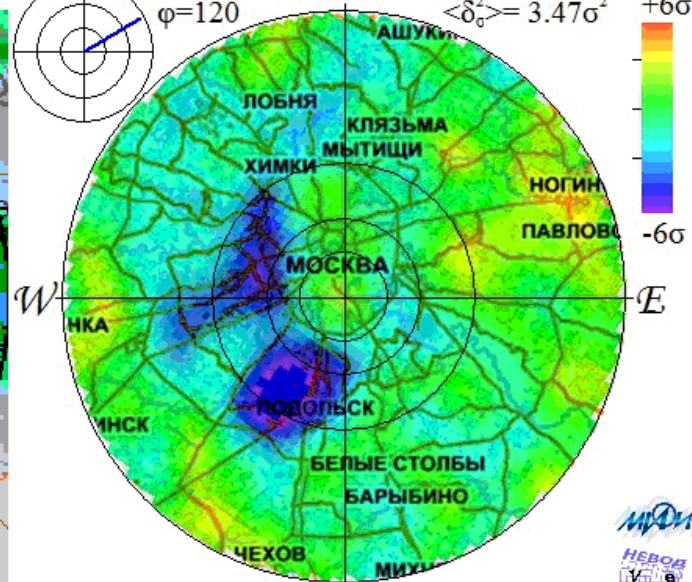
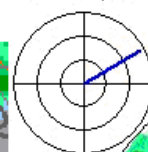
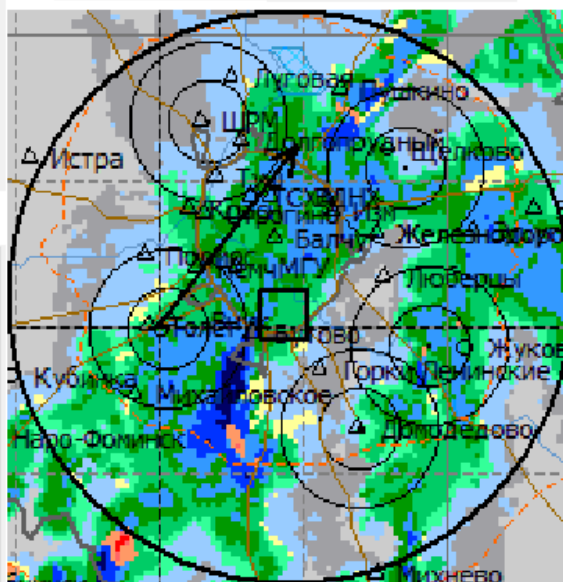
ДМРЛ: RAVN

30.08.2018 22:50:00 UTC

 SM1,3,4 Start: 30-08-2018 22:40:00.000, P=1000.552 mbar
 SM1,3,4 Stop: 30-08-2018 22:50:00.000

 $M(\text{tg}\theta_y, \text{tg}\theta_x)$
 $\delta = -0.31\%$
 $\langle \delta_\sigma^2 \rangle = 3.47\sigma^2$
 $r=5.6$
 $\varphi=120$

 +6 σ

 -6 σ


10 minut URAGAN data

S



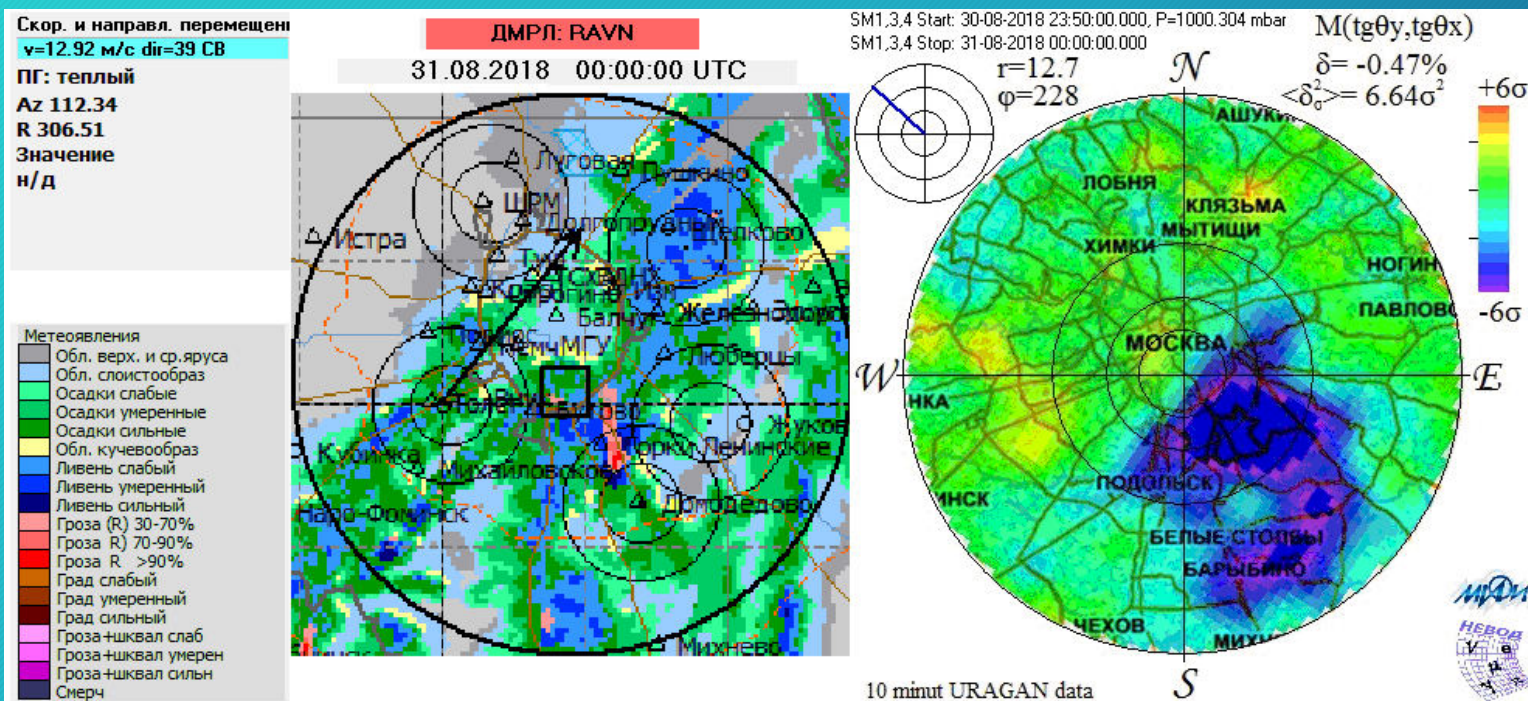
- Метеоявления
- Обл. верх. и ср.яруса
 - Обл. слоистообраз
 - Осадки слабые
 - Осадки умеренные
 - Осадки сильные
 - Обл. кучевообраз
 - Ливень слабый
 - Ливень умеренный
 - Ливень сильный
 - Гроза (R) 30-70%
 - Гроза (R) 70-90%
 - Гроза R >90%
 - Град слабый
 - Град умеренный
 - Град сильный
 - Гроза+шквал слаб
 - Гроза+шквал умерен
 - Гроза+шквал сильн
 - Смерч

It can be noted that shape and position of the shaded areas are similar to each other.



Detailed visual comparison

31.08.2018 00:00



It can be noted that shape and position of the shaded areas are similar to each other.



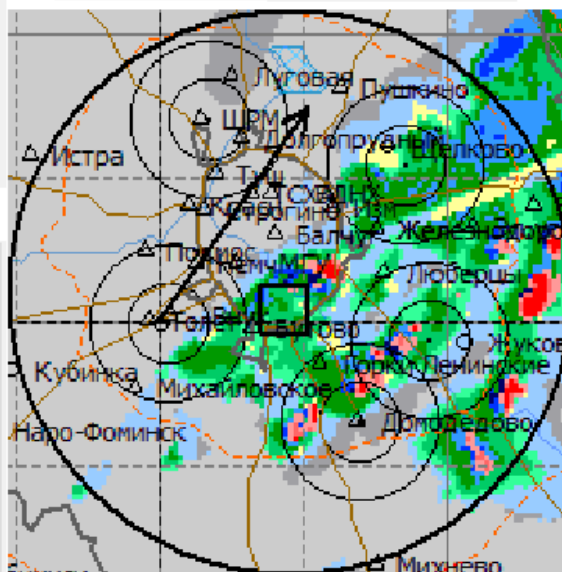
Detailed visual comparison

31.08.2018 05:00

Скор. и направл. перемещен
 $v=15.09$ м/с $dir=35$ СВ
 ПГ: теплый
 Az 83.92
 R 235.83
 Значение
 н/э

ДМРЛ: RAVN

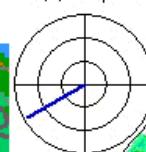
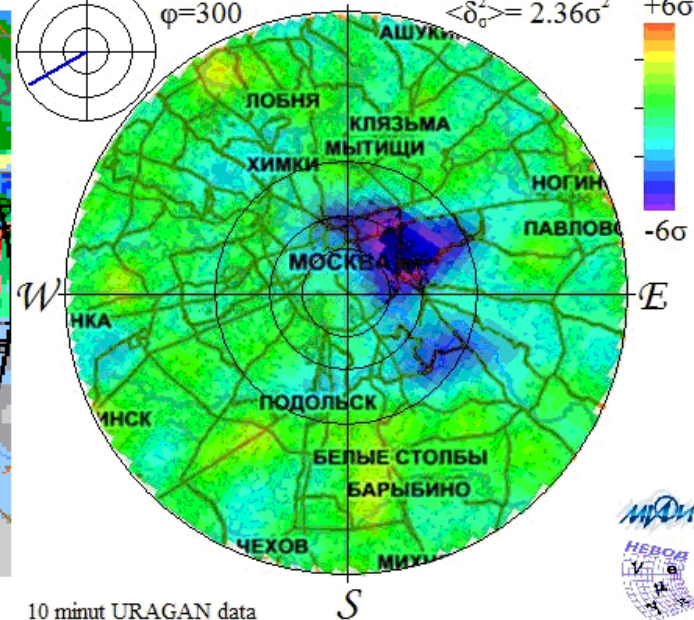
31.08.2018 05:00:00 UTC



- Метеоявления
- Обл. верх. и ср.яруса
 - Обл. слоистообраз
 - Осадки слабые
 - Осадки умеренные
 - Осадки сильные
 - Обл. кучевообраз
 - Ливень слабый
 - Ливень умеренный
 - Ливень сильный
 - Гроза (R) 30-70%
 - Гроза (R) 70-90%
 - Гроза R >90%
 - Град слабый
 - Град умеренный
 - Град сильный
 - Гроза+шквал слаб
 - Гроза+шквал умерен
 - Гроза+шквал сильн
 - Смерч

SM1,3,4 Start: 31-08-2018 04:50:00.000, P=1000.625 mbar

SM1,3,4 Stop: 31-08-2018 05:00:00.000

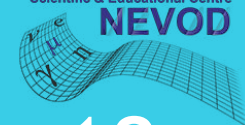
 $M(\text{tg}\theta_y, \text{tg}\theta_x)$
 $\delta = -0.41\%$
 $\langle \delta_\sigma^2 \rangle = 2.36\sigma^2$

 $r=5.7$
 $\phi=300$


10 minut URAGAN data

S

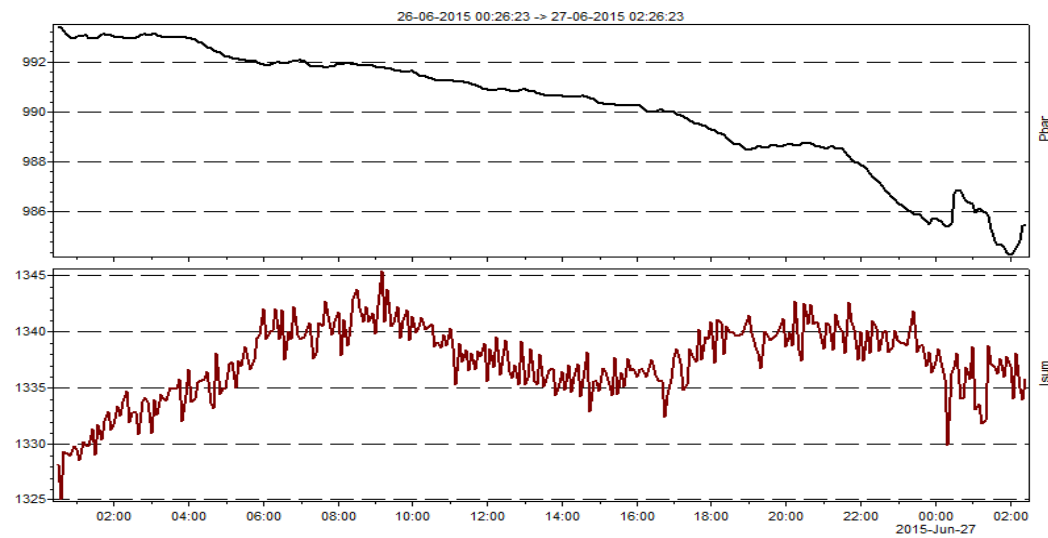
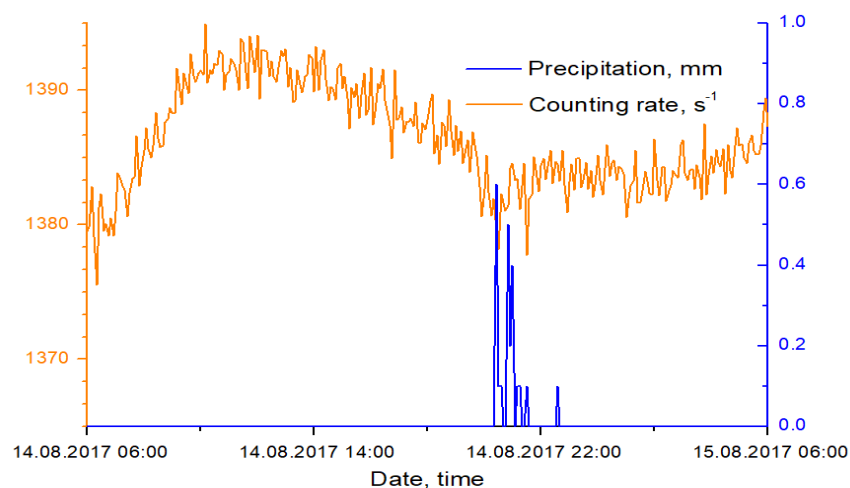
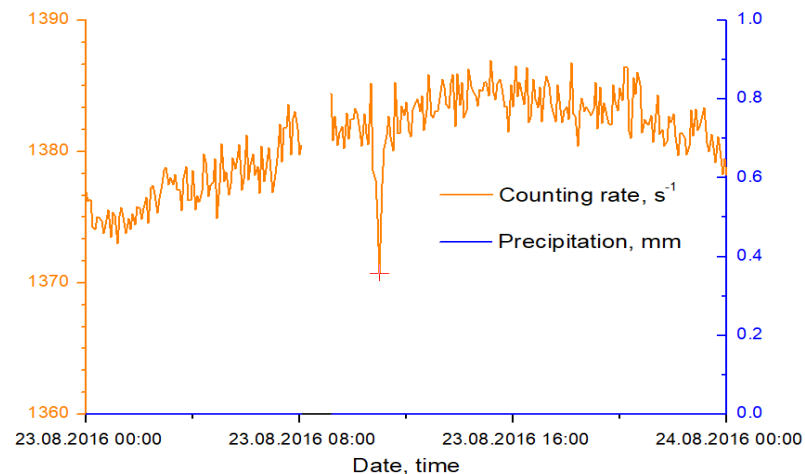


It can be noted that shape and position of the shaded areas are similar to each other.



Possible explanations of the effect

- pressure effect
- presence of a huge water mass in non-stationary state
- influence of the thundercloud electric field



- Results obtained from the analysis of data provided by MH URAGAN are consistent with DMRL-C data
- Characteristics of the muon flux provide a good reaction to the passage of a thunderstorm
- MH URAGAN can be used as thundercloud imaging tool
- Possible explanations for the sharp decrease of the muon flux in thunderstorm activity areas are pressure effect, presence of a huge water mass in non-stationary state and influence of the thundercloud electric field

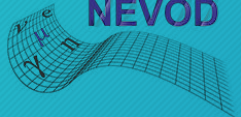
Conclusions

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Scientific & Educational Centre

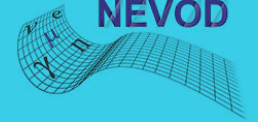
NEVOD

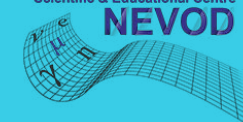


**Thank you for
your attention!**



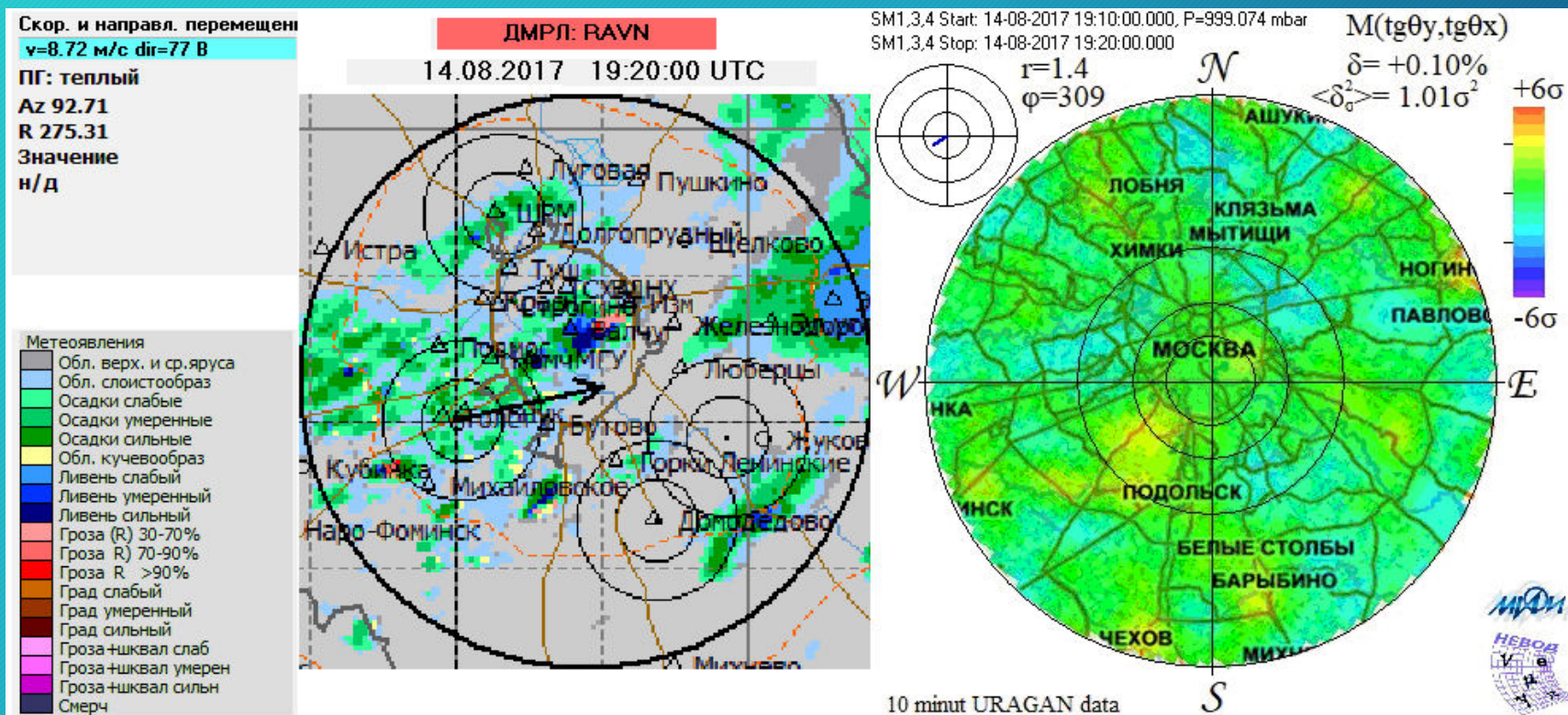
Scientific & Educational Centre
NEVOD





Other examples

14.08.2017 19:10 UTC - 23:50 UTC

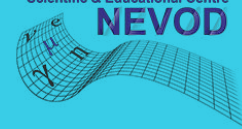


14.07.2018



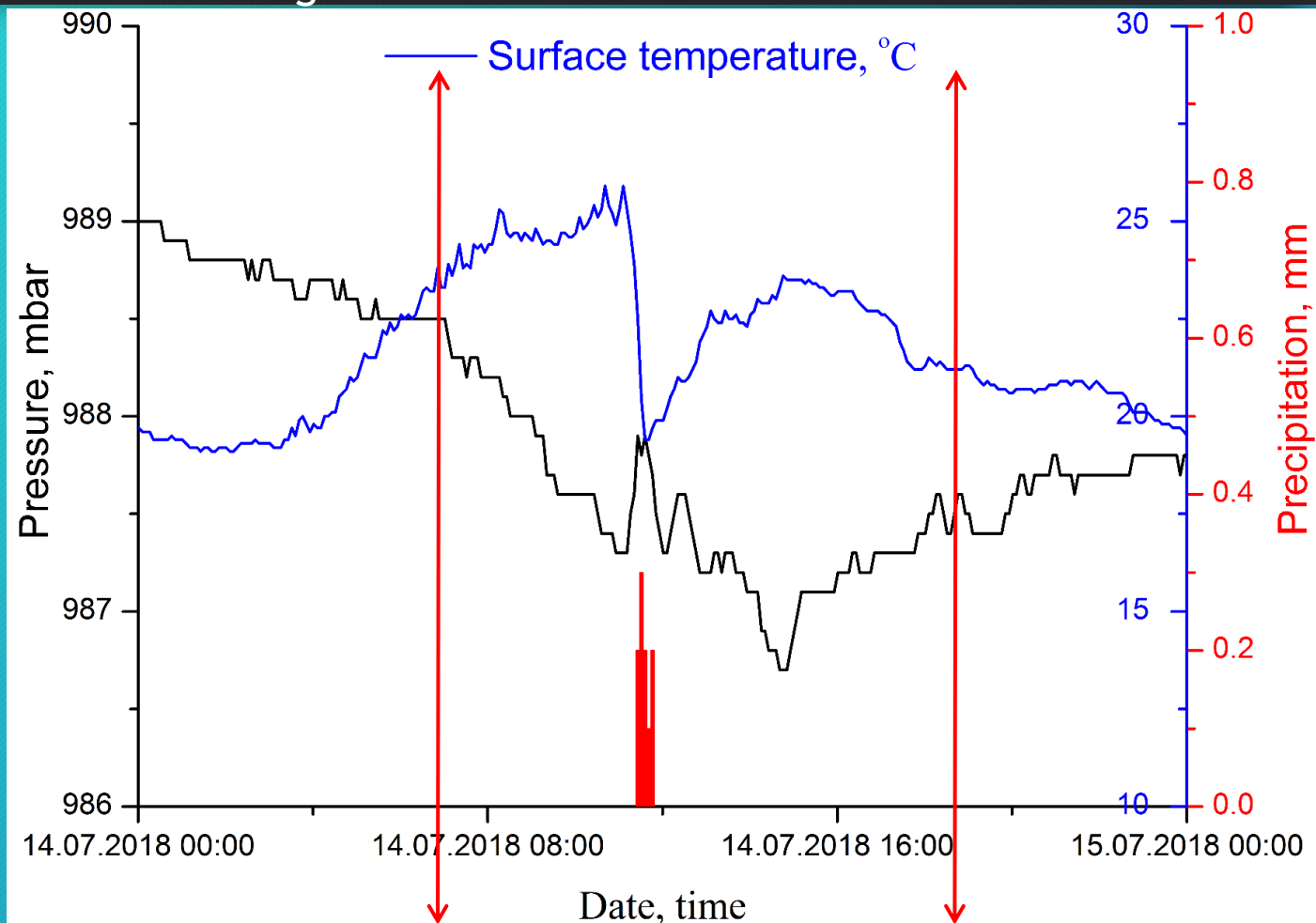
Scientific & Educational Centre

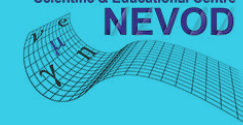
NEVOD



22

The thunderstorm was observed at the Domodedovo airport meteorological station at 14:00 (UTC time) and at the VDNKh meteorological station from 14:00 to 17:00





Comparison (11:30 - 13:10)

Скор. и направл. перемещени

$v=4.06$ м/с $dir=0$ С

ПГ: теплый

Az 69.89

R 314.15

Значение

н/д

ДМРЛ: RAVN

14.07.2018 12:10:00 UTC

SM1,3,4 Start: 14-07-2018 12:00:00.000, P=987.825 mbar

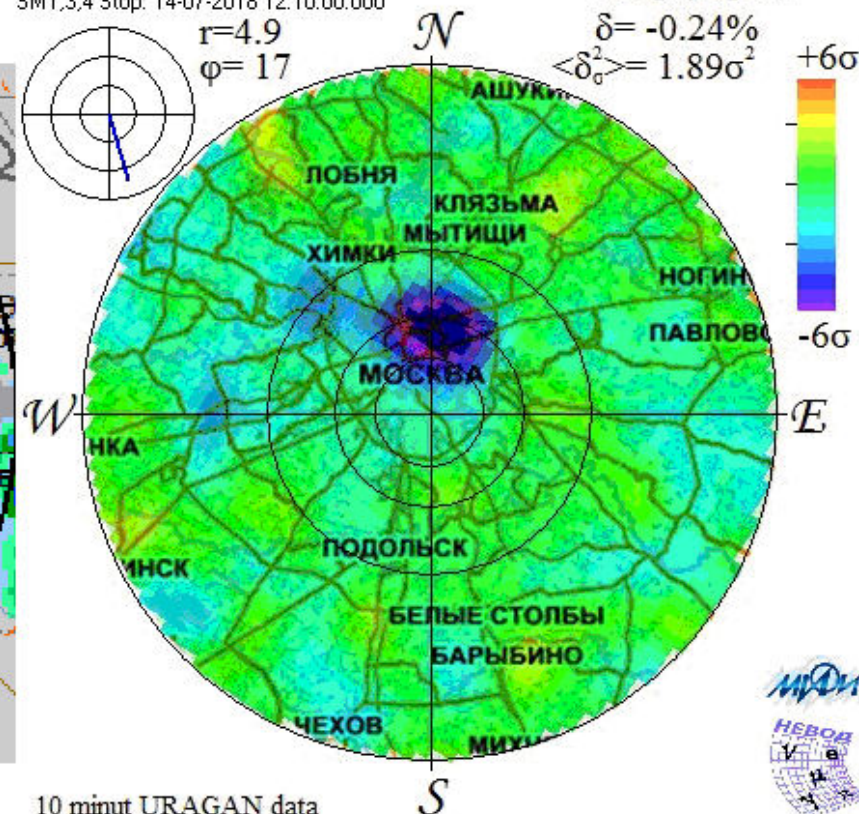
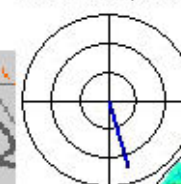
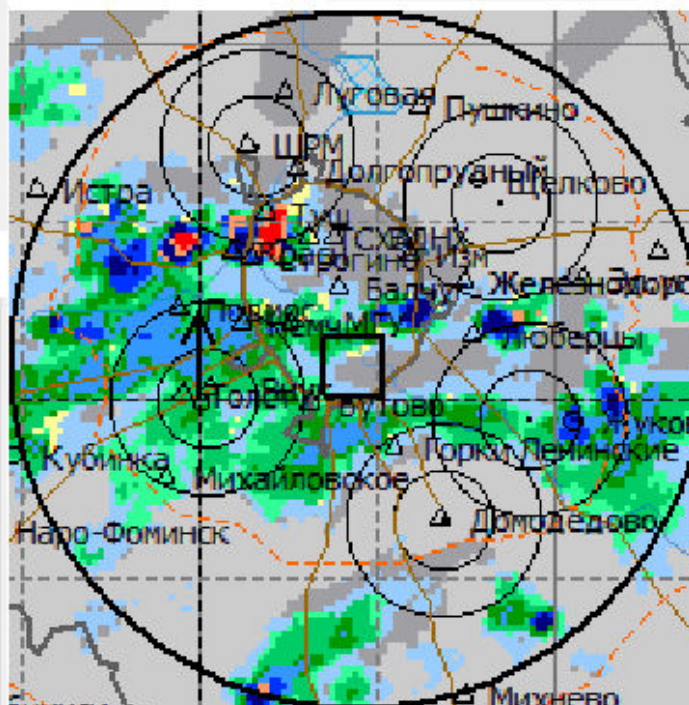
SM1,3,4 Stop: 14-07-2018 12:10:00.000

$M(tg\theta_y, tg\theta_x)$

$\delta = -0.24\%$

$\langle \delta_\sigma^2 \rangle = 1.89\sigma^2$

$r=4.9$
 $\phi=17$



10 minut URAGAN data



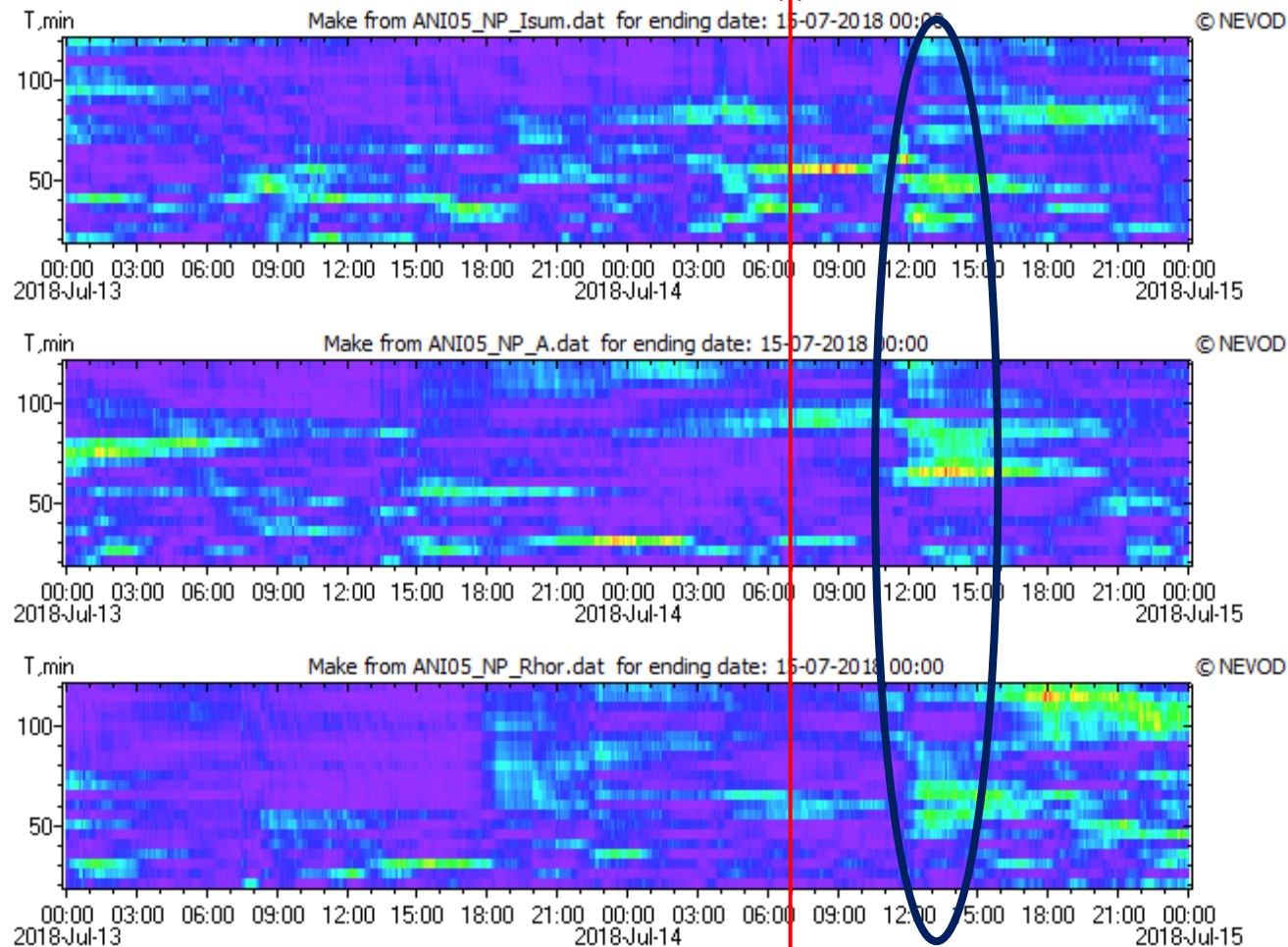
- Метеоявления
- Обл. верх. и ср. яруса
 - Обл. слоистообраз
 - Осадки слабые
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 - Град сильный
 - Гроза-шквал слаб
 - Гроза-шквал умерен
 - Гроза-шквал сильн
 - Смерч

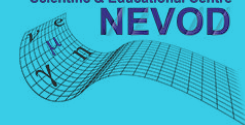
Wavelet analyses of URAGAN data

I_{sum}

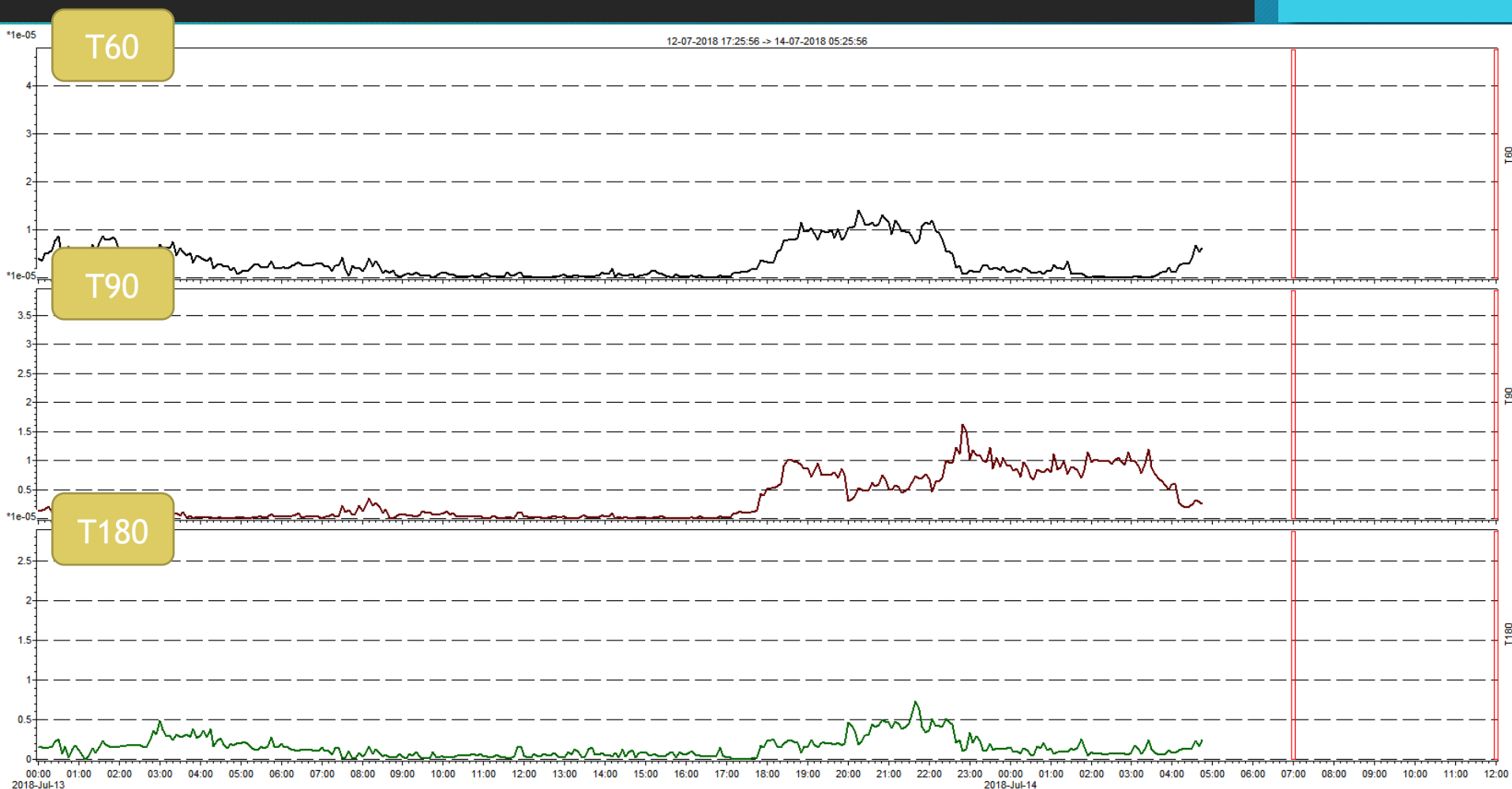
A

r_{hor}



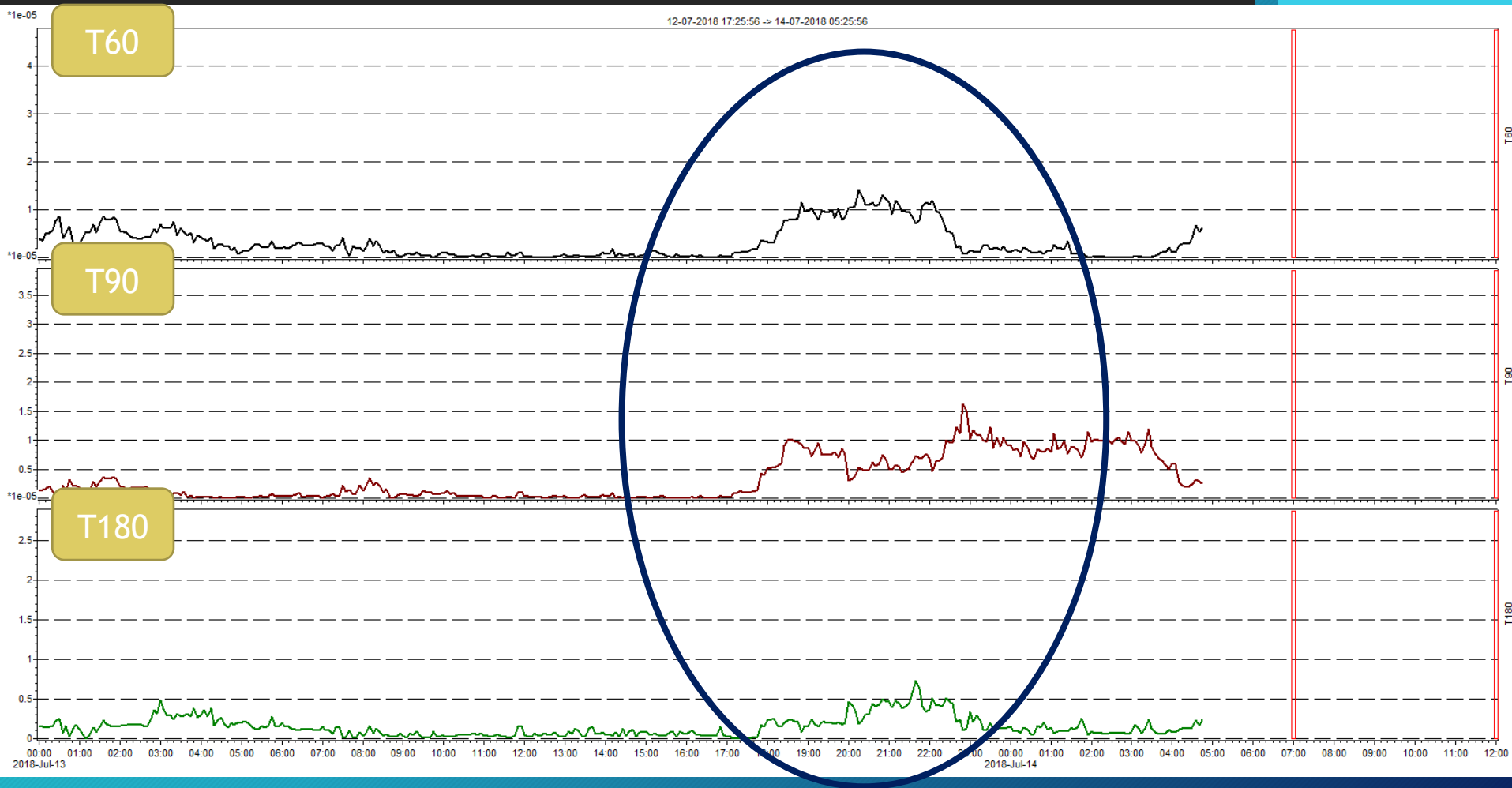


Wavelet analysis: r_{hor}

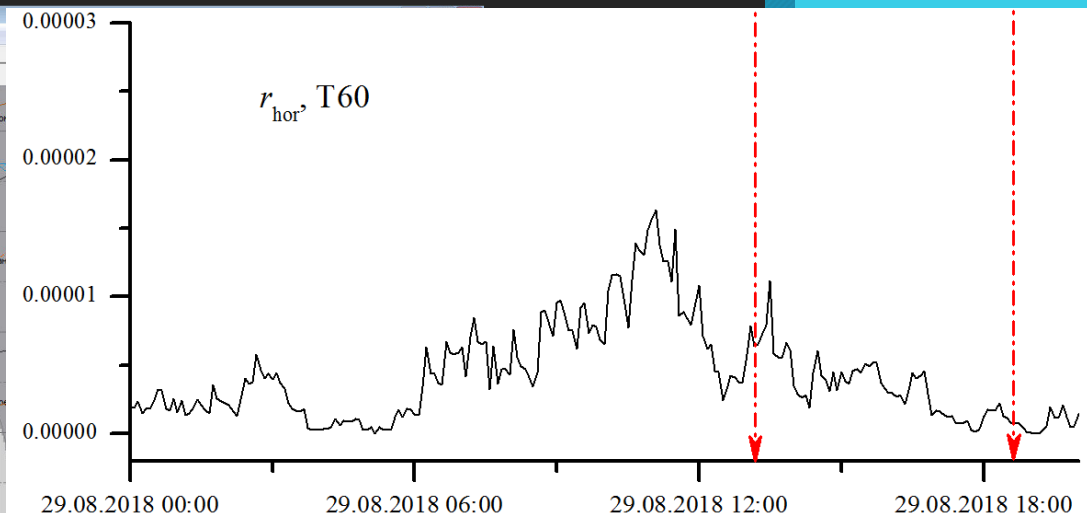
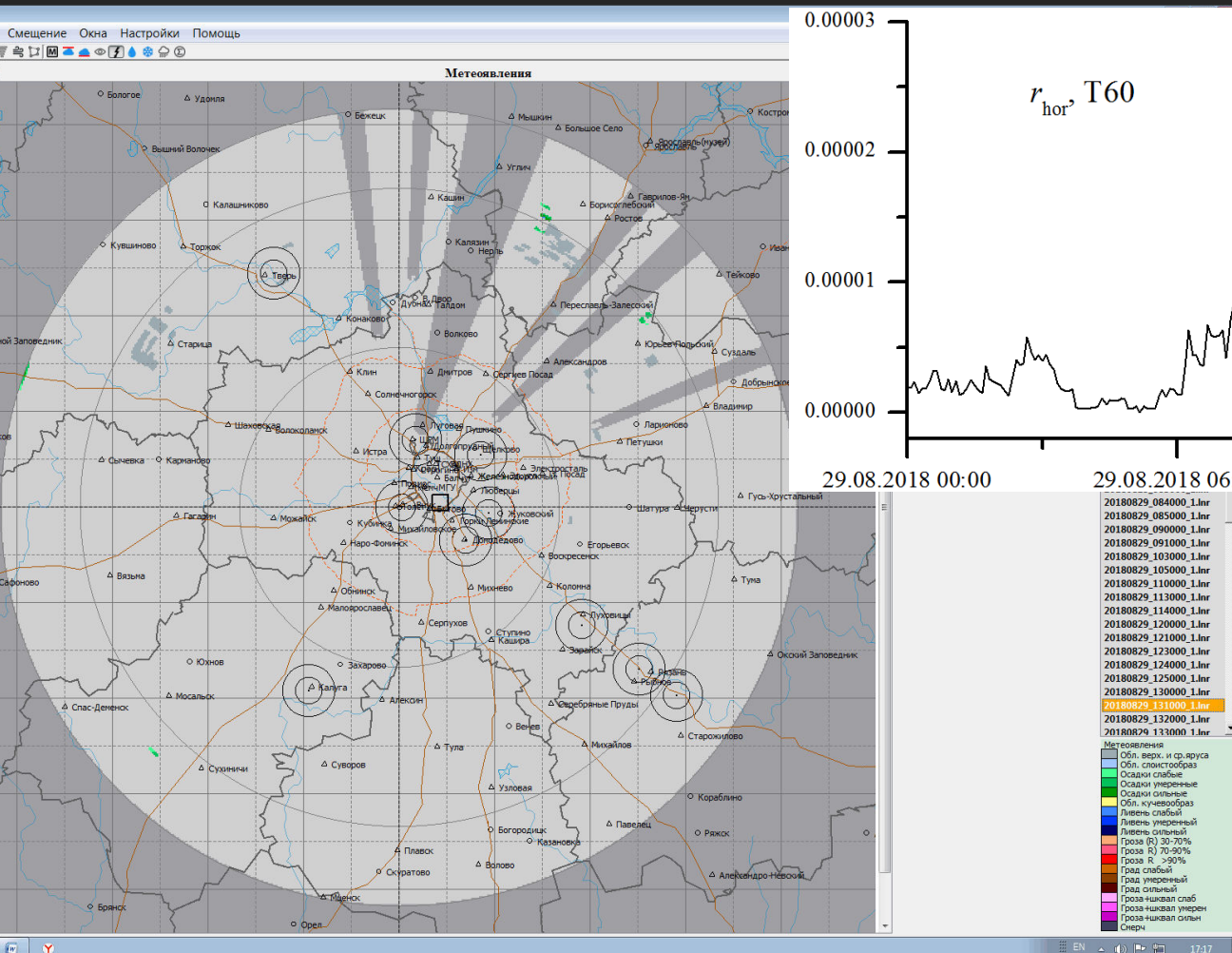




Wavelet analysis: r_{hor}



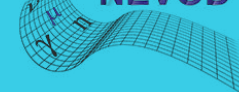
Thunderstorm activity outside the Moscow region, which is preceded by an increase in the power of the wavelet coefficient



20180829_084000_1.lnr
20180829_085000_1.lnr
20180829_090000_1.lnr
20180829_091000_1.lnr
20180829_103000_1.lnr
20180829_105000_1.lnr
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20180829_113000_1.lnr
20180829_114000_1.lnr
20180829_120000_1.lnr
20180829_121000_1.lnr
20180829_123000_1.lnr
20180829_124000_1.lnr
20180829_125000_1.lnr
20180829_130000_1.lnr
20180829_131000_1.lnr
20180829_132000_1.lnr
20180829_133000_1.lnr

Метеоявления
 Обла. верх. и ср. яруса
 Обла. слоистообраз.
 Осадки слабые
 Осадки умеренные
 Обла. кучевообраз.
 Ливень слабый
 Ливень умеренный
 Ливень сильный
 Гроза R < 30-70%
 Гроза R 70-90%
 Гроза R > 90%
 Град слабый
 Град умеренный
 Град сильный
 Гроза началась слаб
 Гроза началась умерен
 Гроза началась сильно
 Смерч

**29.08.2018
13:10 - 18:40**



Distant thunderstorms are most often preceded by the following periods of wave disturbances:

I_{sum} : 110-120 and 210 minutes.

A: 115, 150, 280, 290, 310 and 320 minutes.

I_{hor} : 100-115 minutes.

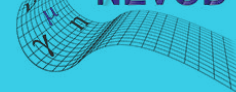
Simultaneously with distant thunderstorms, the following periods of wave processes most often appear:

I_{sum} : 115-120 and 170 minutes;

A: 160 and 310 minutes;

I_{hor} : 115 minutes.

- Wavelet analysis of different time series shows that before and during the passage of a thunderstorm there are periodic disturbances in the characteristics of the muon flux. Periods of those disturbances are ranging from 60 up to 320 minutes



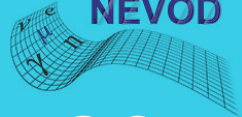
- Obtained data demonstrate the possibility of using wavelet analysis of time series of muon flux characteristics as a tool for detecting or predicting thunderstorms.
- Those results can be used as a basis for the development of methods for the early detection of thunderstorm events by methods of muon diagnostics; they can also be used to exclude atmospheric effects in the study of outer space, the state of the magnetosphere and the heliosphere.

Muon diagnostics



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- Formation of the muon flux: in the atmosphere at an altitude of 10 - 20 km
- The top of a typical thunderstorm cell: at a height of 8 - 12 km

The muon flux is modulated by changes in the basic thermodynamic parameters of the atmosphere.

$$\frac{\Delta N_{\mu}}{N_{\mu}} = \beta_p \Delta p + \beta_T \Delta T$$

The greater the pressure, the greater muons absorption (due to an increase the amount of substance)

The higher the temperature, the:

- higher pion generation point
- longer geometric path of the muon to the surface of the Earth
- higher probability of decay

