Numerical simulation of intense precipitation in Moscow region: a case study of a heavy rainfall event on June 30, 2017

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Abstract: This paper considers physical and synoptic mechanisms of an extreme rainfall on June 30, 2017 in the central part of European Russia, which was the maximum of daily precipitation sum in Moscow (65 mm) since 1970. Based on meteorological observations, radar data, and ERA5 reanalysis data, we show that the rainfall was associated with three mesoscale convective systems (MCSs) that formed in the warm sector of a cyclone in a strip of anomalously high moisture content in the considered region, which developed further due to advection and evaporation. A numerical simulation with mesoscale model COSMO shows a significant contribution to the precipitation intensity of evaporation from the Earth's surface: a 10-times decrease in soil the moisture in the initial conditions leads to a 3-times decrease in the amount of precipitation and its intensity. Additionally, we consider urban-induced effects on this rainfall event by switching on and off urban parametrization TERRA_URB. The application of the urban surface parametrization has not changed the average amount of precipitation in Moscow region. It causes, however, a redistribution of precipitation sums within it.

1. Introduction

An observable climate change and increase in the mean temperature in the troposphere [1] lead to increase in the atmospheric water vapor content [2,3] and decrease in static stability [4], which together may cause higher frequency of extreme weather phenomena associated with deep convection [5,6].

Deep convection phenomena (e.g. single convective cells, squall lines, mesoscale convective complexes) are hardly predicted nowadays due to their small spatial and temporal scale (the size of an individual convective cell is up to 10 km, and the lifetime is up to 1 hour [7]) as well as the
2. Data and methods

2.1. Atmospheric observations

For the most complete understanding of the atmospheric processes over Moscow region on June 30, we analyzed different data sources, including the data of available atmospheric observations in Moscow region: atmospheric sounding data from the University of Wyoming [http://weather.uwyo.edu] and IGRA [11] archives; observations at Roshydromet weather stations at standard 3-hourly intervals and 1-minute resolution data from the automatic weather station (AWS) of Moscow State University, which made possible high resolution analysis of meteorological parameters near the earth's surface during the passage of MCSs for determining the stages of their evolution.

The remote measurements included an archive of radar data provided by the Central Aerological Observatory, Dolgoprudny. These data are the main source of information for identifying the type of convective systems and observing their dynamics due to the appropriate temporal resolution (10 minutes). Areas of intense convective precipitation on radar maps were determined by the intensity and shape of the radar echoes [12]: convective cells had values of reflectivity of more than 40-45 dB; areas with a reflectivity of more than 56-60 dB have been determined as intense hail cells [13].

2.2. Methodology and data for assessing the balance of water vapor in the atmosphere

The water vapor balance equation for a tropospheric column in discrete form was derived from the integral equation of moisture transfer according to [14] for Moscow region (54–57° N, 35–40° E, Figure 1). The upper boundary height was 0.01 hPa [15]. This equation represents the most important processes that defines changes in the atmospheric water vapor content.

Using discrete analogs of two-dimensional and three-dimensional integrals for the volume of the troposphere in a given latitude-longitude region, it can be represented as follows:

\[
M^t + \Delta t - M^t = \left[ F_{x0} - F_{x1} + F_{y0} - F_{y1} \right] \Delta t + E^t \Delta t + R^t \Delta t
\]

(1)

where \( M \), \( E \), and \( R \) are the integrated values of the total column water vapor, vertical turbulent flux of water vapor from the surface, a source function; \( F_x \) and \( F_y \) are the water vapor fluxes through the boundaries of the considered volume (subscripts 0 and 1 denote fluxes through the western and eastern, southern and northern boundaries, respectively); \( \Delta t \) is the time step, and time \( t \) is the
beginning of the time interval (in this work, this is the step of reanalysis data). Herewith, \( F_i = \frac{1}{2}(F_i^{t+\Delta t} + F_i^t), i = x0, x1, y0, y1 \), i.e. streams are calculated as averages over the interval \([t, t + \Delta t]\), and the source function

\[
R = \iiint (-r - \frac{\partial(W_l + W_e)}{\partial t}) \, dx \, dy \, dz
\]  

(2)

is determined by the intensity of precipitation \( r \) and the evolution of the cloud liquid and ice water content \( W_l \) and \( W_e \).

2.3. Numerical experiments with the COSMO model

For a more detailed study of the formation mechanisms of extreme precipitation in the case being considered, series of numerical experiments with the COSMO 5.05urb [16] model were performed. ERA5 reanalysis [15] was used as the initial and boundary conditions for the model. The model domain covered the central part of European Russia (Figure 1), the entire region of formation and passage of MCSs on June, 30. The grid step was 3 km, which is acceptable for convection-permitting simulations [17] and, in particular, allows one to reproduce realistic maxima of precipitation [18]. Downscaling of the ERA5 reanalysis with a grid step of 31 km (0.25°) was performed directly onto a 3-km (0.027°) grid of the model domain (Table 1). The downscaling factor, thus, has a value of 10, which is less than 17, the COSMO-CLM [https://tools.clm-community.eu/] community’s recommended value [19].

![Figure 1. Spatial location of the domain used for numerical experiments with the COSMO 5.05urb model.](image)

The surface height above sea level (in meters) is shown according to the color scale. The inner grey rectangle marks the area for calculating the moisture balance components. The red star shows the location of Moscow.

| Table 1. Basic settings of the COSMO 5.05urb model used in all experiments in this work. |
|-----------------------------------------------|
| (a) Lateral boundary conditions |                      |
| Data source | ERA5 reanalysis |
| Base model resolution | Area 31 km (0.25°) |
| Updating of lateral boundary conditions | 1 hour |
| (b) Model domain settings | |
| North Pole in rotated coordinate system | lon -142.5, lat 34.3 (Moscow) |
| Model grid resolution | 3 km (0.027°) |
| Number of horizontal grids | 500 x 500 |
| Number of vertical model levels (total) | 50 |
| Number of vertical model levels (in the boundary layer 1.5 km) | 14 |
| Number of levels in soil | 7 |
| (c) COSMO 5.05urb settings | |
| Soil model | TERRA_ML |
| Urban parametrization | TERRA_URB (on and off) |
Deep convection parametrization | off
---|---
Shallow convection parametrization | Tiedke
A time step of the simulation process | 40 seconds
A time step of the output data | 1 hour

The effect of a decrease in soil moisture by a factor of 10 in a depth of 1.65 m in the initial conditions (DRY_*) experiments and switching on the urban parameterization TERRA_URB [20] (*_URB experiments) on the amount of precipitation and the structure of convective systems was investigated in four series of experiments (REF_NOURB, DRY_NOURB, REF_URB, DRY_URB). Each series included 11 model runs with different initialization time (50 – 60 hours before the beginning of the analyzed period at 0:00 UTC on 30.06.17), which allows one to minimize stochastic disturbance effects. In further analysis we consider the means over all 11 runs for each series. Series with the initial soil moisture and with the disabled TERRA_URB parameterization (REF_NOURB) were chosen as the reference series. All model experiments were run on the “Lomonosov-2” supercomputer complex of Moscow State University [21].

3. Results

3.1. Synoptic conditions and mesoscale structure of the MCSs

During 9:00 – 19:00 UTC on June 30 three convective systems were observed over Moscow region. Two of them were classified as squall lines (according to specific criteria: the aspect ratio should be greater than 5 [22]) of the meso-γ scale (up to 500 km along the major axis) according to the Orlansky scale classification [23], denoted by numbers 1 and 3 in Figure 2. Number 2 in Figure 2 is a meso-β scale convective system (60 km along the major axis) [24].

![Figure 2](image-url)

Figure 2. (a) Maximum value of radar reflectivity in the atmospheric column (dB) according to data of the Central Aerological Observatory at 12:00, 15:30, and 18:00 UTC. (b) Main surface meteorological values according to data of the AWS of Moscow State University for June 30, 2017. (1), (3) linear convective systems of meso-α scale (squall lines), (2) meso-β scale MCS.
All three MCSs were accompanied by a specific local pressure extremum [25] and a slight increase in the wind speed with a changing direction (Figure 2b). A noticeable decrease in the temperature (10 °C per 30 minutes) and a corresponding increase in the relative humidity in the surface layer up to 100% were observed only during the passage of the first squall line.

All convective systems caused precipitation of varying intensity (up to 7 mm per 10 minutes). According to the data of Moscow State University, the maximum contribution to the daily amount of precipitation (25 mm) was from the first squall line (53%); the meso-β scale MCS determined 31% of the total amount of precipitation, and the second squall line, only 15%. The possibility of such evaluation was determined by the access to detailed meteorological data with high temporal resolution (1 minute) available from the AMS of Moscow State University only. The maximum value of daily precipitation amount according to another meteorological station in Moscow (the VVC weather station) was 65 mm. This value was 87% of the monthly precipitation climatic norm for June in Moscow (75 mm [26]). Based on the data for other stations in Moscow region, high spatial heterogeneity of the total precipitation amount was noted, which is typical for convective precipitation.

The first squall line observed on June 30 was most intense among the observed MCSs not only in the precipitation intensity, but also in the radar reflectivity value. During its passage over Moscow, reflectivity centers of more than 60 dB were observed (Figure 2a). The maximum value of radar echo (which indicates convective clouds’ top) was 13 km, whereas the tropopause height was nearly 12 (according to sounding data at 12:00 UTC for the Ryazan and Sukhinichi aerological stations). These values satisfy the likelihood criteria of squalls and large hail [13] and indicate an exceptional intensity of convective phenomena compared to the average seasonal (up to 30 dB; 8-9 km) and some extreme (more than 31 dB; 11.6 km) values of radar reflectivity and cloud top for summer [27,28]. The lifetime of the first squall line was also significant: it reached more than 1.5 days which, however, is acceptable for deep convection systems and is described by Veltishchev [24] as a very typical phenomenon.

All MCSs observed on June 30, 2017 arose in the warm sector of the Atlantic cyclone under the impact of the most favorable factors for deep convection occurrence [7]: convective available potential energy (MLCAPE [29]) up to 1300 J/kg; a 0 – 6 km deep-layer wind shear (DLS [30]) up to 20 m/s, and an extremely high total column water vapor content for Moscow region of 41.5 kg/m². This value exceeds the 0.995 percentile in the sounding data from Dolgoprudny for the summer seasons of 1957 – 2018. The area of high water vapor content values was a submeridionally elongated structure, a so-called atmospheric river [31], usually associated with extreme precipitation cases all over the world [32-34].

3.2. A water vapour balance structure of June, 30 2017 over Russia’s central part
Based on an analysis of the components of equation (1) obtained from the ERA5 data, it was shown that advection played a significant role in the increase in the water vapor content over the considered region: an advection term of (1) in the period from 5:00 to 17:00 UTC on June 30 had a positive sign (Figure 3). Also, the daytime evaporation from the earth’s surface made a noticeable contribution to the change in the total moisture content. An accumulated evaporation value for 6:00 – 12:00 UTC amounted 3 kg/m², which represents up to 86% of the average daily evaporation in the third-fourth decade the summer period in the European territory of Russia [35]. The processes of evaporation and condensation in the clouds did not have such a significant contribution.

Both advection and evaporation led to an increase in the atmospheric moisture content over Moscow region to 41.5 kg/m² by 14:00 UTC. In combination with favorable thermodynamic atmospheric conditions, this led to the occurrence and intensification of mesoscale convective systems, which determined the extreme daily precipitation amount.

The precipitation observed in the period from 12:00 to 19:00 UTC led to a decrease in the atmospheric water vapor content (Figure 3). The decreased advection of water vapor after 13:00, a
nocturnal decrease in the evaporation from the surface, and static instability also contributed to weakening of the MCSs and the beginning of their dissipation.

![Components of water vapor balance equation](image)

**Figure 3.** Components of the water vapor balance equation (kg/h) for June 30 - July 1, 2017 (time - UTC) according to ERA5 reanalysis data. (1) Change in integral moisture content, (2) change in water vapor content due to advection, (3) change in the water vapor content due to evaporation, (4) a change in the content of cloudy particles - liquid and solid, (5) moisture removal by precipitation.

3.3. Numerical simulation of intense precipitation and assessment of its sensitivity to external factors

3.3.1. Estimation of MCSs and precipitation accuracy in the model. Generally, the COSMO model reproduced the dynamics and structure of the squall lines and the precipitation extremum (64 mm in the model output data) with a good accuracy in the intensity value, but worse in the spatial arrangement. The precipitation maximum in the model output data was observed in the southeast of Moscow region, whereas the observed maximum was in the central part of Moscow. Both convective systems in the model passed over Moscow with some delay relative to the observed ones: up to 1 – 3 hours later. Moreover, only the first squall line in the model (number 1 in Figure 4a) had a quasilinear structure and was accompanied by a pronounced extremum of precipitation. The second squall line (number 3 in Figure 4a) looked like chaotically scattered convective cells, with less precipitation intensity than was observed in reality. The meso-β scale MCS was not reproduced by the model.

3.3.2. Influence of changes in soil moisture on convective systems. A tenfold decrease in the soil moisture in the initial data (ERA5 reanalysis) led to a noticeably lower moisture value at the time when MCSs were observed over Moscow region. Thus, in the DRY-* experiments series the average soil surface (1 cm) moisture at 12:00 UTC on June 30 within Moscow region was 0.43 kg/m². Such a noticeable decrease led to a significant change in the intensity and structure of the reflectivity and precipitation fields in all experiments of the DRY-series.

In the reflectivity field at 15:00 UTC, the first convective system in the DRY-series had a wider convection zone than in the REF-series and in reality (more than 100 km, Figure 4a-c) and a slightly lower intensity: the maximum radar reflectivity value in Moscow region was up to 61 dB (in the basic series – 64 dB, Figure 4b,c). Also, in the DRY-series there was no organized convective line, but only separated convective cells in the area of 100-km width.

The soil moisture change also gave a strong response in the precipitation field at 15:00 UTC. During the period with the highest precipitation intensity in the REF-series at 15:00 UTC (36 mm/h, Figure 4d-e) over Moscow region, in the experiments of the DRY-series only isolated areas of low precipitation intensity (up to 13 mm/h, Figure 4f) were observed. Thus, the REF and DRY experiments differed in the precipitation intensity almost in 3 times (Figure 4e,f).
Figure 4. (a-c) Radar reflectivity in the central part of Russia at 15:00 UTC: (a) according to radar data, (b) averaged over all experiments of REF_NOURB-series, (c) averaged over all experiments of DRY_NOURB-series. (d-f) Precipitation intensity: (d) according to radar data, (e) averaged over all experiments of REF_NOURB-series, (f) averaged over all experiments of DRY_NOURB-series. (g-h) Atmospheric water vapor content averaged over all experiments of: (g) REF_NOURB-series, (h) DRY_NOURB-series. (i-j) Difference in daily precipitation amount in experiments: URB minus NOURB averaged over all experiments of: (i) REF-series, (j) DRY-series. The purple arrow indicates the movement direction of MCSs. (1,3) squall lines, (2) meso-β scale MCS.
Such a significant effect of changes in the soil moisture on convective systems was obviously determined by the lower evaporation value from the earth's surface. The average value of evaporated water vapor for the DRY-series on the area of Moscow region during 6 hours (6:00 – 12:00 UTC) was only 0.05 kg/m², whereas the values obtained in the REF-series reached 2.65 kg/m², which agreed well with the evaporation amount obtained from the reanalysis data (3.0 kg/m²) and considered in Section 3.2.

According to the water vapor balance equation (1), a decrease in the total evaporation determines a decrease in the integral moisture content of the atmosphere. For Moscow region, the average value of water vapor content in the DRY-series was 3 kg/m² less than in the REF-series and amounted to 34 kg/m² (Figure 4g,h). Also, the spatial structure of the water vapor content field differed: in the DRY-series, a narrower area of high moisture content value was observed.

3.3.3. Influence of urbanized surface on convective systems. It was shown that the fields of radar reflectivity and precipitation did not differ significantly between the URB and NOURB series of the experiments. Thus, the urban precipitation anomaly (the difference in the precipitation value between the URB and NOURB series) was characterized by significant inhomogeneity associated with the stochastic arrangement of convective cells in the model. However, the positive precipitation anomaly observed from the leeward side of Moscow is traced in both (REF and DRY) differences of the series (Figure 4i,j) which, probably, might be caused by the influence of the urban environment, and is of interest for further study.

4. Conclusions
On June 30, 2017, a region of extremely high tropospheric moisture content was observed over the central part of Russia, in the warm sector of an Atlantic cyclone. Under a significant wind shear and moderate convective instability of the atmosphere, it led to the occurrence of three intense mesoscale convective systems (MCSs) that caused extreme amounts of precipitation.

In surface observations, all three convective systems are expressed with varying intensity but in the same way: surface pressure extrema, changes in wind speed and direction, and temperature decreases are clearly observed. The greatest contribution to daily precipitation was caused by the first squall line and the MCS of meso-β scale.

An analysis of the tropospheric water vapor balance equation according to ERA5 reanalysis data has revealed that the change in the vertically integrated moisture content on June 30 was mainly determined by water vapor advection. In addition, an important factor in the water vapor budget is intense evaporation from the Earth's surface, which has been confirmed by numerical experiments with mesoscale non-hydrostatic model COSMO 5.05urb with a grid step of 3 km. A significant decrease in the initial soil moisture led to a noticeable decrease in the atmospheric moisture content, which was the reason for a reduction in the precipitation and the formation of a more fragmented structure of the convective system. In general, when comparing the radar data and the numerical simulation data, it has been shown that the model reproduces well the dynamics and structure of the squall lines as well as the daily precipitation maximum. However, the precipitation extrema in the model have shifted locations compared to the observational data: the global maximum is not in the center of Moscow, but in the southeast of Moscow region.

Switching on urban parametrization TERRA_URB has not significantly changed the average amount of precipitation in Moscow region. However, it caused a redistribution of precipitation within it and, partially, an increase in precipitation from the leeward side of the city.

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