Verification of numerical modeling of atmospheric dynamics using the measurements of radar reflectivity

E Svechnikova1,2,*, N Ilin1, E Mareev1,2, S Hovakimyan3

1Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS), Nizhny Novgorod, Russia
2Lobachevsky State University, Nizhny Novgorod, Russia
3SNCO «Hydrometeorology and monitoring center» of the Ministry of Environment of RA, Erevan, Armenia

*E-mail: svechnikova@ipfran.ru

Abstract. Numerical modeling is one of the main research tools in modern atmospheric physics. The complexity of the verification of modeling is related to the probabilistic nature of the atmospheric processes under study. We define the quality of modeling as the accuracy of describing the general dynamics, and not as the equality of measured and modeled physical quantities at any specific time moment. The paper proposes a verification method based on comparing the measured and modeled spatial distribution of radar reflectivity. The method is applied to compare the quality of modeling with different microphysical schemes for the mountainous region.

1. Introduction

Numerical modeling is a powerful tool for studying convective phenomena [1]. The analysis of the simulation results together with the measurement data makes it possible to draw conclusions about the properties of the described system by comparing the quality of the description of the observed properties obtained on the basis of simulation for different parameters. The need to compare the simulation results with observational data leads to the problem of modeling verification. The evolution of convective systems has a probabilistic nature which is reflected in their numerical models. Thus, the behavior of both the observed system and the model contains an essential element of randomness. This leads to the fact that even a perfect model cannot reproduce the dynamics of a convective phenomenon in all details. When solving real problems, the discrepancy between the simulated and the measured is partially caused by the error of both measurements and modeling - the inaccuracy of the model itself and errors of the applied initial and boundary conditions based on the measurement results. To assess the quality of simulation of the general properties of a convective phenomenon, comparison methods with averaging over the coordinate and time are usually used. Our goal is primarily to describe the dynamics, «pattern», the structure of the convective phenomenon, and not a specific physical quantity at a specific moment. In other words, we consider the modeling to be successful if the simulated development of the convective structure corresponds to the measurement results in terms of «general» parameters: spatial size, time duration, development rate, and direction of movement. We consider the displacement of the structure in space or time within the modeling area to be acceptable and compatible with high quality modeling.

In this paper, we analyze the meteorological radar data as a source of the most detailed information available on the cloud structure for the vicinity of the high-mountain Aragats Research Station.
Numerical modeling of the state of the atmosphere was performed using the Weather Research and Forecasting Model (WRF model) [2] – a free access software known for its successful application to a wide range of forecasting and research problems. Comparing the measured and simulated radar reflectivity is an acute problem in atmospheric physics, for the case of WRF modeling considered in [3]. In this paper, a verification method is proposed, based on the analysis of the spatial distribution of radar reflectivity – a characteristic describing the «general structure and dynamics» of the phenomenon, taking into account systematic error in coordinates, time, and amplitude of the measured value.

2. Modeling the state of the atmosphere
A strategy of two nested domains was applied for WRF modeling. The domains are centered at the location of the Aragats Research Station. The outer domain has a size of 2700×1800 km and completely covers the Black and Caspian Seas, Caucasus and mountains, Asia Minor, Armenian and Iranian highlands. The inner domain, 90×90 km, reproduces Mount Aragats in detail. The simulation grid step along the horizontal coordinate is 1 km for the inner domain and 3 km for the outer one. The step along the vertical coordinate changes from 50 m at the surface to 600 m at the altitude of 20 km. The NCEP GFS 0.25 Degree reanalysis data were used as the initial and boundary conditions.

The first 6-10 hours of the simulated interval - «spin up» - give unreliable results. Therefore, the beginning of the simulated time interval should be 6-10 hours before the convective event of interest. In addition, the absence of clouds during the «spin-up» in the area under consideration is necessary for reliable modeling. The absence of disturbances in the surface electric field indicates the absence of significant convective systems above the observation site. The simulated time interval can start at 00:00, 06:00, 12:00, or 18:00 UT because the measurement data for initial conditions are available for these moments.

The WRF model contains a large set of parameterization schemes, which are methods of describing processes with spatial scale under the model discretization step. The choice of parameterizations for the simulation described below is based on the recommendations for fine meshes (RA_LW_PHYSICS = 4, RA_SW_PHYSICS = 4, SF_SFCLAY_PHYSICS = 1, SF_SURFACE_PHYSICS = 2, BL_PBL_PHYSICS = 2). Microphysical schemes (parametrization of microphysics) describe the processes of transformation of water particles of one type into another. The method of modeling verification described below makes it possible to choose microphysical parametrization, the application of which gives the most reliable simulation of the structure and evolution of the convective phenomenon. Microphysical schemes applied in the research are listed in table 1.

3. Verification of the modeling
A preliminary estimation of the quality of modeling is based on the meteorological measurements made at the Station, available in the open archive [4]. The results of comparing the measured and simulated dynamics of surface temperature and pressure are shown in figure 1. All considered microphysical schemes are shown to describe the local dynamics of meteorological parameters equally successfully. The dynamics of temperature and pressure for 8-10 hours after the spin-up (approximately from 09:00 to 19:00 UT) can be reproduced using any parameterization of the set under consideration. For this reason, a choice of the most suitable modeling parameters requires additional verification.
The main goal of the numerical modeling of a convective phenomenon is to describe the spatio-temporal structure, the «pattern» of the event. Therefore, the assessment of the quality of modeling should be based on the space-time distribution of a physical quantity. Satellite data or meteorological radar data can be used to observe the dynamics of the pattern. The verification method proposed below is applicable for the simulation of a spatial distribution for which measurement and simulation results are available with a resolution corresponding to the scale of the phenomenon under study.

To verify the modeling of convective phenomena occurring near the Aragats Station, data from the meteorological radar located 25 km from the Station were used. To estimate the reliability of modeling, let us compare the measured and observed distribution of radar reflectivity maximized over an air column (hereinafter referred to as «maximum reflectivity»). The results for the measurements and simulation are presented in figure 3, the radar is shown by a red marker on the map of measured reflectivity.

For each point of the considered area (45×45 km), the value of the maximum reflectivity is known. We divide the area into squares 1×1 km, based on the simulation grid step. Then let us divide the entire range of values of maximum reflectivity into intervals (in this study, the interval width is 5 dB). Then, for each unit square (1×1 km), the reflectivity values are known: measured and modeled for it. Let us find the number of square units corresponding to each of the intervals of reflectivity values (for measurements and modeling separately), and divide it by the number of all area units in the region under consideration (45×45 km). The found values can be displayed on the graph: we get the distribution of the area by reflectivity values, figure 2. The shape of the curve «reflectivity – area fraction» characterizes the properties of the «pattern», the structure of the investigated convective phenomenon.

Figure 1. Dynamics of surface temperature (left) and pressure (right), according to the modeling (colored curves) and measurements (black curves), for the convective phenomenon 2016-06-11, 04:00 - 20:00 UT.

Figure 2. Dependence «reflectivity – area» for the simulation results obtained using seven microphysical schemes (colored curves) for 11:45 UT 2016-06-11. On the right picture: for reflectivity values of more than 5 dB, the black curve is the measurement data.
Figure 3. Distribution of the maximum reflectivity in the area of 45×45 km in the vicinity of the Aragats Research Station, 11:45 UT 2016-06-11: the results of modeling using seven microphysical schemes and the data of the meteorological radar. The axes are marked in km, the axis origin is the location of the Station.

In figure 2, the distribution «reflectivity – area fraction» is presented for all investigated microphysics schemes, table 1. Reflectivity values below 0 dB are not informative when describing
the structure of clouds. Therefore, for a clear comparison of the simulation results with the measurement data, the reflectivity interval from 5 dB is considered, figure 2.

Table 1. Properties of microphysical parameterizations for the WRF model.

| Mp_physics | Scheme                  | Reference                                    | Added  |
|------------|-------------------------|----------------------------------------------|--------|
| 1          | Kessler                 | Kessler (1969)                               | 2000   |
| 2          | Lin (Purdue)            | Lin, Farley and Orville (1983, JCAM)         | 2000   |
| 3          | WSM3 Hong               | Hong, Dudhia and Chen (2004, MWR)            | 2004   |
| 6          | WSM6 Hong               | Hong and Lim (2006, JKMS)                    | 2004   |
| 8          | Thompson                | Thompson, Field, Rasmussen, Hall, (2008, MWR)| 2009   |
| 10         | Morrison 2-mom          | Hong and Pan (1996, MWR)                     | 2008   |
| 28         | Thompson Aerosol-Aware  | Thompson (2014)                              | 2014   |

One of the key properties of a convective structure is the difference between the maximum and minimum (over its area) reflectivity values. The absolute reflectivity values are less important, in particular, because both measurement and modeling have systematic, «area-uniform» errors. Thus, a general structure of the convective phenomenon can be judged by the shape of the «reflectivity – area» curve, and not its location along the reflectivity axis. In figure 2, plots for simulation results using schemes MP3, MP6, MP8, MP10, MP28 have maximums on higher reflectivity values than the measurement curve: that is, these parameterizations tend to overestimate the reflectivity. The other two microphysical schemes – MP1 and MP2 – on the contrary, underestimate the reflectivity. We make a preliminary conclusion about the suitability of each of the parameterizations by comparing the shape of their «reflectivity – area» curves with the curve for the measurement results: the best fit is obtained using MP3, MP6, and MP10, less close for MP8 and MP28. Curves for MP1 and MP2 significantly differ from the measurement curve. Moreover, it can be concluded that MP1 and MP2 give similar accuracy results, the accuracy of using MP8 and MP28, MP6 and MP10 are also similar.

A quantitative characteristic of the quality of modeling the distribution of reflectivity can be obtained by introducing an arbitrary metric for the «reflectivity – area» functions. We will apply one of the simplest metrics: the difference between the two functions is described by the modulus of the difference in the relative area, averaged over the intervals of reflectivity values:

$$\frac{1}{n} \sum |\text{obs}_j - \text{mod}_j| = \Delta$$

Here n is the number of intervals of reflectivity values, obs$_j$ and mod$_j$ are the area fractions (%) in modeling and measurements for the interval $<j>$ of reflectivity values, $\Delta$ is the estimate of the modeling quality – the average deviation (%).

Systematic errors in modeling and measuring the absolute values of reflectivity leads to the fact that the location of the «reflectivity – area» curves along the horizontal axis is uninformative. Let us take this error into account by minimizing the estimate of $\Delta$ over all possible mutual shifts of the modeling and observation curves along the horizontal axis. The «deviation» of the simulated reflectivity distribution from the measured one, defined as described above, allows one to compare the simulation reliability for different sets of parameters. The smallest deviation from the measured value is provided by the parameterizations MP6, MP8, MP10, MP28 – about 3-5%, for other investigated parameters the deviation reaches 10-20%. Additional criteria for choosing a parameterization are the mesh size, a set of described types of water particles, a set of other available modeling options (for example, methods for describing processes with aerosol particles).

Let us consider the change in the reliability of modeling over the modeling time for the example of using MP6 parameterization, figure 4: the deviation $\Delta$ for the times 11:40, 11:45, and 11:50 UT is
3.3%, 3.4%, and 4.2%, respectively, indicating a sufficiently high quality of modeling over the entire considered interval. The detected increase in the mean deviation is associated with the inevitable accumulation of errors over the simulated time interval.

![Image](image_url)

**Figure 4.** Dependence «reflectivity – area» according to measurement data (black curves) and modeling using the microphysical scheme MP6 (red curves), for 11:40, 11:45, 11:50 UT 2016-06-11.

4. **Discussion**

The paper proposes the method of verification of modeling of convective events using weather radar data. The developed verification technique characterizes the reliability of simulation of the general structure and evolution of the convective phenomenon, taking into account the systematic errors of modeling and measurements. The technique is based on comparing the «patterns» of the spatial distribution of radar reflectivity and can be used for verification based on data on the distribution of other physical quantities, including satellite monitoring data and other types of remote sensing with sufficient spatial and temporal resolution.

The operation of the method is demonstrated by the example of comparing the measured and modeled maximum radar reflectivity over a column of air for a convective event observed in the mountainous region of Aragats. More detailed information about the structure of the convective phenomenon can be obtained from the distribution of reflectivity at different altitude levels.
To compare the simulation results of radar reflectivity with weather radar data, the properties of the errors of both information sources should be taken into account, as discussed below. The MRL-5 radar is located in 20 km from the Aragats Station (red mark in figure 3). The measurement range of the radar is up to 300 km. Scanning is carried out at eleven values of the inclination angle of the beam. A full scan is obtained in about 3 minutes, which determines the time resolution of the measurement results since a full scan includes scans at different angles taken at different times. The horizontal distribution of the maximum radar reflectivity in the air column, as well as the horizontal reflectivity for fixed altitudes, are the results of processing the scanned data. The difference in data processing algorithms for the near and far zones leads to an increase in the error at their junction – about 30 km from the radar [5]. Mountainous terrain increases the error of the radar data, especially when scanning low clouds, as landforms can block the cloud from view.

The accuracy of the modeling of the radar reflectivity is determined by the accuracy of describing microphysical processes within the framework of the model, since the integral reflectivity depends not only on the concentration of water particles but also, to a significant extent, on their types and size distribution (as far as the Rayleigh backscattering cross-section on a particle is proportional to the sixth power of its size), which is especially important for snowflakes [6]. When calculating radar reflectivity using WRF, the contribution of Mie scattering, which is negligible for sensing at centimeter wavelengths, is not taken into account.

When analyzing the results of both observations and modeling, it should be noted that radar reflectivity is an integral characteristic, insufficient for the estimation of the impacts of water particles with different characteristics (solid and liquid particles of different sizes). The maximum reflectivity over the air column is additionally averaged over the vertical coordinate. Therefore, a good correspondence between the measured and modeled reflectivity pattern does not guarantee high modeling reliability, although it is evidence in favor of the high quality of the modeling.

Thus, a comparison of the «reflectivity – area» distributions gives an informative assessment of the reliability of the modeling of the convective phenomenon, because 1) the area of a region with a certain reflectivity is more important than the shape of this area, 2) the relative values of reflectivity at different points of the same structure are more important than the absolute values. The proposed verification technique provides an estimation of the modeling quality defined as the accuracy of reproducing the general evolution of the convective system.

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References
[1] Bauer P, Thorpe A, and Brunet G 2015 The quiet revolution of numerical weather prediction Nature 525 47–55
[2] WRF model www.mmm.ucar.edu/weather-research-and-forecasting-model [Accessed 20.10.20]
[3] Chu X et al 2014 A Case Study of Radar Observations and WRF LES Simulations of the Impact of Ground-Based Glaciogenic Seeding on Orographic Clouds and Precipitation. Part I: Observations and Model Validations Journal of applied meteorology and climatology 53 2264–86
[4] Advanced data extraction infrastructure of Aragats Space Environmental Center http://crd.yerphi.am/adei [Accessed 10.12.2020]
[5] Manual for MSL radar http://elib.rshu.ru/files_books/pdf/img-515154150.pdf [Accessed 11.01.2019]
[6] Matrosov S Y 2007 Modeling backscatter properties of snowfall at millimeter wavelengths J. Atmos. Sci. 64 1727–36