Reanalysis of Atmospheric Circulation for the Black Sea-Caspian Region

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The results of numerical simulations aimed at dynamic downscaling the *ERA-Interim* reanalysis data for the Black Sea-Caspian region using the *RegCM*4 climate model are described. The downscaling results in reconstruction of the atmospheric circulation fields in the region with the increased spatial resolution (25×25 km) for 1979–2013. The modeling results are compared with the original large-scale fields with the purpose to validate the regional model. The analysis shows that the model correctly reproduces climate in the region; at that original integral climatic characteristics are retained. Realistic annual cycle and seasonal spatial distribution of main meteorological parameters (temperature, precipitation and wind circulation) are obtained by the model simulations. However, the following discrepancies are found.

In the northern part of the region summer air temperature is overestimated by 1.5–2°C. This effect is observed in the flat areas and it does not related to the model orography differences. Probably, overestimation of summer temperature is related to disadvantages of cloud cover parameterization schemes and inaccuracies of radiation calculation. In favor of this assumption comes underestimation of summer precipitation amount in the northern areas of the domain.

Overestimated (by 25–30 %) precipitation in the autumn-winter period and the heightened (by 1.5–2 °C) air temperature in summer are noted in the northern part of the region. Further analysis shows that the increased precipitation is, mainly, a result of overestimating its intensity, whereas the simulated precipitation frequency approximates the original data. Precipitation intensity according to regional model data significantly exceeds the one obtained according to reanalysis data during the entire year. In the cold season this is related to more intensive large-scale (non-convective) precipitation prevailing in this period.

Hence, the scheme of precipitation parameterization requires optimization.

Keywords: Black Sea region, Caspian region, climate modeling, regional model, reanalysis.

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Introduction. Numeral modeling is one of the basic instruments for studying climate and its changes. In course of two previous decades, on the basis of global models of the atmosphere and ocean general circulation, the climate in XX century was studied and the projections of its changes in XXI century were obtained. At the same time spatial resolution of the global models, in spite of their permanent perfection, remains insufficient for reproducing regional features of atmospheric circulation which are governed by the underlying surface inhomogeneities. One of the methods of specification of the global models' data is dynamic regionalization. In a climate regional model, the results of global modeling are used as input data. The input data with low spatial resolution constitute boundary conditions on the lateral boundaries of a simulation domain. For its internal region, integration is carried out with the increased spatial resolution which permits to take into account regional features of the underlying surface (for example, orography and characteristics of soil and vegetation) and the coastline contour. In contrast to the global models which do not consider these local climate-forming factors, the regional model reproduces meso-scale atmospheric circulation including long-term processes in a climatic system.

Application of regional models for studying climate of the Black Sea-Caspian region is especially actual as insufficient spatial resolution of the global models does not permit to reproduce realistically climate of the region with such a complicated relief.

Last years the regional models are actively used for constructing projections of climate changes occurring due to anthropogenic impact. The authors of the paper have published a few works on modeling the Black Sea region climate using the model *HadRm*3*P* (*PRECIS*) [1, 2]. Within the framework of the joint project of the Marine hydrophysical institute (MHI) and the ICM of RAS, these studies were continued using more modern climate models *INMCM4* and *RegCM*4. Application of a few models for studying climate changes is important by many reasons. The major one consists in possibility to use statistical ensemble methods. The first stage of a regional model application implies its validation based on the known climate data of previous years. It is aimed at choosing and debugging optimum schemes of the sub-grid processes' parameterization. The results of the regional model validation using input data of the global retrospective analysis of atmospheric circulation are described in the present paper. In our case the regional model was supplied with the *ERA-Interim* reanalysis data for 1979 – 2013 of the European Center for Medium-Range Weather Forecasts (*ECMWF*).

The obtained data array can be used for solving a number of important scientific and applied problems, such as, for example, the following: variability of regional climate and its relations with the global climatic indexes, climatic characteristics of mezoscale of the atmosphere dynamics and the atmosphere-ocean interaction on regional scales, statistical characteristics of the weather extreme phenomenon and the applied problems of wind and solar power engineering. Besides, the obtained data can serve as input fields for the Black Sea hydrodynamic models. Their increased spatial resolution permits to consider correctly the atmospheric influence and to reproduce more accurately physical processes in the sea.

Description of the model *RegCM*4 and input data of the *ERA-Interim* reanalysis. In the present paper the climate regional model *RegCM*, version 4, developed in the Abdus Salam International Center for Theoretical Physics (*ICTP)* [3] was used. The fourth version of this model is one of modern ones and is widely used for reproducing climate of many regions in the world. It was also used in the known projects on assessing and comparison of the following regional models: *PRUDENCE* (*Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects*) [4], *ENSEMBLES* (*Ensemble-Based Predictions of Climate Changes and Their Impacts*) [5], *CECILIA* (*Central and Eastern Europe Climate Change Impact and Vulnerability Assessment*) [6], *CORDEX* (*Coordinated Regional Downscaling EXperiment*) [7], *NARCCAP* (*North American Regional Climate Change Assessment Program*) [8] and others. In a series of other works the model *RegCM*4 was applied for modeling the East Mediterranean climate [9, 10]. In this paper the model is adapted for the territory including the Black and Caspian seas, Balkan Peninsular, Ukraine, Caucasus and south of the European part of Russia.

The regional model base consists in a finite-difference scheme for solving nonlinear three-dimensional equations of the atmosphere thermohydrodynamics in hydrostatic approximation. The explicit scheme with temporal splitting the formula of which did not undergo considerable changes as compared to the model previous versions [11, 12], the Arakawa spatially «shaken» grid of *B* type and vertical σ-coordinates are used. 18 vertical σ-levels are preset in the model. Its spatial resolution is 25×25 km and time step is 1 min. The dynamic scheme of the regional model corresponds to the scheme of the well-known mezoscale model *MM*5 [13] which is actively used in MHI for operative weather forecast for the Black Sea region.

The model *RegCM*4 includes a set of modern schemes of parameterization of the sub-grid physical processes, i.e. those which are not resolved obviously on the model grid. Calculation of some processes permits one to make a choice among a few alternative schemes. The parameterization schemes' configuration recommended as the most suitable for the majority of regions was chosen. Modification of the scheme with the Holtslag nonlocal closure [14] is used for parametrizing turbulent mixing in the atmosphere boundary layer. The processes of cumulus convection and convective precipitation are calculated by a mixed scheme: according to the developers' recommendations [15], the Grell scheme [16] with closure is chosen for land and the Emanuel scheme [18] – for sea. Large-scale cloudiness and atmospheric precipitation are parametrized by the method proposed in [19]. The base of the scheme for calculating cloudiness consists in traditional diagnostic approach when a part of a cell occupied with clouds is calculated depending on relative humidity. Calculation of large-scale precipitation includes the processes of raindrops accretion and evaporation. The Kiehl adapted scheme [20, 21] from the global model *CCM*3 is used for parametrizing the radiation fluxes in the model *RegCM*4. The values of cloudiness and concentrations of radiation-active gases and water vapor are used as the input parameters in the scheme. The scheme of parameterization of the processes proceeding in the soil upper layer *BATS (Biosphere-Atmosphere Transfer Scheme)* [22] is also included in the model. This scheme permits to calculate snow amount, temperature and soil moisture load that permits to reproduce correctly the features of the atmosphere-underlying surface interaction.

It was already noted that the *Era-Interim* reanalysis data [23] for 1979 – 2013 with spatial resolution 0.75×0.75° were used as boundary conditions of the regional model. The prepared data of global reanalysis are assimilated on the spatial domain lateral boundary in a buffer zone which occupies the area of 12 model cells. The data on temperature, humidity, wind speed and ground pressure are assimilated by introducing exponential relaxation terms to prognostic relations. Since a united data array on the sea surface temperature (SST) for 1979 – 2013 is not available yet, monthly average SST values from the *GISST* array were used for the period 1979 – 1981, and for the period 1982 – 2014 – weekly average values from the *OISST* array . In both cases spatial resolution of SST fields was 1 × 1°. Application of the reanalysis data most accurately describing real weather conditions in previous years permits, on the one hand, to debug and verify the regional model and, on the other hand, to reconstruct the atmospheric circulation fields with high spatial resolution. Having been comprehensively analyzed, the obtained data array can be used for solving a number of scientific and applied problems.

Comparison of the results of the regional model simulations with the global reanalysis data implied the procedure of the *Era-Interim* data interpolation on a finer grid by the Bessel method.

Results of numerical simulations. Quality of regional modeling is conditioned by ability of the models to introduce a useful mezoscale signal (*added value*) into the global models' fields preserving at that integral climatic characteristics.

In the internal region of the simulation domain, the regional models which include the approach of data assimilation in the buffer zone reproduce their proper atmospheric circulation. It permits to introduce a useful signal into the initial fields. Thus, the primary task of regional modeling consists in comparison of the input and output model fields.

Temperature. First, let us consider the features of reproducing temperature condition in the Black Sea-Caspian region by the regional model. Here and below we will examine climatic parameters' distributions for two seasons – summer (June, July and August) and winter (December, January and February). It is important to note that the air temperature values are directly assimilated by the regional model in the buffer zone. But for the internal region of the spatial domain, proper atmospheric circulation is simulated that permits to specify temperature for the internal region in comparison with the input data. Since the observation data for the internal region are not assimilated, some deviations from the integral characteristics of the input signal are possible. Fig. 1 *a, b* represents seasonal distributions of the air temperature values on 10m height based on the regional model data. In summer season the temperature values' spread in the region is considerably smaller than that in winter. Nevertheless, temperature anomalies related to the Carpathian, Caucasian and Pontic Mountains are distinguished. These anomalies are absent in the global reanalysis initial fields. The air temperature values in summer vary from 19 °C in the northern parts of the spatial domain to those exceeding 30 °C on the continental sector of its southern part and on the Caspian eastern coast. In the European part of the simulation area maximum values of the air temperature in summer are observed in the Northern Caucasus and on the Caspian western coast. Arid zones are distinguished in the northern part of the Black Sea region, in the Azov Sea region and in the Crimea where average values of the air temperature attain 23 – 24 °C. In winter the temperature gradients in the region under investigation are more significant. In the domain north-eastern zone the winter temperature decreases up to –10°C gradually growing towards south-west. The coastal areas are significantly affected by the Black and Caspian seas – in most regions the temperature values in winter exceed zero. Note that ability to reproduce temperature conditions on such small coastal zones is one of important arguments for applying regional models. The global models' resolution does not permit yet to reproduce correctly climatic conditions on such spatial scales.

Fig. 2 *a*, *b* shows seasonal average distributions of differences between input and output data in the surface air temperature fields. In winter season the differences are small; distinctions are observed mainly in the alpine and coastal regions. It was already noted that it was related to the fact that many relief objects were practically absent in the global model. The regional model data demonstrate, in general, temperature understating. As a rule, it is also related to different orography in two models. In the region to the north from the Caspian Sea the model heightens the air temperature seasonal values by 1.5 – 2 °C. In summer divergence of the air temperature data is more considerable. Practically, in the whole northern part of the spatial domain the air temperature is heightened by 1.5 – 2 °C. This effect is observed in the flat regions and is not related to distinctions in the model orography. Physical reasons of temperature overstating require individual consideration. As a rule, the errors in reproducing temperature conditions in a summer season are related to the drawbacks of the cloud cover parameterization schemes and inaccuracy of radiation calculations. This assumption is confirmed by understating of summer precipitation amount in the domain northern regions (this fact will be discussed below). Note that such shortcomings as overstating of the surface temperature values in summer, are inherent to many models; they were also revealed in the papers on modeling the Black Sea region climate using the *HadRm*3*P* (*PRECIS*) model [2]. On the whole, the divergence value is in an admissible range and does not exceed the divergences resulted from simulations by other models and for other regions (see, for example, the *NARCCAP* project [8]).

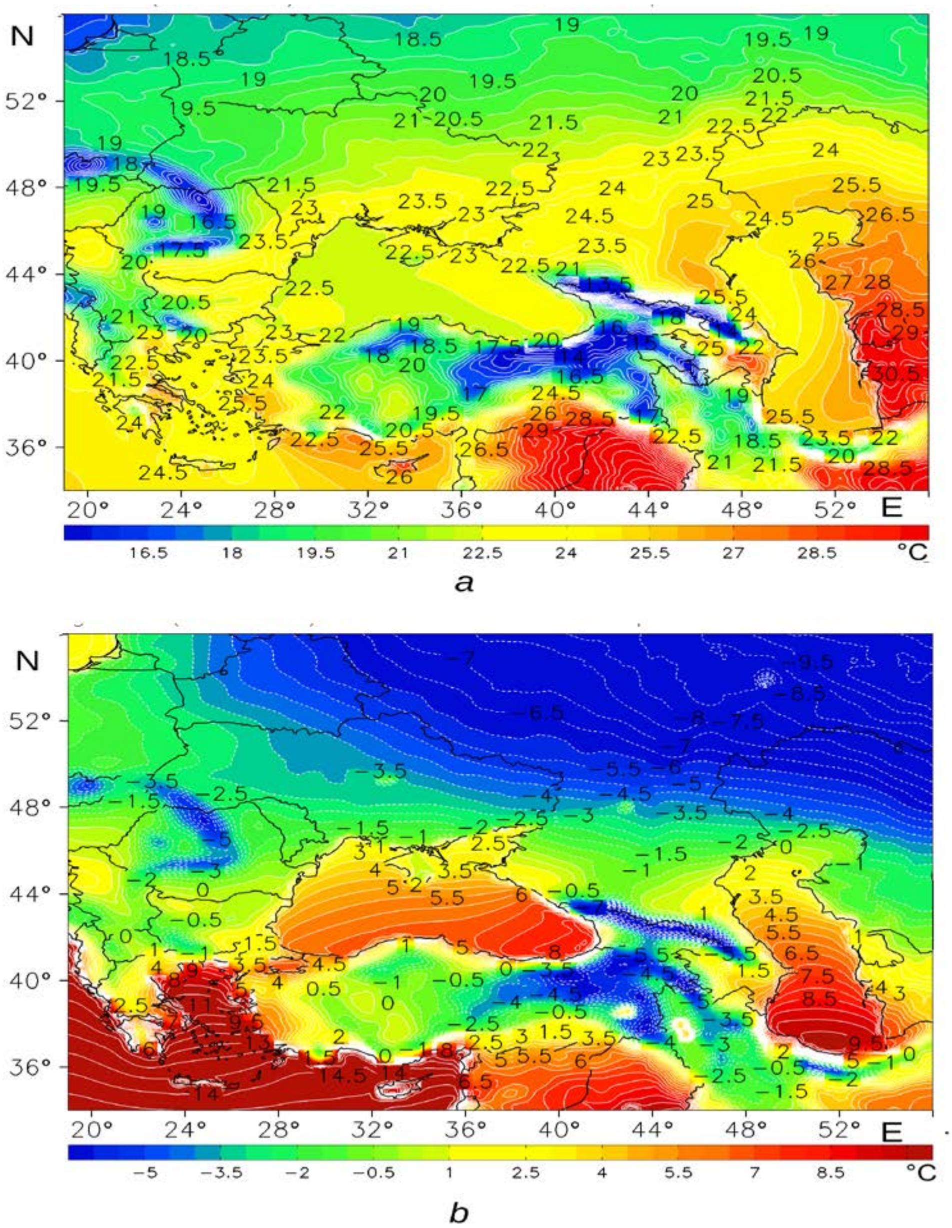

Fig. 1. Values of the surface air temperature (°C) based on the *RegCM*4 model for 1979 – 2013 for summer (*a*) and winter (*b*)

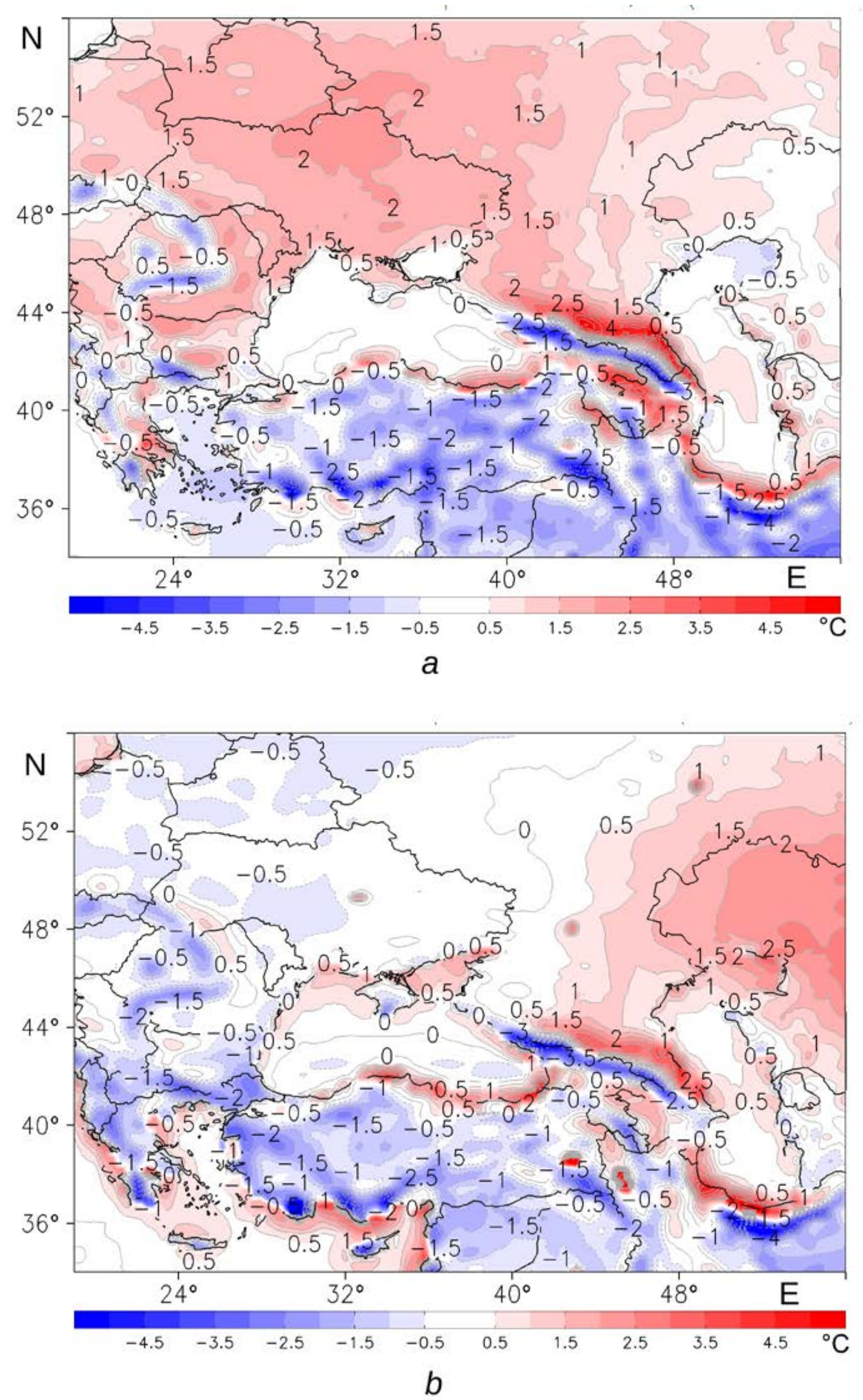

Fig. 2. Seasonally average differences between the surface air temperature values (°C) resulted from the *RegCM*4 model output data and those of the *ERA-Interim* reanalysis (1979 – 2013) for summer (*a*) and winter (*b*)

Atmospheric precipitation. Let us consider the features of the simulated precipitation conditions. Fig. 3 demonstrates the model-derived values of the precipitation amount in the Black Sea-Caspian region and the lines of motion of the seasonally average wind speed for the European region based on the *Era-Interim* reanalysis data.

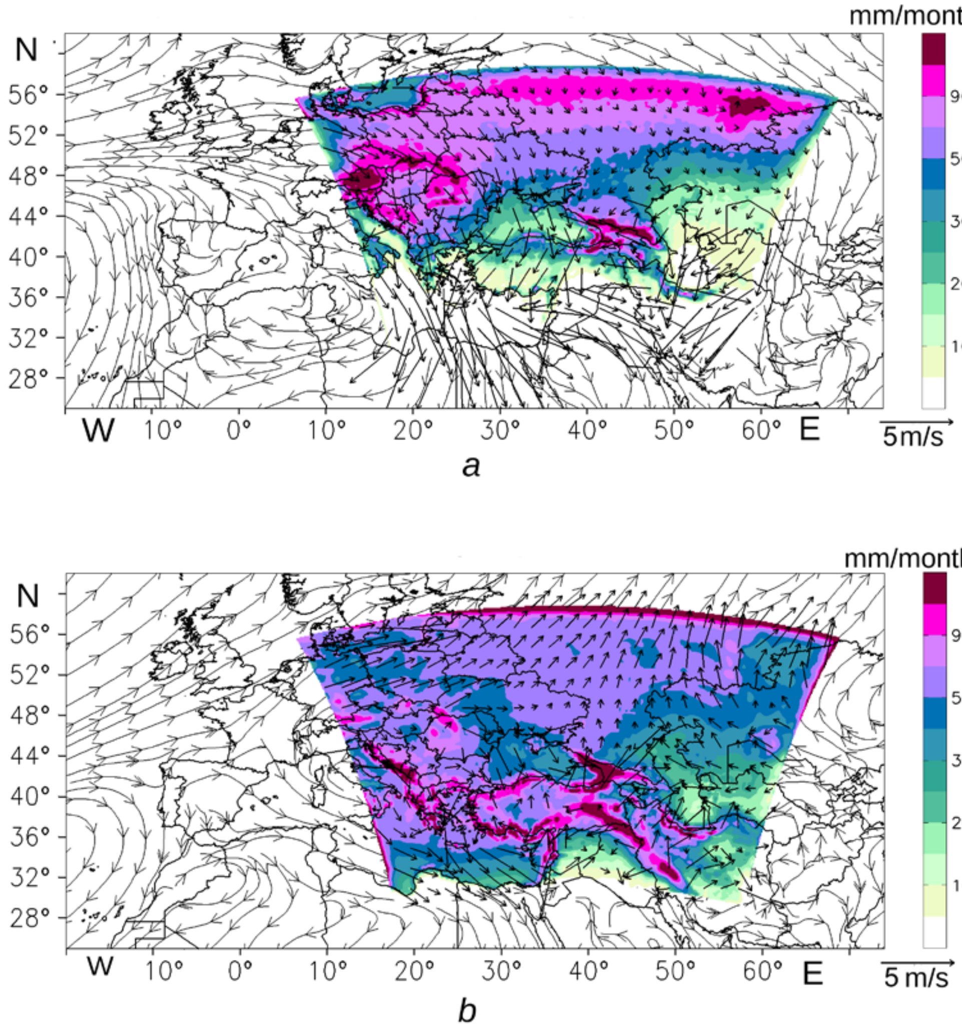

Fig. 3. Lines of motion of seasonally average surface wind speed resulted from the *ERA-Interim* reanalysis data (external area) and wind speed vectors on 10m height and atmosphere precipitation amount (mm/mon) resulted from the *RegCM*4 model data for summer (*a*) and winter (*b*)

In the simulation domain the wind speed is shown by vectors, and the seasonally average precipitation amount values – by color. Just as the temperature data, the wind speed data are assimilated in the model buffer zone, therefore the wind field in the internal part (Fig. 3) is a «continuation» of the wind circulation large-scale structure. The atmospheric precipitation distributions for summer and winter look realistic. Maximum values of the precipitation amount are observed in the alpine regions. In summer in the Black, Caspian and Aegean seas' water areas the precipitation amounts are smaller than those on the surrounding territories; it is related to the known effect of the reduced convective activity over a rather cold water surface [24]. In summer in the whole southern part of the spatial domain the precipitation is small and does not exceed 10 – 15 mm/mon. Only in the northern parts of the Anatolian Peninsular the model simulations show considerable precipitation. Growth of the precipitation amount there is also related to the orography features, i. e. to elevation of more humid and cold air coming from the Black Sea. According to the model-derived data, in summer mainly the north winds dominate over the Black Sea water area that is in agreement with the previous results [1]. But, of course, more detailed study of the reproduced regional features of the atmospheric circulation over the sea and the surrounding mountains is required. For a winter season the model reproduces more intensive precipitation formation in the southern regions. The climatic atmospheric circulation in the domain southern part is, mainly, conditioned by the west winds which bring warm and humid air from the Mediterranean Sea. It results in occurring of the areas of intensive precipitation formation on the western leeward slopes of the Dinaric Alps, the Caucasian and Taurus mountains. And, vice versa, in winter in the domain northern parts the precipitation amount is smaller as compared to a summer season.

Let us consider differences in precipitation conditions derived from the regional model and the global reanalysis data. It is necessary to stress that the precipitation data from the *ERA-Interim* reanalysis are not assimilated in the regional model. The atmospheric precipitation is a diagnostic model parameter, and as a matter of fact, the numerical schemes of parametrizing the precipitation formation processes are substantially different in different models and significantly depend on spatial resolution. At the same time, in situ and remote observations' data are assimilated in the *ERA-Interim* reanalysis, therefore, with certain restrictions it can be used as a control array. Fig. 4 represents seasonally average differences resulted from the regional model and the global reanalysis, and Fig. 5, a – annual variation of the precipitation total amount averaged for the northern (47 – 54 °N, 24 – 48 °E) and southern (35 – 42 °N, 24 – 48 °E) parts of the simulation zone. The most substantial distinctions (the same for other parameters) are observed in the mountain regions. In summer the *RegCM*4-derived precipitation in the Caucasus is lower than those derived from the *ERA-Interim* data. The model yields somewhat understated precipitation amount in the eastern part of the Balkan Peninsular, in the Carpathian Mountains and in the Central Ukraine. Distinctions are substantial both in absolute values (in some areas up to 0.6 – 0.8 mm$\cdot$day^{-1}) and percentage (in some areas of the Carpathians the distinction makes up to 30 %). Differences in the precipitation conditions exert influence on overstating of summer temperature in these regions by the regional model. In the southern part of the simulation zone the model-derived precipitation amount is also somewhat understated (Fig. 5, *a)*, but as for absolute values, the difference is small. And, vice versa, in the northeastern part of the domain the regional model reproduces more intensive precipitation (as compared to the *ERA-Interim* reanalysis data, the precipitation amount is higher by 0.2–0.4 mm$\cdot$day^{-1}).

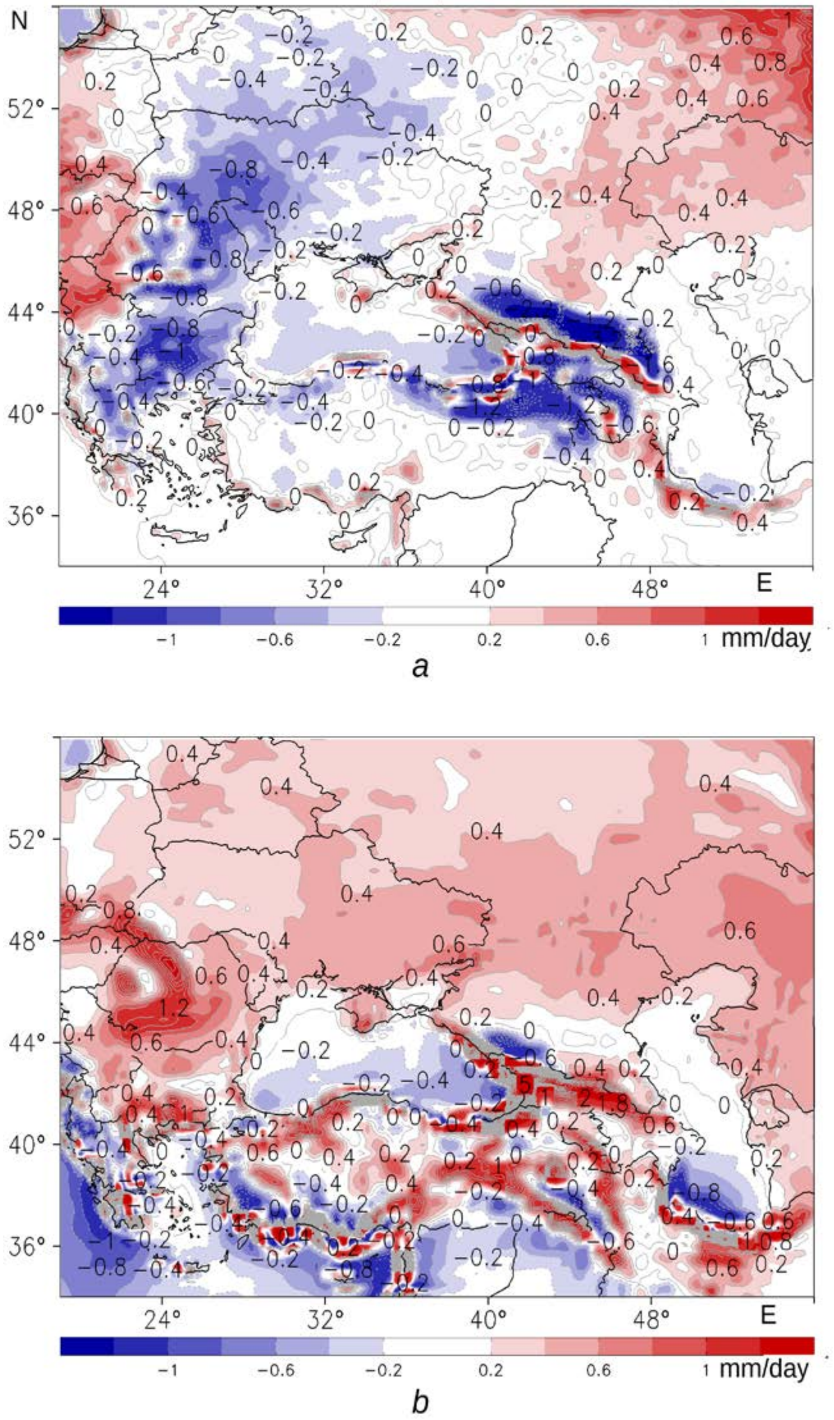

Fig. 4. Seasonally average differences of atmospheric precipitation amounts (mm/day) based on output data of the *RegCM*4 model and input data of the *ERA-Interim* reanalysis for 1979 – 2013 for summer (*a*) and winter (*б*)

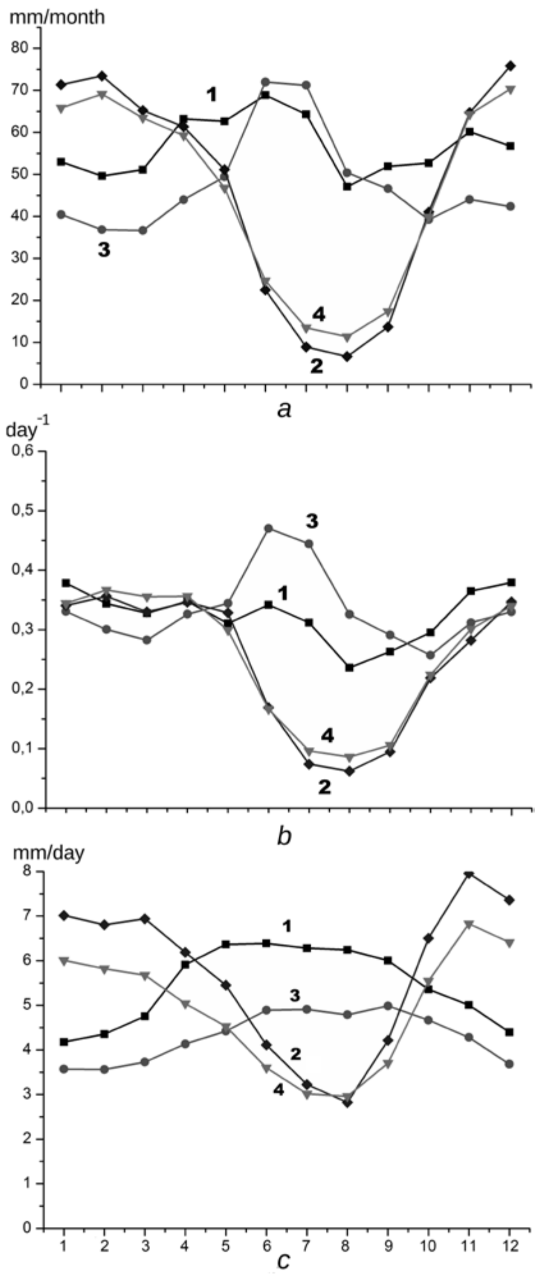

Fig. 5. Annual variation of total precipitation amount, (mm/day) (*a*), its frequency, day^{-1} (*б*) and intensity, mm·day^{-1}(*в*) averaged for the northern (*1*) and southern (*2*) parts of the spatial domain based on the *RegCM*4 model output data and for the northern (*3*) and southern (*4*) parts based on the *ERA-Interim* reanalysis input data for 1979 – 2013

In winter (Fig. 4, *б*) the precipitation conditions differ more substantially. For a vast northern area, the regional model reproduces significantly more precipitation. The difference values are rather evenly distributed over space (although in mountains the difference is more essential) that permits to speak about a certain bias error. In winter the model-derived precipitation amount exceeds the reanalysis data by 0.4 mm/day for the territory from the Central Ukraine to the western Kazakhstan. It is seen on Fig. 5, *a* that such an overstating is characteristic not only of winter but also of spring and autumn seasons.

To consider the precipitation conditions in more details, both frequency and intensity of the atmospheric precipitation were simulated by two models. Fig. 5, *б*, *в* show annual variation of their values averaged for the northern and southern parts of the domain. Frequency was simulated as a relative repetition of humid days. A humid day was determined by a generally accepted threshold – 1 mm/day. Intensity was calculated analogously – as an average precipitation amount in a humid day. It was revealed that in summer (more dry) conditions the precipitation repetition is understated in the domain northern part. It can be related to the drawbacks of the convection parameterization scheme as just the model-derived convective precipitation in summer prevails.

Overstating of the precipitation amount in the northern part of the simulation zone occurs exactly due to their intensity growth (Fig. 5, *в*), since the reanalysis-derived precipitation frequency approximately corresponds to the frequency derived from the *RegCM*4 model throughout the year except for a summer period. On the whole, the precipitation intensity from the regional model data substantially exceeds that of the reanalysis data in course of the whole year. Having not cited the data, we would like to note that in a cold period of a year it is related to more intensive large-scale (non-convective) precipitation which prevails in this period.

Other authors [25] have also pointed out the drawbacks of the parameterization scheme and too intensive winter precipitation simulated by the *RegCM*4 model. For the purpose of searching optimum configuration of this numerical scheme, some papers consider the experiments on defining the model sensitivity to change of the input parameters [15]. Differences in reproducing precipitation over mountains are naturally related to different relief heights in *ERA-Interim* and *RegCM*4, whereas in the flat regions these differences are conditioned by imperfection of the numerical schemes of the very model. It was already mentioned that in our case at reproducing precipitation in the domain flat part, the largest error occurs in the northern region during autumn and winter months (Fig. 5) when the model overstates large-scale (not-convective) precipitation. Thus, the primary task consists in adjusting the scheme of calculating non-convective precipitation *SUBEX* in the *RegCM*4 model to our conditions. According to [26], the *SUBEX* scheme is the most sensible to the following coefficients: C_{evap} presets the speed of precipitation evaporation during their fall and Q_{th} conditions the threshold value for the cloud drops' concentration at which raindrops are formed. Increase of these coefficients, apparently, results in reduction of non-convective precipitation.

Preliminary numerical experiments on adjusting the *SUBEX* scheme permitted to reveal that growth of coefficient Q_{th} by an order results, on the whole, in considerable decrease of precipitation in the domain including its northern part. However, since the *SUBEX* scheme does not imply presetting of variable in time coefficients, the precipitation amount diminishes also in summer when it is undesirable. Besides, numerical experiments reveal evident connection between the variations of precipitation amount and surface temperature: increase of the precipitation total amount results in temperature decrease and vice versa. The basic conclusion may consist in the following: adjusting of the numerical scheme requires more accurate numerical experiments and their debugging for every single region. It seems to be a theme for further researches.

Conclusion. The regional numerical model *RegCM*4 with the heightened spatial resolution 25×25 km was applied for reproducing climate of the Black Sea-Caspian region. The data of the *ERA-Interim* global reanalysis were used as the initial fields. Regionalization of these data resulted in reconstructing the fields of atmospheric circulation in the region with the heightened spatial resolution for 1979 – 2013. The obtained data array can be used for solving of a number of tasks both of scientific and applied character.

To validate the regional model, the obtained results were compared with the input large-scale data. The analysis showed that the model could reproduce correctly climate in the region preserving initial integral climatic characteristics. The model reproduces the climate basic features supplementing the input large-scale fields with the details relating to the local features of the underlying surface and coastline. The model reproduces realistic annual variation and seasonal spatial distributions of the basic meteorological characteristics: temperature, precipitation and wind circulation. The main drawbacks are overstating of the atmospheric precipitation amount by 25 – 30 % in the northern part of the spatial domain in fall-winter and overstating of summer air temperature by 1.5 – 2 °C in the same region. Further analysis showed that increase of the precipitation amount resulted, mainly, from overstating of their intensity, whereas the simulated precipitation frequency approximately corresponds to the input data. Consequently, optimization of the scheme of the atmospheric precipitation parameterization is required.

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