Numerical Climatic Estimations of Precipitation and Surface Air Temperature for the Black Sea Region

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Numerical schemes for precipitation calculation used in *RegCM* regional model are adapted to the Black Sea region. The discrepancies between the results of the *RegCM* modeling and the ERA-Interim reanalysis data are considered in detail on the example of the monthly average fields of precipitation and surface air temperature. It is revealed that the discrepancies between the results of modeling according to *RegCM* and ERA-Interim reanalysis data are quite small due to the fact that the amount of convective precipitation is underestimated in *RegCM* model and the one of non-convective precipitation is overestimated. Therefore, the changes were introduced in the model in such a way as to reduce the amount of precipitation falling over the land only. It is shown that the discrepancies between the monthly average fields of surface air temperature in *RegCM* and *ERA-Interim* are due to the differences in a relief height, errors in *RegCM* (which overestimates the amount of precipitation over the flat land) and errors of the model input data.

The numerical experiments aimed to reduce overestimation of the precipitation amount over the flat land to the north of the Black Sea are performed. It is found that the results of precipitation modeling according to *RegCM* are the most sensitive to the variation of that threshold value which determines specific cloud water content at which the clouds begin to form and to variation of minimum and maximum possible threshold values of "precipitation efficiency". Characteristic rate of raindrop evaporation and a method for calculation of updraft mass in the cloud have little effect on the results of non-convective precipitation modeling.

Using the data on annual average precipitation amount and evaporation from the Black Sea surface an estimation of water discharge through the Bosporus, Kerch Strait and river runoffs (which makes up ~370 mm in both models) was refined.

Keywords: the Black Sea region, climate regional modeling, parameterization of precipitation, reanalysis.

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Introduction. Nowadays spatial resolution of global atmospheric models already reaches 0.7º, but this is not enough for complete reproduction of meteorological field local features. For this purpose, global modeling results in some selected area are recalculated at more small-scaled grid using a local atmospheric model. At the same time, it is not yet possible to create a universal regional model that would be suitable for any region of the Earth. In most cases it is necessary to set up the model for a particular region by changing parameterization schemes used for calculating precipitation and planetary boundary layer, and/or by varying empirical coefficients in the parameterization schemes. Regional modeling results are compared with the observational data (satellite and meteorological station data) or, if they are absent, with the results of global atmospheric models and other regional ones at that. Regional model usually is assessed by its ability for reproduction of the precipitation and surface air temperature fields.

The purpose of the given paper is to set up *RegCM* regional model [1] and to refine model precipitation and temperature monthly average fields for the Black Sea region. This paper may be regarded as continuation and development of [2], where the main discrepancies between *RegCM* modeling results and *ERA-Interim* retrospective analysis (reanalysis) data were described, and [3], devoted to numerical estimations of the Black Sea water balance components. Such differences for summer and winter precipitation fields and surface temperature in the 30 – 58º N, 7 – 69º E computational domain are represented at Fig. 2 and Fig. 4 of [2]. When comparing the results of modeling and reanalysis, the greatest differences were found out above the mountains and at the sea-land boundary. This is due to the differences in terrain height: *RegCM* and *ERA-Interim* horizontal resolution make up 25 km and 1.5°, i. e. differ almost by an order of magnitude. As each point of the computational grid is assigned to average (over the cell) terrain height, smaller size of the cells allows us to describe the mountainous and coastal parts of the relief better [2]. Moreover, the significant differences in the amount of precipitation were also found to the north of the Black Sea region where the mountains are absent. From June to August the amount of precipitation in *RegCM* model is underestimated, and in other months it is overestimated [2]. It is concluded that these differences are related to *RegCM* model drawbacks. In the given paper the ways for elimination of these discrepancies by means of numerical experiments on the model parameter setting-up are proposed. It should be noticed that the numerical experiments on sensitivity for the different areas of the globe (South America, Asia, Africa and Europe (including the Black Sea)) were carried out by *RegCM* model developers in [4]. Particularly, it was determined that in the European region the precipitation modeling results weakly depend on the selection of boundary layer parameterization scheme, but the adaptation of precipitation parameterization schemes for the Black Sea region was not carried out in [4].

The description of the model and input data. The *RegCM* is a well-known climate model and it is widely used for investigation of atmospheric circulation regional features. So, we do not give here a general description of the model, only the parameterization schemes (adapted in the numerical experiments) are represented below. The modeling domain and terrain height are shown at Fig. 1.

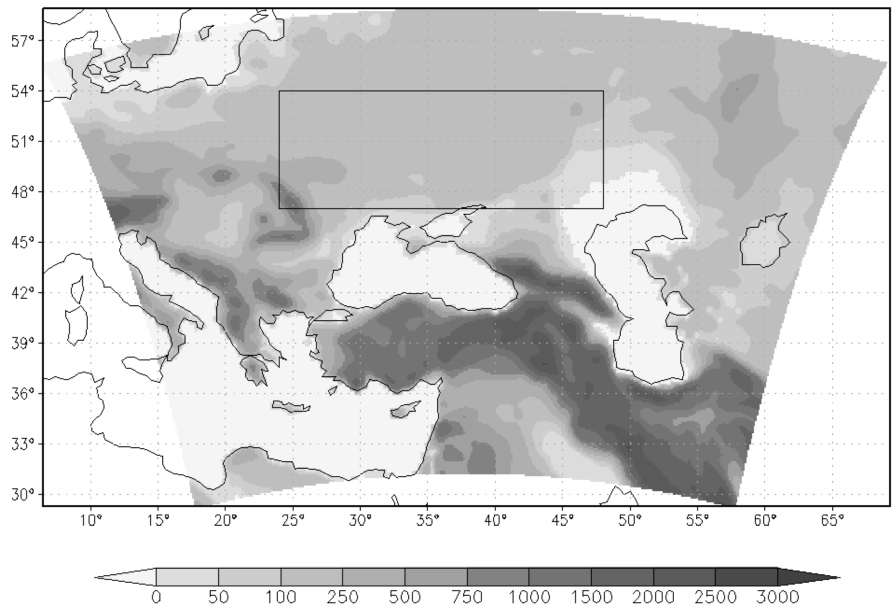

Fig. 1. Terrain height above the Black Sea level (m). The singled out area (northwards of the Black Sea) is the one by which the precipitation amount averaging is performed

The initial and boundary conditions for air temperature, geopotential height, wind velocity and relative humidity in *RegCM* model were set from the *ERA-Interim* reanalysis [5]. Sea surface temperature (SST) has not been calculated during the modeling. The SST was set from the initial and boundary conditions, i. e. SST fields at the model input and output are the same.

Nonconvective precipitation scheme. Nonconvective (large-scale) precipitation in the RegCM model is calculated by the SUBEX scheme [6] where the cloudiness is determined through the relative humidity. The clouds form if the relative humidity exceeds the prescribed threshold value:

$$FC = \sqrt{\frac{RH - RH_{\min}}{RH_{\max} - RH_{\min}}} \text{ at RH > RH}_{\min},$$

$$\text{FC = 0 at RH < RH}_{\min},$$

where FC is the fraction of the grid cell covered by clouds; $RH_{\min}$ is a minimum value of relative humidity at which the clouds begin to form ($RH_{\min}$ makes up 80 % above the land and 90 % above the sea).

In their turn, precipitation forms if the cloud water content (Q_c) exceeds the threshold value (Q_{cth}, $g \cdot kg^{-1}$) calculated by the following formula:

$$Q_{\text{cth}} = C_{\text{acc}} \cdot 10^{-0,489+0,0134t} ,$$

where C_{acc} is an empirical coefficient; *t* is a temperature in degrees Celsius. The amount of the formed precipitation (P, $g \cdot kg^{-1} \cdot s^{-1}$) is calculated as

$$P = C_{\text{ppt}}\left(Q_{\text{c}} / FC - Q_{\text{cth}}\right)FC ,$$

where C_{ppt} is the characteristic rate of raindrop formation. In our case it was the same both over the land and the sea and was equal to $2.5 \cdot 10^{-4}$ s^{-1}.

The *SUBEX* scheme also takes into account the fact of raindrop size increase while passing through the cloud (accretion), and below-cloud evaporation during the precipitation event. The amount of precipitation, formed as a result of accretion (P_{acc}), is calculated by the following formula:

$$P_{\text{acc}} = C_{\text{acc}} Q_{\text{c}} P_{\text{sum}} ,$$

where P_{sum} ($kg \cdot m^{-3}$) is the accumulated precipitation from above falling through the cloud; C_{acc} is the accretion rate coefficient, in our case it is equal to 3 $m^3 \cdot kg^{-1} \cdot s^{-1}$.
The amount of evaporated precipitation (P_{evap}) is calculated as

$$P_{\text{evap}} = C_{\text{evap}}(RH_{\max} - RH)\sqrt{P_{\text{sum}}} ,$$

where C_{evap} is the raindrop evaporation rate coefficient.

Also it should be pointed out that the Black Sea and the Caspian Sea are considered in RegCM model as underlying surfaces referred to the “inland water” category (unlike the Mediterranean Sea, which refers to the “ocean” category). In *SUBEX* scheme for the land and inland water the same values of C_{ppt} and C_{acc} coefficients are used. In general case they differ from the corresponding values for the ocean.

<u>Convective precipitation scheme.</u> In the given paper for the calculation of convective precipitation over the sea we use the MIT scheme, over the land – the Grell scheme [6]. Such scheme combination is used in the model as a default one, and, according to [4], it suits well for the European region. As it will be shown below, in our case it is necessary to carry out the adjustment of the convective precipitation scheme only over the land. This is why we will describe only the Grell scheme.

In the *Grell* scheme the amount of precipitation fallen out in the computational grid cell is determined the following way:

$$P = I_1 m_1 - I_2 m_2 ,$$

where I_1 is a mass of raindrops formed in the updraft, i. e during the lifting of saturated air particle of a unit mass from the bottom boundary of the cloud to its upper one; I_2 is a mass of raindrops, evaporated in the downdraft; m_1, m_2 are the updraft and downdraft mass flux, respectively. It is assumed that m_1 and m_2 do not change with the height in the cloud, i. e. there is no mass flux through its lateral boundaries. The values m_1 and m_2 are related by

$$m_1 I_1 \beta = m_2 I_2 ,$$

here β is determined by the formula

$$\beta = 1 - \left(C_1 + C_2 V_{\text{shear}} + C_3 V_{\text{shear}}^2 + C_4 V_{\text{shear}}^3\right),$$

where C_1, C_2, C_3, C_4 are some constants; V_{shear} is a vertical wind velocity shear in modulus; the value β indicates which part of precipitation will evaporate in the downdraft: the smaller is β, the more precipitation will fall as a result of a convection. Difference $1 - \beta$ is called the precipitation efficiency.

For calculation of the updraft mass flux, in the *RegCM* model we are able to choose one of two methods to prescribe m_1:

$$m_1 = \frac{1}{NA}\frac{CAPE_\tau}{\tau_0} \qquad (1)$$

or

$$m_1 = \frac{1}{NA}\frac{CAPE_{\tau+\Delta\tau} - CAPE_\tau}{\Delta\tau} , \qquad (2)$$

where $CAPE_\tau$, $CAPE_{\tau+\Delta\tau}$ are the convective available potential energy at τ and $\tau +$ $+ \Delta\tau$ moments of time, respectively; $\Delta\tau$ is a time step during the modeling (in our case $\Delta\tau = 1$ min); τ_0 is a time scale ($\tau_0 = 30$ min); *NA* is a change rate of *CAPE* per unit updraft mass flux.

The results of precipitation calculation. At first we are to compare the results of precipitation calculation over the 34 years period (1980 – 2013) by the initial *RegCM* model with the *ERA-Interim* reanalysis data. The discrepancies between the modeling results and reanalysis data for two types of precipitation (convective and nonconvective) are represented in Fig. 2. It is obvious that for the Black Sea region the amount of convective precipitation in *RegCM* model is underestimated and the amount of nonconvective one is overestimated. It is interesting to point out that the amount of convective precipitation above the Black Sea is more overestimated than above the land. This difference is related to the fact that different schemes of convective precipitation calculation above the sea and the land are used in the model. Overestimation of precipitation amount in the northern part of the computational domain was found out not only when comparing with *ERA-Interim* reanalysis data, but also (as it will be shown below) with the data from other sources. In the summer-autumn period the areas of overestimated values of convective precipitation near the Caucasian coast of the Black Sea are well-pronounced in Fig. 2, *a*. This is due to the usage of finer spatial grid (in comparison with the reanalysis) in the model, so the mountain topography as well as regional atmospheric circulation and the formation of precipitation related to it are reproduced better. It should be also considered that in Fig. 2, *b* the discrepancies in modulus in the amount of precipitation for the summer months are small, as nonconvective precipitation in the Black Sea region are insignificant in this period.

Now we are to consider space-averaged values of precipitation. In Fig. 3, *a* their monthly-averaged values according to the data from different sources, spatially averaged over the area shown in Fig. 1, are represented. Precipitation fields obtained by *RegCM* were compared with available observational data and with reanalysis data listed in Annex 1. The *ERA-Interim* and *MERRA* reanalyses are the results of global atmospheric modeling, carried out with the observational data assimilation. *E-OBS* and *CRU* datasets are the land-based meteorological station data, interpolated over the uniform grids. *ECA&D* and *NCDC* are the observational datasets obtained directly from selected meteorological stations. Of course, in all cases the readings are taken from the same meteorological stations, but different methods of incorrect data rejection and different interpolation and smoothing algorithms are used at that. As it is obvious from Fig. 3, *a*, the amount of precipitation above the plain land to the north of the Black Sea region in *RegCM* model is really overestimated. It is interesting to note that, as it follows from Fig. 3, *b*, the discrepancies between the modeling results and reanalysis data over the Black Sea itself are relatively insignificant, despite the fact that *RegCM* model spatial resolution is 5 – 6 times higher than the one of *ERA-Interim* and *MERRA* (see Annex 1). As follows from Fig. 2, this insignificant difference can be explained by the fact that the discrepancies in convective and nonconvective precipitation values over the sea are opposite in sign but relatively similar in modulus. Thus, in numerical experiments it is necessary to adjust the calculation of precipitation only over the land. Moreover, the observational data for adjustment of precipitation schemes over the land are absent. The methods, which allow us to estimate the amount of precipitation over the sea by the satellite data on brightness temperature of clouds or the amount of reflected solar radiation, have been already developed. However, such precipitation data either have a low spatial resolution 2.5×2.5° (*GPCP*, *CMAP* datasets) and are not suitable for regional climate studies, or contain raw errors in the Black Sea region (*TRMM*, *HOAPS* datasets).

According to [7], overestimation of nonconvective precipitation amount in the *RegCM* model can be corrected by increasing C_{acc} and C_{evap} empirical coefficients in the *SUBEX* scheme (which is used for calculation of such precipitation). In our case, the values of these coefficients for the underlying surfaces, related to the “ocean” and “inland water” categories, are left unchanged. According to [7, 8], the *Grell* scheme, which is used for calculation of convective precipitation, is the most sensitive to β value variation and to the method of updraft mass flux parameterization (Formulas (1) and (2)).

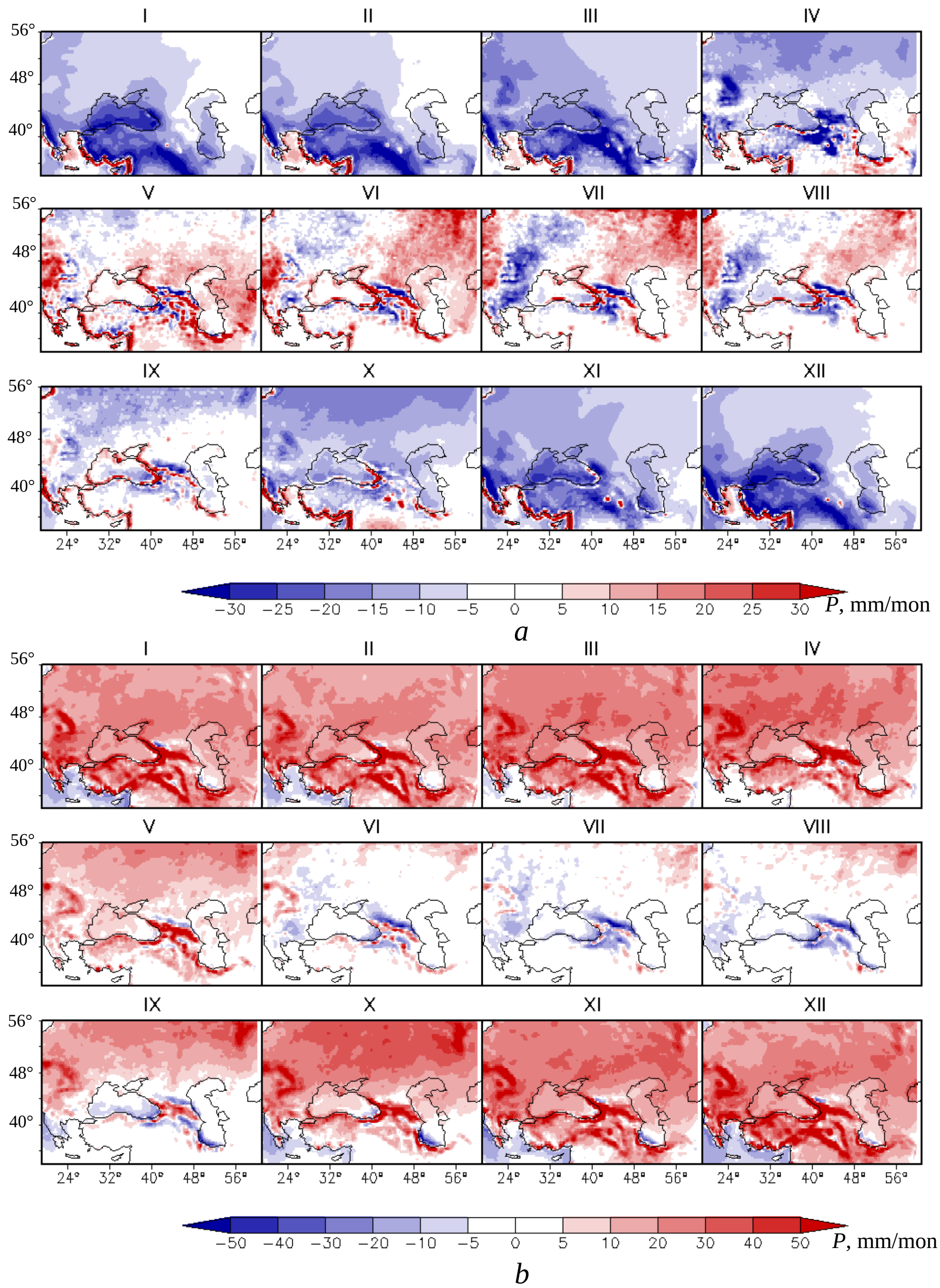

Fig. 2. Discrepancies in monthly average values of convective (*a*) and nonconvective (*b*) precipitation calculated by the *RegCM* model. Time-averaging was performed for 1980 – 2013 period

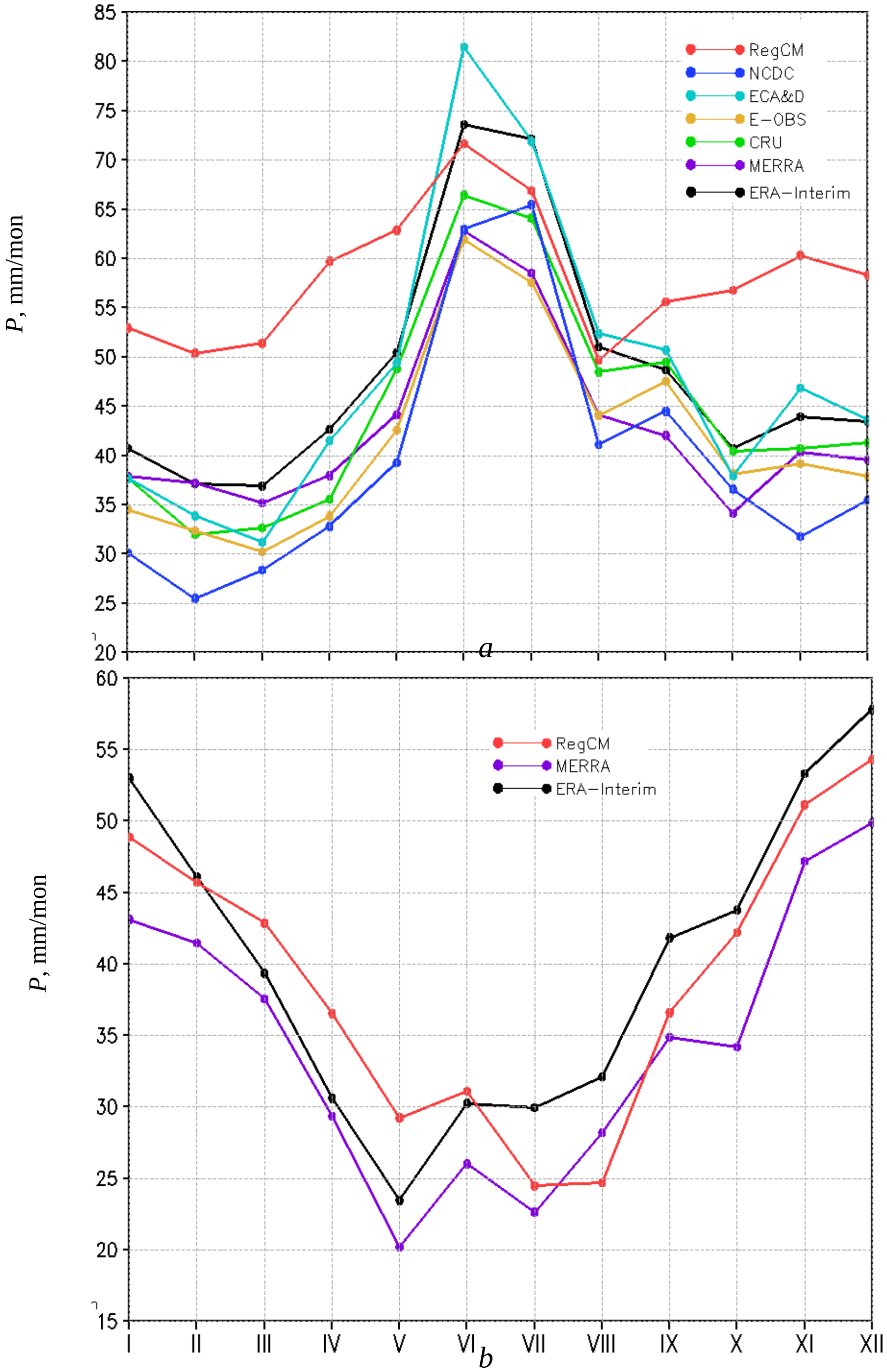

Fig. 3. Monthly mean precipitation values averaged over the area shown in Fig. 1, – *a* and over the Black Sea – *b*. The averaging was carried out using the data from different sources for 1980 – 2013 period

The results of surface air temperature calculation. When comparing monthly average fields of surface air temperature (t_{2m}) from *ERA-Interim* and *RegCM* model, the following discrepancies (Fig. 4) can be seen. Firstly, underestimation of temperature above the Pontic Mountains related, apparently, to the discrepancies in terrain height: in the *ERA-Interim* reanalysis the mountains are lower than in the *RegCM* model. Secondly, t_{2m} overestimation above the land (situated to the north of the Black Sea) in summer and underestimation in winter related to the abovementioned errors in precipitation representation in this area.

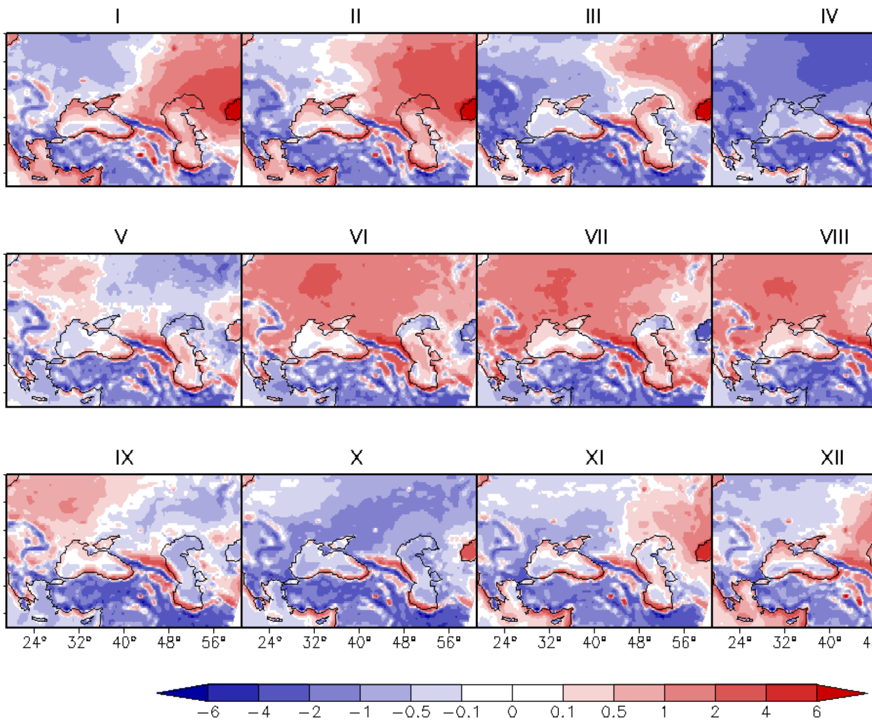

Fig. 4. The difference between monthly average values of surface air temperature obtained by the *RegCM* model and *ERA-Interim* reanalysis data. Time-averaging was carried out for 1980 – 2013 period.

It is of interest to find out the cause of warm anomaly above the Aral Sea. If the anomaly is related to the model errors, the reliability of results of t_{2m} modeling over the Black Sea, which is situated in the same computational domain, become doubtful. As it turned out, the warm anomaly has arisen due to the fact that the model input data on the air temperature and SST were taken from different sources. Air temperature is obtained from the *ERA-Interim* reanalysis where the monthly average temperature of the Aral Sea in winter is 10 – 14 K lower than in *GISST* and *OI_WK* climatic datasets (which have been used to assign the SST during the modeling). Thus, the considered warm anomaly is not related to the model errors, and it is caused by the fact that inconsistent air temperature and SST fields for the Aral Sea were used as the input data. It is possible to correct this drawback by changing the Aral Sea surface temperature in the input data.

Numerical experiments. First of all, it should be pointed out that the calculation schemes in the model are correlated with each other well: when the precipitation field changes, the fields of other meteorological values (surface temperature and pressure, sensible heat flow from the surface) also change in appropriate way. In those areas where the total amount of precipitation has decreased, the surface air temperature has increased overall due to the fact that cooling of the air through the raindrop evaporation has reduced. And vice versa, the areas where the total amount of precipitation has increased correspond to those where t_{2m} has decreased. Moreover, the areas where t_{2m} has increased generally correspond to ones where the surface pressure has reduced. In numerical experiments the underlying surface temperature changes in the same way as t_{2m}. In the *RegCM* model the sea surface temperature is not calculated, it is assigned from the input data. Therefore SST fields do not differ between numerical experiments and control run.

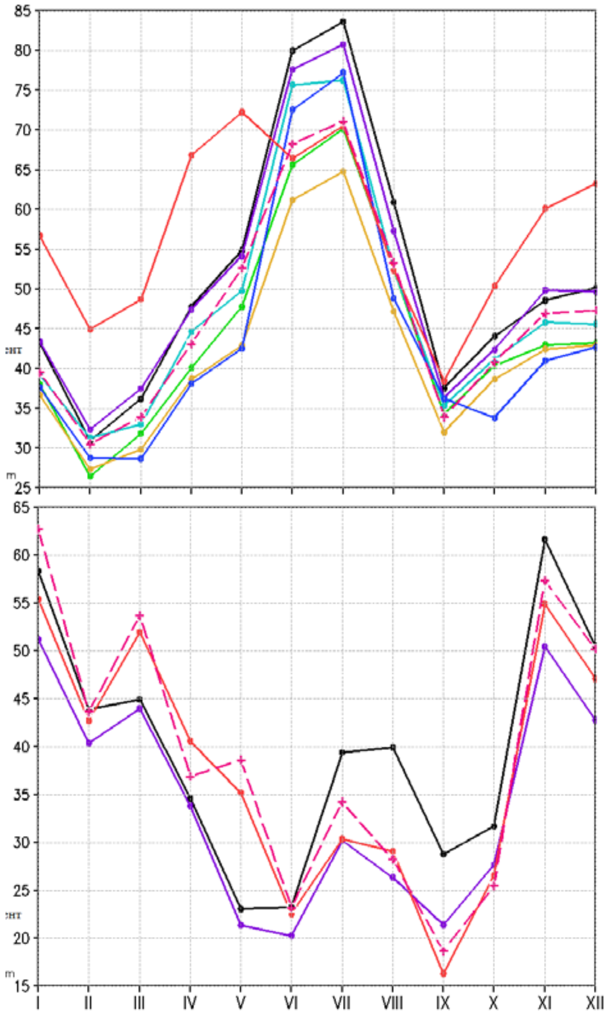

Fig. 5. The same as in Fig. 3, for 1980 – 1984 period. The results of the most successful numerical experiment are represented.

Numerical experiments with the *RegCM* model were carried out in the following way: in the *SUBEX* scheme of nonconvective precipitation calculation C_{acc} and C_{evap} coefficients were changed, in the *Grell* scheme of convective precipitation calculation over the land the method of updraft mass flux calculation as well as β_{min} and β_{max} values were changed.

In our case it turned out that the variation of C_{evap} coefficient results just in insignificant change of precipitation fields. Moreover, it was found out that the results of precipitation amount modeling are almost independent of the calculation methods in the *Grell* scheme – Formulas (1) and (2). It was revealed that such results are the most sensitive to the variation of C_{acc} coefficient as well as β_{min} and β_{max} values (Annex 2). Monthly mean values, averaged over the area represented in Fig. 1 and over the Black Sea, are shown in Fig. 5. As is obvious, the correction, performed in the RegCM precipitation schemes, allowed us to significantly reduce the discrepancies with the ground data. The amount of precipitation, which falls over the sea, remains almost unchanged. For all months of the year model values are situated in the middle of the family of curves, and deviations from the direct measurement data are rather small.

The components of the Black Sea water balance. The equation of the Black Sea water balance has the following form:

$$V^{+} - V^{-} = R + P - E,$$

where V^{+}, V^{-} are water inflow and outflow through the straits; R is a river runoff; P is the amount of precipitation; E is the amount of evaporation. $E - P$ difference determines the water discharge through the Bosphorus, the Kerch Strait and river runoff. Due to the lack of observational data the amount of precipitation and evaporation over the Black Sea are determined by the calculations. According to [3], the most reliable results are obtained from regional numerical modeling, i.e. recalculation of reanalysis data with low spatial resolution at the grid with higher resolution. P and E values, obtained by means of *HadRM*3*P* (*PRECIS*) regional model, are given in [3]. It is interesting to compare them with the corresponding values calculated from the results of *RegCM* regional model (Table 1).

Table 1

Average annual precipitation and average annual evaporation calculated by different models

Model, calculation period	P, mm	E, mm	$E - P$, mm
RegCM, 1980 – 2013	475	844	**369**
PRECIS with *ERA-Interim*, 1990 – 2001	528	900	**372**
PRECIS with *ERA*-40, 1958 – 2001 [3]	564	924	**360**

As in [3] the outdated *ERA*-40 reanalysis was used as an input data for the *PRECIS* model, the regional modeling by the *PRECIS* was carried out once again but already with the improved *ERA-Interim* reanalysis at the model input. As is obvious from Tab. 1, P and E values did not change significantly at that. It is interesting to note that though precipitation and evaporation in the *RegCM* model are on average lower than in *PRECIS* model, $E - P$ difference changes insignificantly in both models. This confirms the estimation of water discharge through the Bosporus, the Kerch Strait and rivers given in [3].

It is also of interest to check how the amounts of precipitation and evaporation over the Black Sea changed in the numerical experiment (see Annex 2).

T a b l e 2

Average annual precipitation and average annual evaporation calculated by *RegCM* model for 1980 – 1984

Calculations	P, mm	E, mm	$E - P$, mm
Control Run	461	807	**346**
Numerical Experiment	468	754	**286**

The amount of precipitation, which falls over the Black Sea (Tab. 2), remained almost unchanged. It is quite expectable because the changes in the model were aimed to reduce the precipitation amount only over the land. The evaporation from the Black Sea surface has decreased at that. Considering the fact that reliable estimation of $E - P$ difference falls within the range of 350 – 370 mm/year, one can assume that the amount of precipitation over the Black Sea is still overestimated in the *RegCM* model in spite of good correlation with the reanalysis data.

Conclusion. In this paper the parameterization schemes for calculating convective and nonconvective precipitation in the regional model *RegCM* has been adapted to the Black Sea region by means of numerical experiments. It was shown that the amount of nonconvective precipitation above the plain land (to the north of the Black Sea) was overestimated. This was confirmed by the comparison of the *RegCM* modeling results both with reanalysis results and observational data. It was also determined that the discrepancies between *RegCM* modeling results and *ERA-Interim* reanalysis data over the Black Sea were relatively small due to the fact that the amount of convective precipitation over the sea in the *RegCM* model was underestimated and the amount of nonconvective one was overestimated. Therefore, the changes, which were introduced to the model, were aimed to reduce the amount of precipitation only over the land. It was revealed that the discrepancies between the monthly average fields of surface air temperature in *RegCM* and *ERA-Interim* were related to the errors of *RegCM* model (which overestimates the precipitation amount over the plain land), errors of the model input data and differences in terrain height.

The numerical experiments aimed to reduce monthly average amount of nonconvective precipitation over the land were carried out. It was revealed that the results of precipitation modeling by *RegCM* were the most sensitive to the change of cloud water content threshold and to the change of maximum and minimum thresholds of β. Characteristic rate of raindrop evaporation and the method of calculation of the updraft mass flux have insignificant effect on nonconvective precipitation modeling results.

Despite the fact that the average annual values of precipitation and evaporation over the Black Sea in *RegCM* are lower than in *PRECIS*, $E - P$ difference in both models makes up ~370 mm. It means that both models provide quite similar estimations of the water discharge through the Bosporus, the Kerch Strait and river runoffs in the Black Sea. In the numerical experiment annual average evaporation from the Black Sea surface has reduced, and due to this fact $E - P$ difference has also decreased. If we assume that during the control run reliable assessment of $E - P$ was obtained, the schemes of precipitation calculation over the sea in the *RegCM* should be also adjusted. Such adjustment seems to be the theme for the further investigations.

Annex 1

Here we represent a brief description of climatic precipitation datasets used in the paper.

Data source	Spatial resolution	Period, years.	Availability of precipitation data over the sea
ERA-Interim	0.5 × 0.5	1979 – 2012	Available
MERRA	2/3 × 1/2	1979 – 2014	«
E-OBS	0.25 × 0.25	1950 – 2013	Not available
CRU	0.5 × 0.5	1901 – 2014	«
ECA&D	Data from selected meteorological stations	1781 – 2015	«
NCDC		1929 – 2014	«
RegCM	0.11 × 0.11	1979 – 2013	Available

Annex 2

Here we represent the values of empirical coefficients for the most successful numerical experiment: $\beta_{\min} = 0.2$, $\beta_{\max} = 0.45$, and also C_{acc} in different months of the year.

C_{acc}	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Over the land	14	16.5	14	15	25	0.2	0.4	0.4	3	3	7	9
Over the sea	5	6	4.5	6	7.5	0.2	0.2	0.2	2	2	3	3.5

N o t e . The *RegCM* model by default includes the following notations: $\beta_{\min}$ = = 0.25, $\beta_{\max}$ = 0.5, C_{acc} = 0.4.

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