The role of dust aerosols in forming the regional climate of Georgia

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Abstract. The scope of this work is to study some aspects of the formation of the regional climate of the Caucasus (with a specific focus on Georgia) against the background of the impact of mineral aerosols using modelling (the RegCM interactively coupled with a dust module, WRF-Chem, and HYSPLIT models) and satellite data (MODIS, CALIPSO). The annual mean, as well as the error in summer and winter temperatures, standard deviation and correlation coefficient compared to the CRU data were calculated for 8 sub-regions with different orographic and climate properties. The calculation results showed that dust aerosol is an active player in the climatic system of the Caucasus (Georgia). Numerical results showed that the inclusion of dust radiative forcing in the RegCM numerical model brought the simulated summer temperature closer to the observed temperature values. The mean annual temperature increased throughout Georgia in simulations that took into account the direct impact of dust. Calculations using the WRF-Chem and HYSPLIT models revealed that during the study period, aeolian dust was brought into the territory of the South Caucasus (Georgia) equally not only from Africa and the Middle East, but also from Central (Western) Asia deserts, which was not noted earlier.

1 Introduction

Dust and smoke, being one of the main components of atmospheric aerosol, are the main sources of uncertainty in climate variability [1]. Aeolian dust aerosols (ADA), generated mainly by desert storms, are the leading natural aerosols (75% of the total aerosol mass is mineral dust) [2]. In general, ADA scatter and absorb both solar and terrestrial radiation and, therefore, intensely affect the radiation balance of the Earth and the climate [3]. Lifted by the wind from soils, rocks, plants, and anthropogenic pollutants into the atmosphere, and then settling into clouds, glaciers, water and soil aeolian ADA change the structure of these systems and, as a result, change the physicochemical processes occurring in them [4]. For example, deposited in clouds coated with sulphur due to chemical reactions, ADA rearrange the molecular and ionic structures of clouds through chemical reactions [5]. In the future, ADA can serve as giant cloud condensation nuclei, which enhances the collision and coalescence of droplets and, consequently, increases the production of warm precipitation [6]. However, satellite, aviation, and laboratory observations have shown that ADA can also suppress precipitation by increasing the number of cloud condensation nuclei in warm clouds [7], and the presence of a large amount of ADA in clouds can prevent the formation of precipitation [8]. Studies have shown that the main sources of dust load are the largest deserts of the world (Sahara and Sahel in Africa, Gobi, Kyzylkum, Karakum, Takla-Makan in Central Asia, Arabian deserts...), while anthropogenic activities on average account for only 30% of the dust load [9, 10]. It should be noted that ADA from nearby deserts has a strong impact on the Mediterranean region, namely, it significantly affects the quality of the atmosphere, their optical properties, changing the microphysics of clouds, the surface albedo and the entire Mediterranean climate system [9, 11, 12, 13]. In general, arid and semi-arid areas adjacent to deserts are the most affected by dust storms, but remote areas are also vulnerable to severe dust storms [14,15]. For example, strong winds that carry a large amount of mineral dust from African deserts into the atmosphere and of which about 30% re-settle in the deserts, 20% are transported regionally and about 50% are transported through the Atlantic and Pacific oceans. out to the USA, the Caribbean, South America and East Asia, which can even reach the island of Japan [14,16]. The Caucasian territory is no exception, and, for example, based on the analysis of samples of long-term desert dust from the peaks of Elbrus and Kazbek mountains, it is shown that even the territory of the North Caucasus was exposed to ADA coming from the desert of Africa and the

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Middle East [17-20]. Although domestic dust is one of the main pollutants in Georgia (Bulletins of the National Environmental Agency (NEA) of Georgia), the transfer of ADA from deserts to Georgia is not yet well studied using mathematical modelling based on satellite data [19-22]. Thus, the main purpose of this article is to study some features of the regional climate of the Caucasus (with a special focus on Georgia) associated with the impact of mineral dust aerosols using modelling and satellite data. Namely, the study of the role of mineral dust aerosols in the formation of the regional climate of the Caucasus (Georgia) and the influence of mineral dust aerosol on the spatiotemporal distribution of temperature and optical thickness of aerosol in the Caucasus (Georgia). Study of possible routes for transporting ADA from the neighbouring deserts of Western Asia to the territory of Georgia using a Weather Research and Forecasting (WRF-Chem) model in combination with the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. The capabilities of the RegCM and WRF-Chem models are evaluated using the observational dataset (particulate matter in situ (PM10)), the satellite products of the Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and the Moderate Resolution Imaging Spectroradiometer (MODIS).

2 Models and data

2.1 RegCM4/WRF-Chem models

This study uses the Fourth Generation Regional Climate Modeling System (RegCM4) with a module for emission, transport and deposition of mineral dust particles. RegCM4/dust is widely used to study the influence of dust aerosols on the formation of the regional climate [11, 23, 24]. The bound dust module includes dust emission, transport (wet and dry removal), gravitational settling and optical properties calculation. The dust emission scheme, the biosphere-atmosphere transfer scheme (BATS), depends entirely on: the simulated threshold friction velocity, surface wind, processes in the atmosphere of the boundary layer, the characteristics of the roughness of the earth's surface and soil moisture, which are provided by the BATS for the transfer of the terrestrial biosphere into the atmosphere [23]. In this study, we consider the role of BATS on climate, that is, the impact of mineral dust on the formation of the regional climate of Georgia according to the RegCM4.7/dust model over 17 years. It should be noted that dust particles are divided into four size bins: small (0.01–1.0 μm), clusters (1.0–2.5 μm), large (2.5–5 μm), giant (5, 0-20.0 μm) using four steps in dust parameterization [25]. Experiments were carried out with and without Dust modules, but in both cases the same physical schemes were used for the experiments: Holtslag PBL Boundary layer scheme; Tiedtke Cumulus convection scheme over the land and the ocean; Explicit moisture scheme. In the experiment with Dust, only dust tracers were involved - a scheme of 4 dust collectors, and the direct effect of aerosol on radiation and atmospheric dynamics was taken into account. To investigate the effect of mesh resolution, each run was performed with nested (reduced) simulations. For coarse domains, we used a time step of 100 s. and for nested - 30 sec. The coarse domains contained 128 grid nodes in each of the horizontal directions and 18 vertical levels, while the nested domains contained 64 and 18, respectively. The nested domain was located in the centre of a large domain and completely covered the Caucasus region.

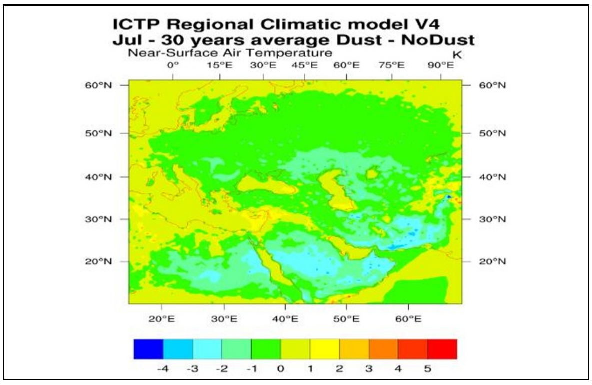
The Weather Research and Forecasting Chemistry (WRF-Chemv.3.6.1) model uses a one-way nesting with two nested regions. A large area with a grid spacing of 100 x 81, a grid spacing of 37.2 km horizontally and 48 vertical levels included the deserts of the Sahara, the Middle East and Central Asia. At the same time, the inner nested area with a grid size of 124x58 points and a step of 12.4 km completely covered the territory of the Caucasus (with the center in the capital of Georgia, Tbilisi). To run the WRF-Chem v.3.6 model, the following were selected: Purdue Lin from microphysics schemes, the Grell-Devenyi ensemble from cumulus cloud parametrization schemes, the Mellor-Yamada-Janich scheme from the planetary boundary layer (PBL), the Noah earth surface model from surface physics. We used the GOCART dust scheme (dust_opt= 1) module_gocart_dust.F, taking into account the amount of dust emissions into the atmosphere and mainly depending on the speed of the surface wind and soil characteristics.

2.2 Data

To evaluate the obtained results, a comparative study was carried out between the outputs of the WRF-Chem v.3.6.1 model, with data obtained from the MODIS (http://modis.gsfc.nasa.gov/), CALIPSO- (http:/ /eosweb. larc.nasa.gov/)) and on-site measurements from the NEA. Also the HYSPLIT(http://ready.arl.noaa.gov/HYSPLIT.php) model used to calculate the dispersion, trajectories and deposition of air masses (pollutants) on a local to global scale. As for the observed dust data. In order to ensure the safety and health of the population, one of the activities of the NEA of Georgia is the collection and free publication of information on the state of air pollution. For this, among other things, NEA disseminates information on PM2.5 and PM10 data from air monitoring stations located in Georgia (https://nea.gov.ge/). The boundary conditions for the RegCM4 model were generated based on the ERA-Interim global atmospheric reanalysis data [26], and the calculation results were confirmed by data from the Climate Research Center (CRU) [27]. Surface temperature measurements among six meteorological variable datasets were interpolated into a 0.75 × 0.75 grid that covered the entire terrestrial surface of the planet.

3 Results and discussion

Since there are no ground-based observations of stratospheric aerosols in the South Caucasus region, and satellite data are the only source for studying the concentration of airborne dust, the results of dust modeling were confirmed by satellite data. So, the simulated results of aerosol optical depth (AOD) were compared with MODIS (MISR, sea waves) data for four seasons in the period 2000-2019. From the analysis of the MODIS data, the AOD values were small in winter, since during this period of the year heavy snowfalls prevented the accumulation of dust, and, therefore, its values over the Caucasus reached only 0.09-0.18 aerosol optical depths observed at characteristic wavelength of 550 nm. The maximum AOD values (0.55-0.63 at 550 nm) occurred in spring (the beginning of the summer season), when domestic dust, enriched with aeolian dust, brought from the deserts of the Sahara, the Middle East and Western Asia through the Mediterranean and Caspian Seas, got into the regions of the Caucasus [17, 22]. Observations also showed that during the dry period (from June to October) dust emissions were frequent due to the extremely stable atmospheric situation (sometimes with episodes of aeolian dust), which contributes to the accumulation of aerosols in the atmosphere in the Caucasus (Georgia) [22, 28]. Problems of this kind, associated with dust and synoptic meteorological conditions, were studied earlier by the authors [28-30]. Some of the results obtained are similar, but some are different, since the Caucasus (Georgian) region has its own characteristics. The nature of the seasonal distribution of the modelled AOD was in good agreement with the MODIS data. It should be noted that in the spring and summer periods, the simulated dust concentrations and the corresponding AOD in the areas of generation of dust storms were overestimated, but for the Caucasus region, the calculated AOD values were close to MODIS satellite data. In order to assess the impact of dust on the simulated temperature at 2 m, all calculated results were interpolated to a grid with a resolution of half a degree (0.50) and compared with the CRU surface temperature data (on land only) for annual and seasonal scales.



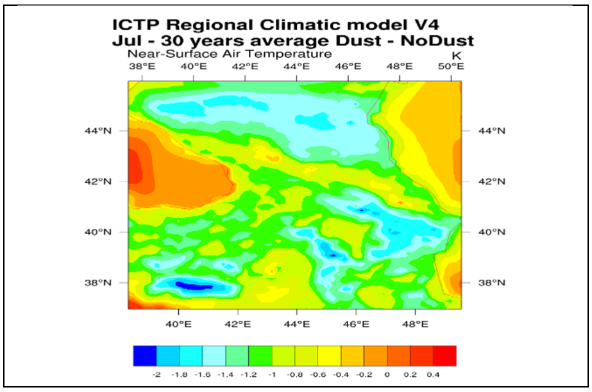


Fig.1 Differences in mean July surface temperatures between simulations with dust and no dust on different resolutions (above-50.1 km; below-16,7 km).

As an example, Fig. 1 shows the differences in average July surface temperatures between simulations with dust and without dust at different resolutions. Calculations obtained on coarse grids with a resolution of 50 km show that the negative difference is greater in the northern and eastern parts of large domains along the Caspian coast and lower in the Black Sea part. Calculations obtained on a fine grid with a resolution of 16.7 km showed that the negative difference is higher along the ridges of the Caucasus, and the positive difference is observed over the Black and Caspian Seas.

The territory of the Caucasus (Georgia) has a complex and heterogeneous orography, especially in certain regions, therefore, for a thorough study of the influence of dust in different regions and the effectiveness of modelling in experiments in these subregions, the nested region of the South Caucasus was divided into 8 subregions. (Fig. 2).

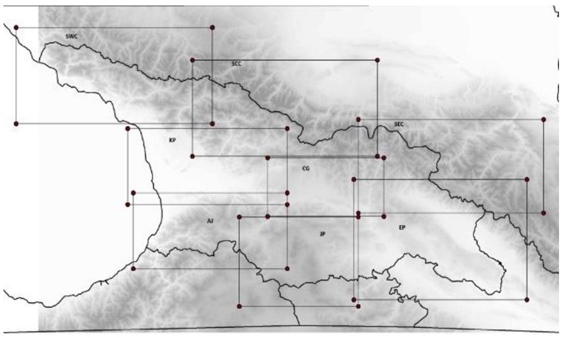


Fig. 2. The contours represent the terrain elevation (m). The location of the blocks and the names of the sub-regions are represented by abbreviations, where SCC is Central part of South Caucasus, SWC - Western part of South Caucasus, SEC - Eastern part of South Caucasus, EP - Eastern plane territory, KP - Kolkhety Down land, AJ - South mountainous part of Ajara, JP - Javakhety Plato, CP - Central part of Georgia including Likhi range.

Annual averages as well as deviations of summer and winter temperatures, standard deviation and correlation coefficient compared to CRU data were calculated with and without dust modelling, and the average values for the mentioned 8 sub-regions were estimated.

Table 1. Mean annual values of the Temperatures Bias, Standard Deviation and Correlation Coefficient for 8 sub-regions calculated with and without dust modelling.

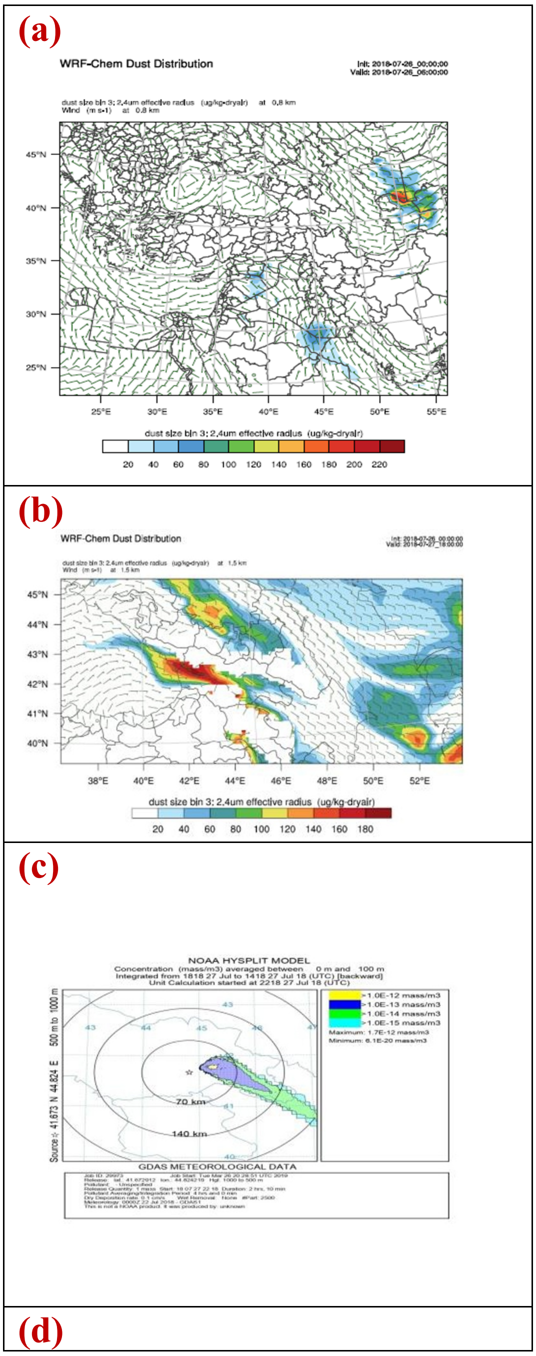
Dust			
	BIAS	STDV	CORREL
SCC	1.91	1.79	0.987
CG	-1.03	1.62	0.988
SEC	2.00	1.90	0.990
EP	-1.99	1.49	0.990
JP	-0.81	1.57	0.987
KP	0.57	2.11	0.984
AJ	0.41	1.79	0.983
SWC	0.60	1.48	0.987

No Dust			
	BIAS	STDV	CORREL
SCC	-0.53	1.94	0.984
CG	-2.79	1.66	0.986
SEC	-0.57	1.77	0.988
EP	-3.15	1.47	0.989
JP	-2.61	1.70	0.984
KP	-1.67	2.21	0.981
AJ	-0.99	1.93	0.981
SWC	-1.41	1.54	0.985

According to Table 1, the annual negative bias appears in all sub-regions for NoDust modeling, but the largest displacements are observed in the sub-regions of the Eastern Plain (EP), Central Georgia (CG) and Javakheti Plateau (DP) territories. In addition, calculations showed that deviations from the Nested NoDust launch were even greater for most sub-regions. Table 1 shows that dust modeling has a clear advantage in reducing the cold bias, and in the western sub-regions gives a warm bias. The same results were obtained for the Nested_Dust runs, which also improved performance and smoothed out bias in almost every other area compared to the course domain

3.1 WRF-Chem and HYSPLIT models calculations .

The WRF-Chem model with the HYSPLIT model identified and modeled 15 cases of mineral dust transport from the surrounding deserts to Georgia between December 2017 and June 2023. Our aim in this study is to discuss some of them associated with the intrusion of Aeoliamic dust from Western Asia. The fact is that, as noted above, based on the analysis of samples of perennial desert dust from the slopes of the Elbrus and Kazbek peaks, it was shown that the territory of the North Caucasus was exposed to ADA coming from the deserts of Africa and the Middle East [17–20]. Therefore, in this study, we will consider only eastern dust invasions on the territory of the Caucasus (Georgia). On July 26, 2018, an unusually strong dust fog invasion was recorded in the capital of Azerbaijan, Baku, and it was reported in the press and on television that a northwest wind brought dust from the Turkmen deserts across the Caspian Sea, which completely occupied the Absheron Peninsula. On July 27, 2018, a strange fog was also detected in the Georgian capital Tbilisi and its surroundings. At first, NEA Georgia was confused and stated that it was ordinary fog, but later clarified that a strong cloud of dust had come from Azerbaijan. Figure 3 shows some results of calculations using the WRF-Chem v.3.6 model (in combination with a dust module) performed on coarse and fine resolution grids (see Fig. 3 (a)-(b)) and calculations using the HYSPLIT model (see Fig. 3 (c)-(d)). Figure 3 (a) shows that there are two large dust clouds above the Karakum desert at an altitude of 800 m above sea level, and in addition, two small dust clouds are observed in Syria and Iraq at 06:00 on July 26, 2018. Calculations showed that the Karakum dust cloud moved westward towards the Caspian Sea, it reached the territory of Azerbaijan, and then was shifted westward towards the territory of Georgia, while a larger dust cloud over the Arabian Peninsula moved towards the Indian Ocean.



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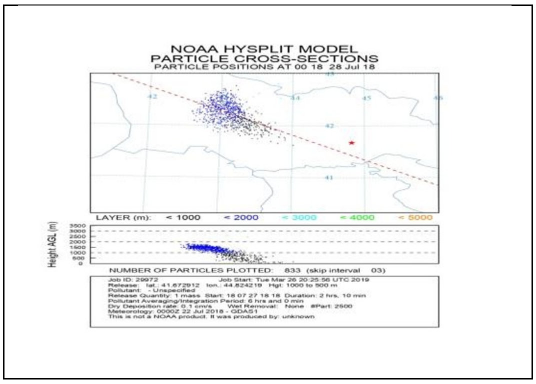

Fig.3. The results of numerical calculations of the model WRF-Chem v.3.6.1, executed on a course (a) at 06:00 on July 26, 2018 and fine resolution grids (b) at 18:00 on July 27, 2018. Backward Trajectories of concentrations (mass/m3) carred out by HYSPLIT model averaged Between 0-100 m and integrated from 18:18 to 14:18 on 27 July 2018 (Fig. (c)), and particles position at 00:18 28 July 2018 (Fig. (d)).

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Aeolian dust source location can be determined using the HYSPLIT model when studying the transport of dust storms. One of the most common applications of HYSPLIT model products is forward and backward trajectory analysis to locate the source of dust storms and mineral dust transport trajectories. In this study, the HYSPLIT model was used to study the backward and forward trajectories of transport, dispersion and deposition of mineral dust in Georgia (Tbilisi (41° 72' N, 44° 78' E)) from 25 to 28 July 2018. Fig. 3 (c) and (d) show backward trajectories of concentrations (mass/m3) carred out by HYSPLIT model. Namely Fig. 3 (c) shows averaged between 0-100 m and integrated from 18:18 to 14:18 on 27 July 2018 backward trajectories of concentrations based on GDAS Meteorological Data, and particles position at 00:18 28 July 2018 are shown on Fig. (d). Analysis of Fig. 3 (c), (d) shows that the dust storm, as in reality, formed in the Karakum desert at an altitude of 800 m above sea level, then the maximum concentration of dust aerosol was observed over the Caspian Sea, and the main part of the dust particles was displaced from Caspian Sea towards Baku, and then penetrated into Georgia through the territory of Azerbaijan. Thus, according to the calculations of the WRF-Chem and HYSPLIT models, the dust storm that originated in the territory of Turkmenistan reached the territory of Azerbaijan, and then the fully accouped the territory of Georgia.

Table 2. 24-hours averaged PM10 concentrations distribution in different districts of Tbilisi from 27 to 29 July 2018.

PM_{10} (mkg/m^3)	27/7/2018	28/7/2018	29/7/2018
Kazbegi Avenue	**179.0**	**78.0**	52.0
Varketili District	**152.0**	**74.0**	53.0
Vashlidjvari District	**206.0**	**76.0**	54.0

The distribution of daily averaged PM10 concentrations in different districts of Tbilisi from July 27 to July 29, 2018 presented in Table 2 confirms that the remnants of the Karakum dust storm reached the territory of Tbilisi on July 27, 2018. Indeed, the concentrations of PM10 (averaged over 24 hours) are several times exceed the corresponding maximum permissible concentrations (MPC) - (50 µg/m3) in all districts of Tbilisi. Namely, the average concentrations were 3.58 times higher than the corresponding MPCs on Kazbegi Avenue, 3.04 times in the Varketili region, and the maximum concentration was observed in the Vashlijvari region (4.12 times), which is the easternmost district of Tbilisi. The uneven distribution of PM10 concentrations in Tbilisi can be explained by the complex topography of Tbilisi and the peculiarities of local circulation processes. In addition, field measurements showed that even in Batumi (Black Sea coast), the average concentrations of PM10 were 3.14 times higher than the corresponding MPCs (50 µg/m3) on July 27, 2018, and the average concentrations of PM10 remained high until July 29, 2018 2018 in Batumi.

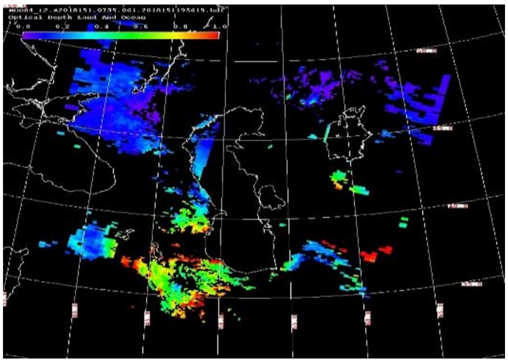

Fig.4 The maps of the altitude-orbit- cross–section horizontal measurements of AOD obtained using MODIC) on 31 May 2018.

In addition, the results of calculations using the WRF-Chem model and the HYSPLIT model, performed from 2018 to 2023, showed that during this period, 7 cases of dust entry into the territory of Georgia from the east were recorded. For example, Fig. 4 shows one of them, which took place on May 31, 2018 and is depicted using MODIS. Figure 4 shows that several dust storms originating from the territory of Turkmenistan and Iran penetrate Azerbaijan and move towards Georgia.

4 Conclusions

In this article, one climate parameter, temperature at 2m altitude, was studied and found the difference between Dust and No-Dust simulations. The annual mean, as well as the error in summer and winter temperatures, standard deviation and correlation coefficient compared to the CRU data were calculated for 8 sub-regions with different orographic and climate properties. The calculation results showed that dust aerosol is an active player in the climatic system of the Caucasus (Georgia). The mineral dust aerosol affected the spatial and temporal inhomogeneity of the temperature distribution and the optical thickness of the aerosol on the territory of Georgia, and the simulation results were generally consistent with the MODIS and CALIPSO satellite data. Numerical results showed that inclusion of dust radiative forcing improved the simulated summer temperature. The mean annual temperature increased throughout Georgia in simulations where the direct effects of dust were taken into account. The mean annual temperature increased throughout Georgia in simulations that took into account the direct impact of dust. This is the first attempt to study this problem using the RegCM model with a dust module, taking into account the radiative forcing of aerosols in Georgia, and the results obtained can be of both theoretical and practical importance for such a complex territory as Georgia. Calculations using the WRF-Chem and HYSPLIT models revealed that during the period under study, dust was brought into the territory of the South Caucasus (Georgia) equally from the deserts of Africa, the Middle East, and Western Asia. The results of numerical calculations performed from 2018 to 2023 showed that during this period 3 cases of dust transfer from the deserts of Western Asia to the territory of the Caucasus (Georgia) were recorded. One of them, held on July 26-28, 2018, is modeled and discussed in this article. Comparison of the calculations of the WRF-Chem and HYSPLIT models with field data showed that the WRF-Chem model well reproduced the transfer of dust aerosols from the Kara-Kum and Kyzylkum deserts to the Caucasus in conditions of complex relief (traces of which have not yet been recorded in the glaciers of the Caucasus mountains Elbrus and Kazbeg). Thus, it can be said that dust aerosols have a strong influence and are an active player in the climate system of Georgia.

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