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ASSESSING REGIONAL CLIMATE MODEL REGCM4.7.1: INSIGHTS FROM SIMULATIONS IN GEORGIA

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ABSTRACT: This study aims to assess the ability of the Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climate Model version 4.7.1 to reproduce historical monthly mean temperatures and precipitation in different physical geographical conditions of Georgia. RegCM4.7.1 simulation has been done at 12 km resolution over the territory of Georgia from 1985 to 2014, with the hourly ERA5 high-resolution atmospheric reanalysis of the global climate data of the European Centre for Medium-Range Weather Forecasts (ECMWF) as boundary conditions. Standard deviation is used to evaluate the model's performance against Georgia's meteorological station data. This metric helps quantify the agreement between model outputs and observed data. Conducting historical runs and validating the model against observed data contributes to understanding how regional climate models perform in regions with diverse geographical features and is crucial for ensuring the reliability of future climate projections. A group of weather stations with the best data modeling results in all months of the year when the difference between the actual and model data does not exceed the standard deviation value is Kutaisi, Gori, Sagarejo, Tbilisi, and Tsalka for air temperature and Akhalkalaki, Akhaltsikhe, Dedoplistskaro, Gori, Sagarejo, Tbilisi, Telavi, and Tianeti for precipitation. The modeling results are generally satisfactory, indicating that the model can be used effectively for future climate projections in Georgia. These findings provide valuable insights for policymakers, stakeholders, and researchers working on climate change adaptation in Georgia.

Keywords: Climate-resilient infrastructure, Standard deviation, Projection, High resolution, Observational data

1. INTRODUCTION

Understanding climate change impacts on infrastructure and designing resilient infrastructure is essential for ensuring communities' safety, security, and sustainability and supporting economic development in a changing climate.

Climate data plays a crucial role in informing infrastructure design and resilience measures. For example, climate data evaluates how shifting precipitation patterns affect stormwater management systems. This data aids engineers in designing infrastructure capable of efficiently capturing, storing, and treating surplus rainwater, thereby mitigating the risks of flooding and water pollution [1-3].

Regional climate modeling is vital for developing climate-resilient infrastructure because it provides detailed, region-specific climate information [4].

Historical simulations and model validation ensure the reliability of climate projections [5,6]. Historical simulations allow climate models to be tested against past climate conditions for which observations are available. If a model can accurately simulate past climate variability and trends, there is greater confidence in its ability to project future climate changes. Reliable climate projections are crucial for guiding adaptation measures aimed at reducing the impacts of climate change. By understanding how the climate has changed in the past and how it is likely to change in the future, policymakers and planners can make more informed decisions about how to prepare for and respond to these changes [7].

Therefore, it is essential to provide high-resolution climate simulations for historical periods and future climate change projections for Georgia. For the territory of Georgia, there are very few studies regarding future climate change projections with a horizontal resolution of 20 km and 25 km [8,9].

A horizontal resolution of 20 km is considered relatively coarse for climate change assessments, especially for a region like Georgia with diverse topography and complex terrain features. Higher-resolution models can better capture fine-scale processes, such as local winds, precipitation patterns, and temperature gradients, which are essential for accurately representing regional climate variability and impacts.

The higher-resolution climate information will benefit Georgian stakeholders by providing them with the information they need to make informed decisions about climate change adaptation and sustainable development. It will also significantly impact regional and global policymaking, providing policymakers with the necessary information to develop effective climate change policies and strategies [7].

This study enhances the field of climate change research not only in Georgia but also internationally. It adds to our understanding of how regional climate models perform in complex terrain and coastal regions, benefiting regions facing similar climate challenges. The study improves our understanding of the impacts of climate change in Georgia, including changes in temperature and precipitation patterns. The study's findings can inform policy and decision-making processes within Georgia and internationally.

Georgia's complex topography and proximity to the Black Sea result in diverse microclimates across the country. High-resolution climate information can help identify regional variations in climate change impacts, allowing for more targeted adaptation and mitigation strategies. Providing high-resolution climate information for Georgia is crucial for developing effective climate change adaptation and mitigation strategies to help reduce vulnerability and build resilience to climate impacts.

In this work for the first time, 30-year RegCM4.7.1 simulations have been done at 12 km resolution for Georgia for the historical period, with the hourly ERA5 high-resolution atmospheric reanalysis of the global climate data of European Centre for Medium-Range Weather Forecasts (ECMWF).

Conducting 30-year RegCM4.7.1 simulations at a 12 km resolution for Georgia during the historical period can capture localized climate patterns, which is essential for understanding the regional climate variability of a specific area like Georgia. Georgia's complex topography and proximity to the Black Sea create diverse climatic conditions, which can be better represented with higher resolution. This simulation provides a more detailed understanding of the historical climate of Georgia, including temperature and precipitation patterns, which is crucial for assessing the impacts of climate change on the region. This simulation is also the first step towards the high-resolution future climate projections for Georgia, which can provide quality impact-level information and assessments. This can help decision-makers at all levels understand the implications of climate change and make informed decisions to mitigate its impacts and build resilience.

This study aims to evaluate a 30-year (1985-2014) high-resolution regional climate simulation of historical monthly mean temperatures and precipitation from the RegCM4.7.1 model against meteorological station observation data in Georgia. Regional climate simulation of historical monthly mean temperatures and precipitation were compared with observation data only using standard deviations. Standard deviation is one of the best criteria for assessing the degree of compliance between model data and actual data because it shows the amount of average deviation of the data regarding its mean value.

The research gave us an idea of how RegCM4.7.1, with the selected configuration, describes mean monthly temperatures and monthly sums of precipitation for the historical period in the territory of Georgia. Georgia's climate is shaped by its unique geographical features, including its proximity to the Black Sea and the presence of the Caucasus Mountain ranges. The contrast between the humid subtropical conditions in the west and the transitional climate in the east underscores the diverse climate patterns found within the country.

In the subsequent sections of the article, the research significance is underlined. Then, the study area, the regional climate model used for the simulation, the model setup, boundary conditions, and the validation process are considered. Following this, the results of the historical climate simulation are presented, and the implications of the findings, highlighting the significance of high-resolution climate simulations for understanding climate change impacts in Georgia and the study's limitations, are discussed. Finally, conclusions and recommendations for future research directions are presented.

2. RESEARCH SIGNIFICANCE

The study is significant from both scientific and societal perspectives, as it improves our understanding of regional climate modeling and its applications. This understanding is essential for addressing the challenges of climate change in complex terrain like Georgia and ensuring society's well-being.

The novelty of the research lies in evaluating a high-resolution regional climate simulation for Georgia, which features complex terrain and climatic conditions. This adds to understanding how regional climate models perform in areas with diverse geographical features. Evaluating the climate simulation over 30 years is crucial for understanding the model's ability to capture long-term climate trends and variability.

3. RESEARCH METHODS AND DATA

3.1 Study area

Georgia (Fig.1) is located at the junction of Europe and Asia, in the western part of Transcaucasia on the eastern coast of the Black Sea. It belongs to Eastern Europe and Western Asia. Georgia is a mountainous country. In the northern part of the territory, the Greater Caucasus stretches in the direction from northwest to southeast. In the southern part, parallel to the Greater Caucasus stretches the South Georgian Highland. Between the Greater

Caucasus and the South Georgian Highland lies a tectonic depression, which is represented by lowlands, river valleys, plains, and plateaus. The nature of Georgia is very diverse. The Greater Caucasus protects the territory of Georgia from the direct penetration of cold air masses from the north. The Black Sea has a great impact on the climate. Almost all types of climates found on the globe are found here, from the climate of permanent snow and glaciers in the high mountains of the Greater Caucasus to the humid subtropical climate of the Black Sea coast and the steppe continental climate of the eastern part of Georgia [10,11]. On the territory of Georgia, two contrasting climatic regions are formed - western Georgia with a marine humid subtropical climate and eastern Georgia with a moderate subtropical climate and a transitional climate from the moderate humid subtropical to the dry climate of West Asia. It is enough to judge the contrast of Georgia's climatic conditions by the ranges of changes in mean annual temperatures and precipitation. On an area of about 69,700 sq. km. the mean monthly air temperature varies from minus 6 to plus 15 ^{O}C, and annual precipitation sums range from 300-4000 mm [12].

Georgia is experiencing significant impacts from climate change, with various indicators such as temperature increases, changes in precipitation patterns, glacier size reduction, sea level rise, and alterations in extreme weather events. The complexity of Georgia's topography and proximity to the sea exacerbate these effects [13-15].

The tendencies of the temperature increases are not uniform across the country, with arid regions in eastern Georgia experiencing faster warming than the more humid western regions. This non-uniformity highlights the localized effects of climate change. The data indicates a clear trend of rising temperatures since the 1960s, with both monthly minimum and maximum temperatures showing increases by 0.22 and 0.36 °C respectively. Moreover, warm extremes exhibit larger variations and trends than cold extremes, indicating a shift towards more extreme heat events [13-15].

The intensification, frequency, and duration of heat waves in Georgia have also seen significant increases over the past five decades, posing risks to human health, agriculture, and ecosystems. Overall, these observations underscore the urgent need to address the impacts of climate change in Georgia, including strategies for managing water resources, protecting vulnerable populations, and promoting sustainable development practices.

Heat waves have not only increased in frequency by 0.7 events/decade but also in duration by 4.3 days/decade/event, with significant implications for various sectors including health, agriculture, and infrastructure [13-15].

The observed increase in precipitation in western Georgia and decrease in eastern Georgia highlights the complex spatial patterns of climate change effects within the country. This divergence in precipitation trends can have profound consequences for water availability, agriculture, and ecosystems [13-15].

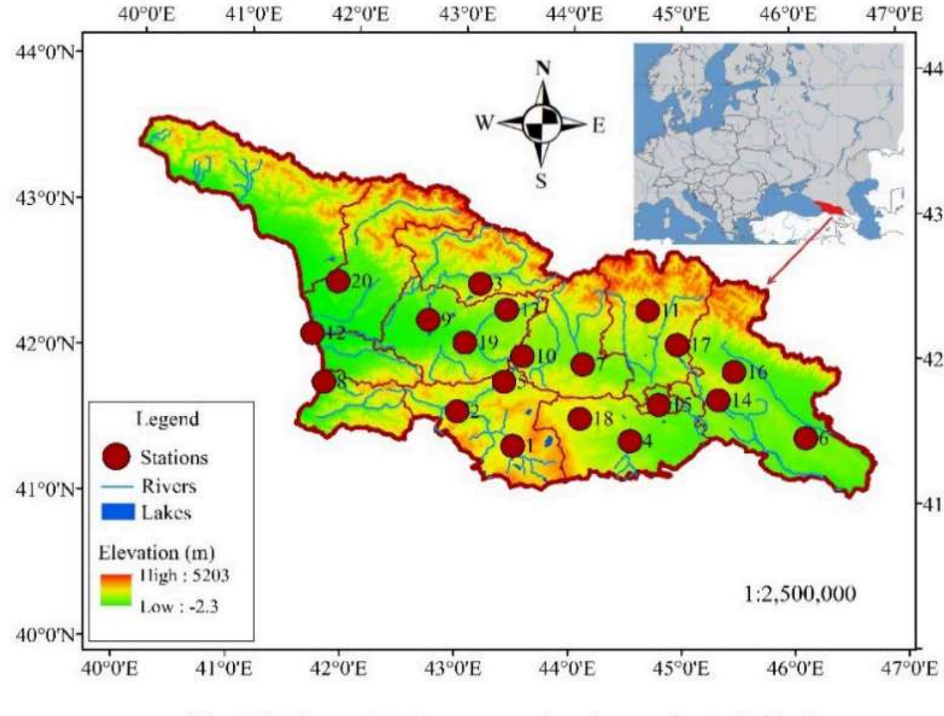

Fig. 1 Study area (stations are numbered according to Table 3)

In eastern Georgia the severity of drought has increased markedly in the past 30 years; the annual duration of the dry season has increased from 54 to 72 days, and the frequency of its occurrence has risen two-fold [6]. The marked increase in drought severity in eastern Georgia over the past few decades, along with the extension of the dry season and its increased frequency, underscores the growing water stress in this region. These changes have already led to water shortages in many areas, posing significant challenges for water resource management and agricultural production [8-10].

3.2 The Regional Climate Model

Regional Climate Model – RegCM is a widely used tool developed initially by the National Center for Atmospheric Research (NCAR) and currently maintained by the Abdus Salam International Centre for Theoretical Physics (ICTP) [16-20].

Its versatility and reliability have made it a popular choice for studying regional climate patterns worldwide [21–28].

In this study, the Regional Climate Model version 4.7.1. was applied to Georgia territory and the surrounding area. RegCM4.7.1 model was compiled with the CLM 4.5 option. For the simulation, the following configuration was used: the Holtslag boundary layer scheme [29], Zeng Ocean flux scheme [30], Tiedtke cumulus convection scheme over land and ocean [31], WSM5 moisture scheme [32, 33], RRTM radiation scheme [34, 35] and the Community Land Model scheme CLM4.5 [36]. The simulation was conducted from 1 January 1984 to 31 December 2014 at 12 km horizontal grid spacing using non-hydrostatic dynamics.

The first year, 1984 was selected as a spin-up, to allow the model's components, such as the atmosphere, ocean, land surface, and sea ice, to adjust and stabilize under the specified initial and boundary conditions. Ensuring that the model undergoes a spin-up phase and reaches equilibrium before data analysis increases confidence in the results. This approach helps confirm that observed changes or variability are not solely due to initial conditions or transient model behavior. The results for the thirty years 1985–2014 were used in this study.

For the model simulation, the hourly ERA5 high-resolution atmospheric reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF) 's global climate data and the weekly sea surface temperature from the National Oceanic and Atmospheric Administration (NOAA) [37] were used as initial and lateral boundary conditions.

The model domain consists of 200 points in the East-West direction (jx = 200), 128 points in the North-South direction (iy = 128), and 41 vertical levels (kz = 41) with the model top set at 15 hPa. The center of the simulated area is located at clat = 41.5 N., clon = 41.2 E. The domain completely covers Georgia's territory, as well as the most important terrain characteristics such as the Caucasus Mountains, and the full Black Sea and Caspian Seas (25.67 – 56.89 N, 34.10 – 48.24 E).

3.3 Weather station data

The research used the observation data of 20 meteorological stations on Georgia's territory for the years 1985-2014, particularly the average monthly air temperature values and the monthly sums of atmospheric precipitation. The National Environment Agency provided the observational data. The coordinates of meteorological stations are presented in Table 1.

In this study, average monthly air temperature values and the monthly sums of atmospheric precipitation from meteorological station observations and model simulations were used.

The selected 20 meteorological stations reflect different climatic zones of Georgia and are characterized by different climatic conditions. In particular, Kobuleti and Poti are characterized by excessively humid subzone with prevailing sea breeze during the year and maximum precipitation in autumn-winter; Kutaisi and Zugdidi - Humid subzone with well-expressed monsoon like winds and maximum precipitation in spring-autumn; Zestaponi-Sufficiently humid climate with moderate cold winter and comparatively dry hot summer; Ambrolfuri, Mta-Sabueti and Sachkhere - Humid climate with cold winter and prolonged cold summer; Bolnisi-Moderate warm steppe climate with hot summer and precipitation with two minimums per year; Borjomi, Dedoplistskaro, Fasanauri and Tianeti - Moderate humid climate with moderately cold winter and prolonged warm summer, precipitation with two minimums per year; Gori, Sagarejo and Tbilisi - Transitional climate from moderate warm steppe to moderate humid climate with hot summer and precipitation with two minimums per year; Telavi - Moderate humid climate with moderately cold winter and hot summer, precipitation with two minimums per year; Akhalkalaki and Akhaltsikhe - Highland steppe climate with less snowy cold winter and prolonged cold summer; Tsalka - Transitional climate from moderately humid climate to highland steppe climate with cold winter and prolonged summer [38].

Because of this, the National Environment Agency uses the data from these 20 meteorological stations for climate analysis in Georgia and sends information to the WMO (World Meteorological Organization) based on the data from these stations. Long-term observations are conducted at these stations using standard meteorological instruments that continue to this day. The data of the National Environmental Agency are available to scientific institutions without any fees.

3.4 Standard deviation

Model temperature and precipitation values do not always coincide with actual data, and they often differ significantly from each other. The standard deviation is used to assess the correspondence of model data to actual data. It is one of the criteria for assessing the degree of agreement between model data and actual data because it shows the amount of the data's average deviation relative to its mean value.

The reliability of a regional climate model is checked by comparing model data with actual data, taking into account the standard deviation. Standard deviation is very important in identifying the plausibility of the phenomenon under study compared to the value predicted by the theory. If the mean value of the measurements differs greatly from the values predicted by the theory, then the obtained values or the method of obtaining them should be rechecked.

The standard deviation reflects the variability of a given parameter over a selected period. It allows us to estimate how large the difference is between the mean values of actual and model data at different points in time. In a normal distribution, about 68% of observations fall within one standard deviation of the mean. Approximately 95% of observations are within two standard deviations of the mean. Almost 99.7% of observations are within three standard deviations of the mean [39]. This property of the normal distribution is widely used in statistics to assess probability and interpret data.

Empirical distributions of monthly temperature and precipitation values are mostly close to the normal distribution function (Gaussian distribution) [39], therefore, taking into account the above 3 degrees of correspondence between model data and actual data were considered:

1. The best - when the difference between the actual and model data does not exceed the standard deviation (St Dev) of the actual data. – (about 68% of observations).
2. Satisfactory - when the difference between actual and model data fluctuates within St Dev-2St Dev. – (about 27% of observations).
3. Unsatisfactory - when the difference between actual and model data is more than 2St Dev. – (in total 4% of observations).

Thus, the simulation results largely depend on the nature of the standard deviation, i.e. from the measure of dispersion of the actual mean. The larger the standard deviation value, the larger the difference is acceptable between the actual and model values, and vice versa, the smaller the standard deviation value, the smaller the difference between the actual and model values is sufficient to assess their compliance.

In this regard, it is important to know the nature of the spatial and temporal distribution of standard deviations of mean monthly air temperatures and monthly sums of atmospheric precipitation.

In the research, standard deviations were calculated from the sums of mean monthly temperatures and monthly precipitations of 20 weather stations.

4. RESULTS AND DISCUSSION

Fig. 2 presents the annual course of average and extreme values of standard deviations of mean monthly air temperatures and monthly sums of atmospheric precipitation for the entire sample (20 stations) from 1985 to 2014.

Standard deviation is the most common indicator of the dispersion of the values of a random variable relative to its mathematical expectation (analogous to the arithmetic mean). It displays the variability of a given parameter over a selected period and allows an estimate of how large the difference is between the mean values of real and model data at different points in time.

It follows from Fig. 2 that the mean value of the standard deviation of the mean monthly air temperatures has an evident annual course with a maximum from January to April and a minimum in summer and early autumn.

Table 1 Location of meteorological stations

N	Weather stations	Coordinates Lat, N°	Lon, E°	N	Weather stations	Coordinates Lat, N°	Lon, E°
1.	Akhalkalaki	41.42	43.48	11.	Pasanauri	42.35	44.70
2.	Akhaltsikhe	41.63	43.00	12.	Poti	42.13	41.70
3.	Ambrolauri	42.52	43.15	13.	Sachkhere	42.35	43.42
4.	Bolnisi	41.45	44.55	14.	Sagarejo	41.73	45.33
5.	Borjomi	41.83	43.40	15.	Tbilisi	41.72	44.80
6.	Dedoplistskaro	41.47	46.08	16.	Telavi	41.93	45.48
7.	Gori	41.98	44.12	17.	Tianeti	42.12	44.97
8.	Kobuleti	41.82	41.78	18.	Tsalka	41.60	44.08
9.	Kutaisi	42.27	42.69	19.	Zestaponi	42.11	43.05
10.	Mt. Sabueti	42.03	43.48	20.	Zugdidi	42.52	41.88

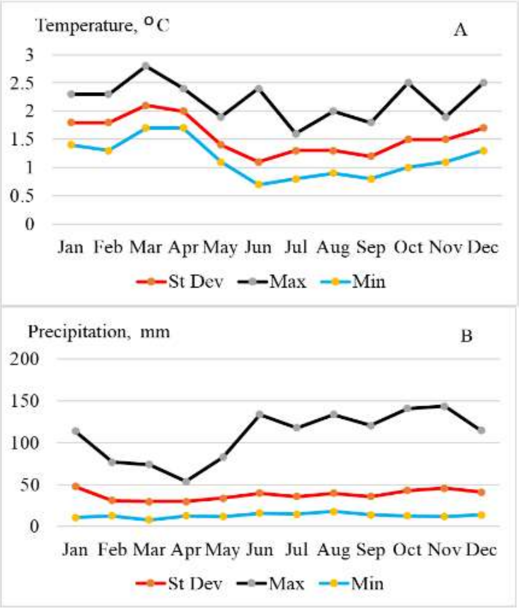

Fig. 2 Annual course of average and extreme values of standard deviations of mean monthly air temperatures (A) and monthly sums of atmospheric precipitation (B) in 1985-2014

A similar regime is noted in the annual course of extreme values of standard deviations.

A larger value of the standard deviation shows a greater scattering of values in the presented set with the mean value of the set, a smaller value, respectively, shows that the values in the set are grouped around the mean value.

In the annual course of the standard deviation of the monthly sums of atmospheric precipitation, 2 maxima are noted in October, November, and January, and a minimum is observed from February to May with significant precipitation.

In Table 2, for 3 weather stations located in different physical and geographical conditions of Georgia, an example of the assessment of model data to actual data for the years 1985-2014 is presented. Akhalkalaki characterizes the climate of the southern Georgian highland, Pasanauri – the climate of the southern slope of the Greater Caucasus, Poti – Black Sea coast, and Tbilisi – plains of eastern Georgia.

According to Table 2, in Poti, the difference between the actual and model data of the sum of precipitation in July is 160 mm, which is estimated as a satisfactory result. At the same time, when the much smaller difference between the actual and model data of the sum of precipitation in Pasanauri is 89 mm, it is estimated as an unsatisfactory result. The reason for this is a large value of the standard deviation in the first case (St Dev=118 mm) compared to the second one (St Dev=41 mm).

The outcomes of modeling of monthly temperatures and monthly sums of atmospheric precipitation for 1985-2014 for each of the 20 stations can be judged in Table 3.

Table 3 shows that the weather stations discussed in the article are located at different heights above sea level. The table shows that a group of weather stations is identified with the best result of data modeling in all months of the year when the difference between the actual and model data does not exceed the standard deviation. These are Kutaisi, Gori, Sagarejo, Tbilisi, and Tsalka for air temperature.

There are several stations at which unsatisfactory modeling results prevail throughout the year when the difference between actual and model data is more than twice the standard deviation; these are Ambrolauri, Kobuleti, Mt. Sabueti, Pasanauri, and Poti.

Table 2 Example of assessment of model data to actual data (1- Best, 2-Satisfactory, and 3-Unsatisfactory)

Weather Station	Tmean_Obs.	Tmean_Calc.	St Dev	Assessment	Sum Prec_Obs.	Sum Prec_Calc.	St Dev	Assessment
	Temperature, ^{O}C, January				Precipitation, mm, January			
Akhalkalaki	-6.8	-4.0	2.2	2	33	32	21	1
Pasanauri	-2.9	-5.3	2.0	2	113	157	68	1
Poti	5.9	9.3	1.8	2	157	47	76	2
Tbilisi	2.3	2.4	1.4	1	16	22	13	1
	Temperature, ^{O}C, July				Precipitation, mm, July			
Akhalkalaki	16.2	16.1	1.5	1	54	57	37	1
Pasanauri	19.3	15.3	1.1	3	94	183	41	3
Poti	23.1	27.0	1.4	3	200	40	118	2
Tbilisi	24.8	23.3	1.5	1	34	46	26	1

In all months of the year, the results of temperature modeling are the best, and they are satisfactory - at the vast majority of stations, when the difference between the actual and model data, respectively, does not exceed the standard deviation or fluctuates within St Dev-2St Dev.

Thus, in January, March, April, November, and December, such outcomes were obtained at 17 weather stations and in February at 18 out of 20 stations. In these months, unsatisfactory modeling outcomes, when the difference between the actual and model data was more than twice the standard deviation, were noted only at several stations - Dedoplistskaro, Kobuleti, Mt. Sabueti, and Poti.

In the summer period of the year, the number of stations with the best and satisfactory agreement between model data and actual data is smaller and amounts to 14 stations in May-June, 13 in July, and 12 stations in August.

At this time, the number of weather stations with unsatisfactory modeling outcomes increases to 6-8, which can be explained by local geographical factors that contribute to the development of convective processes in the summer season, and increasing temperature and the standard deviation are characterized by a minimum.

Despite this, the outcomes derived can generally be considered quite satisfactory. It also follows from Table 3 that when modeling precipitation, the number of weather stations with the best modeling outcomes in all months of the year, when the difference between the actual and model data does not exceed the standard deviation, is comparatively greater than when modeling air temperature – Akhalkalaki, Akhaltsikhe, Dedoplistskaro, Gori, Sagarejo, Tbilisi, Telavi, and Tianeti. This will be explained by the significant scatter of precipitation data over time.

Large values of the standard deviation within the set differ greatly from the mean values, therefore, the precipitation simulation results are better than the temperature simulation results. The most undesirable modeling outcomes were obtained for the Pasanauri and Poti stations. In all months of the year, the results of modeling precipitation sums are the best and satisfactory at the vast majority of stations when the difference between the actual and model data, respectively, does not exceed the standard deviation or fluctuates within St Dev-2St Dev.

Thus, in May, June, October, and November such outcomes were derived at all 20 stations; in January, March, April, and December the best and most satisfactory outcomes were obtained for 19 stations. In the summer period of the year, when the standard deviation of precipitation is minimal, the number of stations with the best agreement between model data and actual data decreases due to an increase in the frequency of intra-mass weather.

At this time, the number of weather stations with unsatisfactory modeling outcomes increases to 4 - Borjomi, Pasanuri, Poti, and Zugdidi. In general, these outcomes can also be considered quite satisfactory. Potential reasons why certain stations demonstrate unsatisfactory modeling outcomes include many factors - the complex physical and geographical conditions of Georgia, a significant

Table 3 Outcomes of modeling monthly air temperatures /monthly precipitation sums for 1985-2014: 1-Best, 2-Satisfactory, 3- Unsatisfactory

	Weather	Alt, m,	Months											
№	station	a.s.l.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Akhalkalaki	1,716	2/1	1/1	1/1	1/1	1/1	1/1	1/1	1/2	1/2	1/1	1/1	1/1
2	Akhaltsikhe	982	1/1	1/1	1/1	1/1	2/1	3/1	3/1	3/1	1/1	1/1	1/1	1/1
3	Ambrolauri	544	1/1	2/3	3/2	3/2	3/1	3/1	3/1	3/1	3/1	3/1	2/2	1/3
4	Bolnisi	534	1/1	1/1	1/1	1/1	1/1	2/1	3/2	3/1	3/1	1/1	1/1	1/1
5	Borjomi	789	1/1	1/2	1/1	1/1	1/1	3/1	3/2	2/3	2/2	1/1	1/1	1/1
6	Dedoplistskaro	800	3/1	3/1	2/1	2/1	3/1	2/1	2/1	1/1	2/1	2/1	3/1	3/1
7	Gori	588	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1
8	Kobuleti	3	3/1	2/2	1/2	3/1	3/2	2/2	2/1	3/2	2/2	3/2	3/1	3/2
9	Kutaisi	150	1/1	1/2	1/2	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1
10	Mt. Sabueti	1,242	3/1	3/1	3/1	3/1	3/1	3/1	3/2	3/2	2/1	3/1	3/1	2/2
11	Pasanauri	1,070	2/1	2/2	3/2	2/3	3/2	3/2	3/3	3/3	3/3	3/2	2/2	1/2
12	Poti	4	2/2	2/2	1/2	1/2	3/2	3/2	3/2	3/2	3/3	3/2	1/1	3/3
13	Sachkhere	415	1/2	1/3	2/3	2/1	2/1	2/1	1/2	3/2	2/1	1/2	1/2	1/2
14	Sagarejo	802	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1
15	Tbilisi	403	1/1	1/1	1/1	1/1	1/1	2/1	1/1	2/1	1/1	1/1	1/1	1/1
16	Telavi	568	1/1	1/1	1/1	1/1	2/2	2/1	2/1	2/1	1/1	2/1	1/1	1/1
17	Tianeti	1,099	2/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/2	1/1	1/1
18	Tsalka	1,457	1/3	1/2	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1
19	Zestaponi	201	1/1	1/1	1/2	1/1	1/1	2/1	1/1	2/2	2/1	1/2	1/1	1/1
20	Zugdidi	117	1/1	1/2	1/2	1/2	1/1	2/2	2/3	2/2	1/2	1/2	1/1	1/1

range of altitudes, microclimatic conditions, local circulation, seasons of the year, features of the annual variation of the standard deviation, etc.

Figs. 3- 6 (stations are numbered according to Table 1) represent the spatial distribution of the outcomes of the simulation assessment of mean monthly air temperatures for the central months of the seasons of the years 1985-2014 by weather stations.

From Figs. 3-6, it follows that in January the modeling outcomes were unsatisfactory only for 3 stations: Dedoplistskaro, Kobuleti, and Mt. Sabueti. In other cases, the simulation outcomes are quite acceptable. In April, modeling outcomes were also unsatisfactory for Dedoplistskaro and Kobuleti, as well as for Ambrolauri. In the summer months, the number of stations with unsatisfactory modeling outcomes increased and in July amounted to 7: Akhaltsikhe, Ambrolauri, Bolnisi, Borjomi, Mt. Sabueti, Pasanauri, and Poti. As noted, this can be explained by the development of convective processes in the summer, as a result of which the temperature increases. In October, the number of weather stations with unsatisfactory modeling outcomes decreases to 5: Ambrolauri, Kobuleti, Mt. Sabueti, Pasanauri, and Poti.

Figs. 7-10 represent the spatial distribution of the outcomes of the simulation assessment of mean monthly sums of atmospheric precipitation for the central months of the seasons of the years 1985-2014 by weather stations.

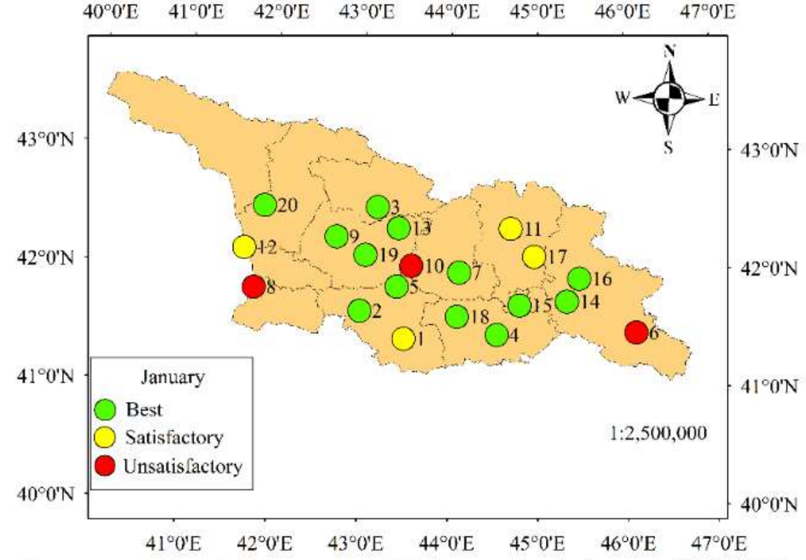

Fig. 3 Outcomes of assessment of modeling mean monthly temperature in January 1985-2014 by weather stations (stations are numbered according to Table 1)

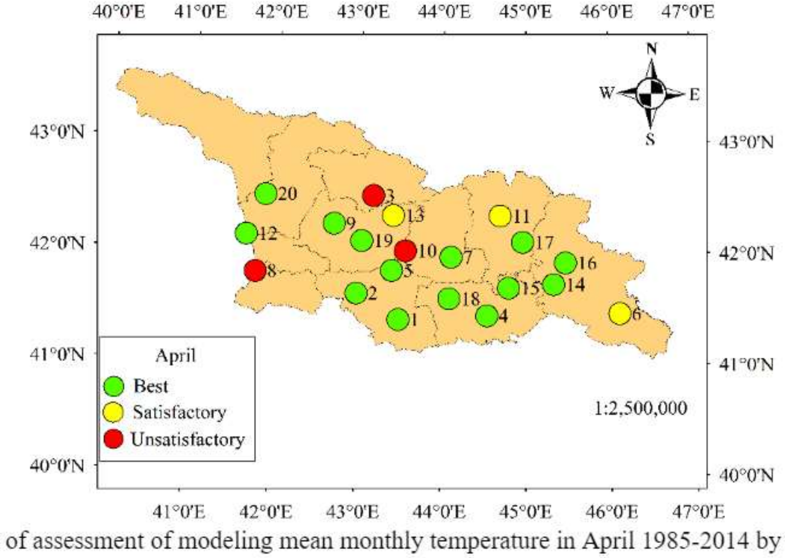

Fig. 4 Outcomes of assessment of modeling mean monthly temperature in April 1985-2014 by weather stations

From Figs. 7-10 (stations are numbered according to Table 1), it follows that in January and April, the outcomes of modeling monthly precipitation sums were unsatisfactory for only one weather station (Tsalka and Pasanauri, respectively), in July, unsatisfactory outcomes were derived for 2 stations – Pasanuri and Zugdidi, while in October, an unsatisfactory modeling outcome was not derived.

One of the main reasons for the incompatibility between actual and model data is the convective processes characteristic of Georgia, which develop in an unstable atmosphere, when the air masses at the surface of the earth are heated, they become lighter than the air located in higher layers, and intense vertical air mixing begins. The rise of air masses causes them to cool, and condensation of water vapor occurs, releasing a colossal amount of latent heat. And, the higher the relative humidity and the higher the temperature in the underlying layers, the greater the instability, the higher the developing clouds can be and intense downpour occurs. These processes cannot be reflected in the model.

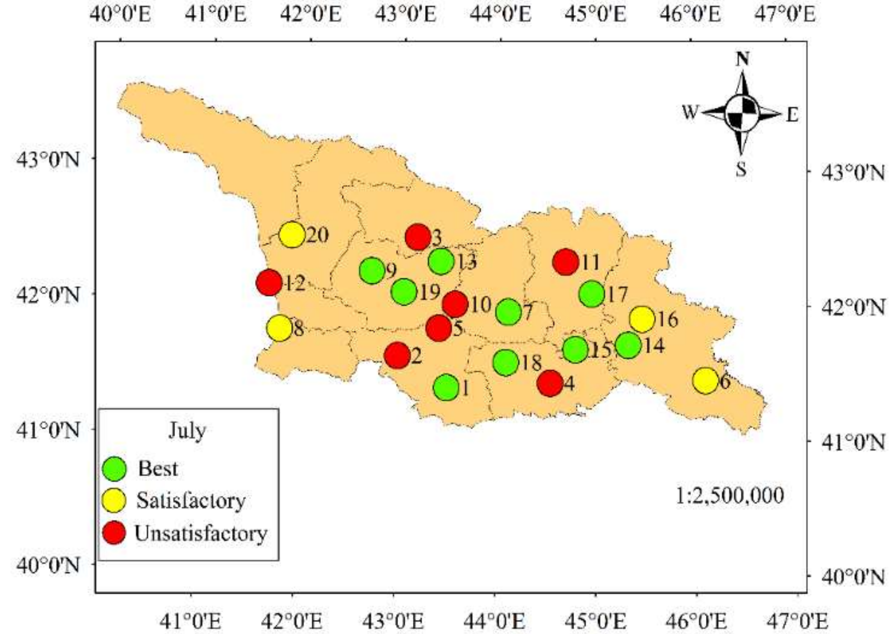

Fig. 5 Outcomes of assessment of modeling mean monthly temperature in July 1985-2014 by weather stations

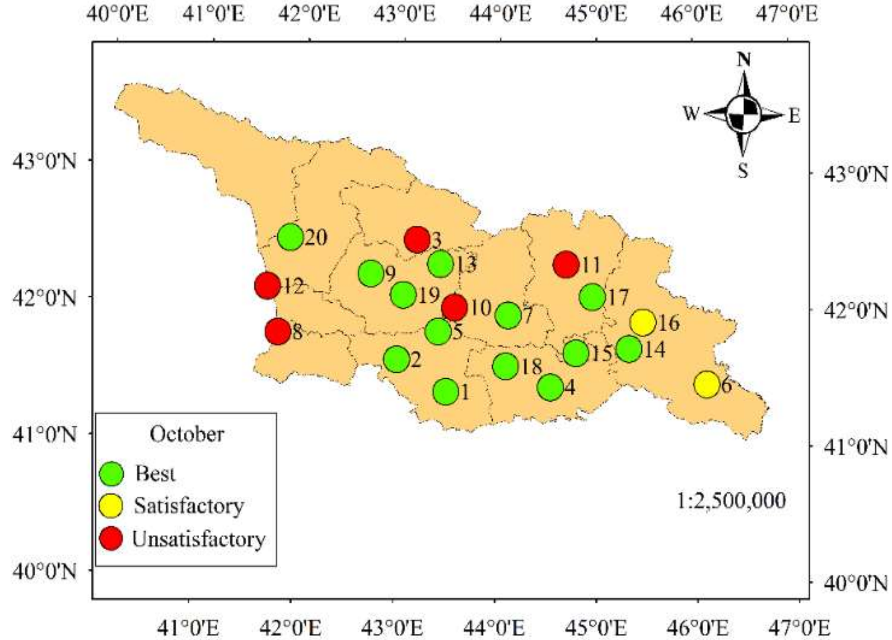

Fig. 6 Outcomes of assessment of modeling mean monthly temperature in October 1985-2014 by weather stations

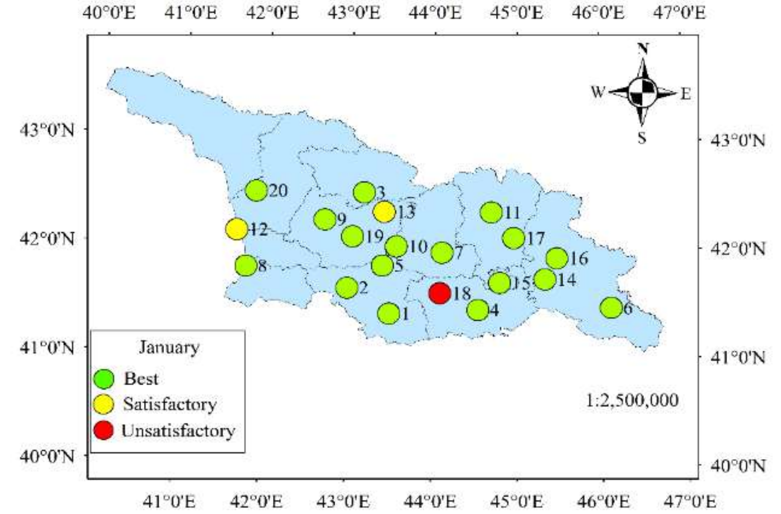

Fig. 7 Outcomes of assessment of modeling mean monthly sums of precipitation in January 1985-2014 by weather stations (stations are numbered according to Table 1)

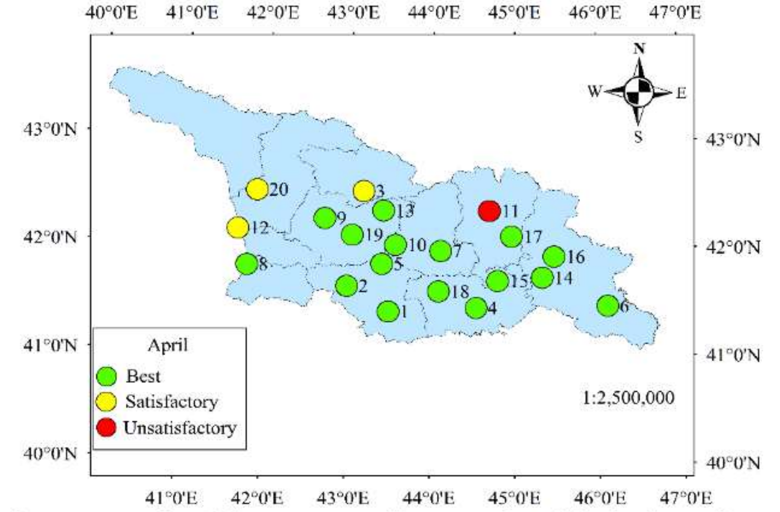

Fig. 8 Outcomes of assessment of modeling mean monthly sums of precipitation in April 1985-2014 by weather stations

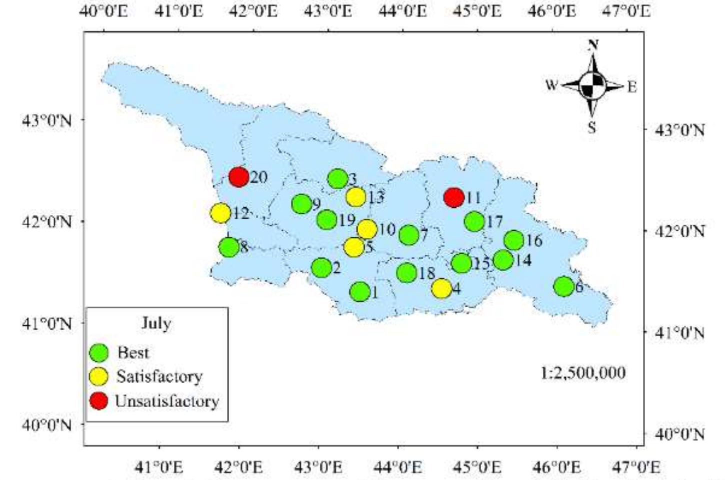

Fig. 9 Outcomes of assessment of modeling mean monthly sums of precipitation in July 1985-2014 by weather stations

Two regional climate simulations were done for Georgia one in 2009 for the preparation of the Second National Communication to the UNFCCC of Georgia, and the second in 2015 for the preparation of the Third National Communication of Georgia. In 2009 the PRECIS (Providing Regional Climates for Impacts Studies) model at a 25 km resolution over the South Caucasus domain for the historical period of 1961-1990 was driven with ERA40 boundary conditions. The simulation results were validated against Climatic Research Unit (CRU) data [8,9, 40,41].

Regarding temperature, the CRU data consistently showed higher values than the simulated data obtained from the PRECIS model for both western and eastern Georgia. In some instances, the average annual temperature difference between the two datasets exceeded 7°C. This suggests that the model may underestimate temperature trends, particularly in certain regions. There was a significant discrepancy between the model and CRU data for precipitation, particularly along the Black Sea coast. The precipitation calculated by the PRECIS model was notably lower than observational data, indicating potential limitations or biases in the model's representation of precipitation patterns in coastal areas. The study conducted two future simulations (2020–2050 and 2070–2100) for the IPCC SRES A1, A2, and B1, B2 climate scenarios. These simulations were used to analyze the changes in average values of major climatic parameters across Georgia [8].

Later, in 2015, within the Third National Communication to the UNFCCC of Georgia, the Abdus Salam ICTP regional climate model RegCM4 was used at a 20 km resolution for future periods 2021–2050 and 2071–2100 for a South Caucasus domain, without historical runs or validation. Future changes in mean values of main climate parameters and extreme climate indices have been analyzed by comparing model data (2021–2050 and 2071–2100) to meteorological observation data (1986–2010) [9]. This approach is deemed unacceptable for climate change assessment, with the resolution considered too coarse for Georgia's climate. Higher-resolution models are crucial for accurately simulating local and regional climate characteristics. Historical simulations and validation are essential for ensuring the reliability and accuracy of the climate model forecasts.

Failure to validate model outputs against observed data increases uncertainty in future projections and undermines trust in the model outcomes. Based on these simulations, the impacts of climate change on various sectors in Georgia, such as agriculture, water resources, and ecosystems, have been assessed. These studies have highlighted the potential risks and vulnerabilities associated with climate change and the need for adaptation strategies. The studies conducted within the Second and the Third National Communication provide valuable insights into the potential impacts of climate change on the region and the performance of regional climate models in simulating Georgia's climate. However, further research is still needed to improve model performance, reduce uncertainty, and enhance the reliability of climate change projections for the region.

In recent years, after some sensitivity experiments with RegCM4.7.1 (a newer version compared to previous simulations) over Georgia territory [42-46], later a long-term high-resolution simulation was performed for the period 1985–2008 [38].

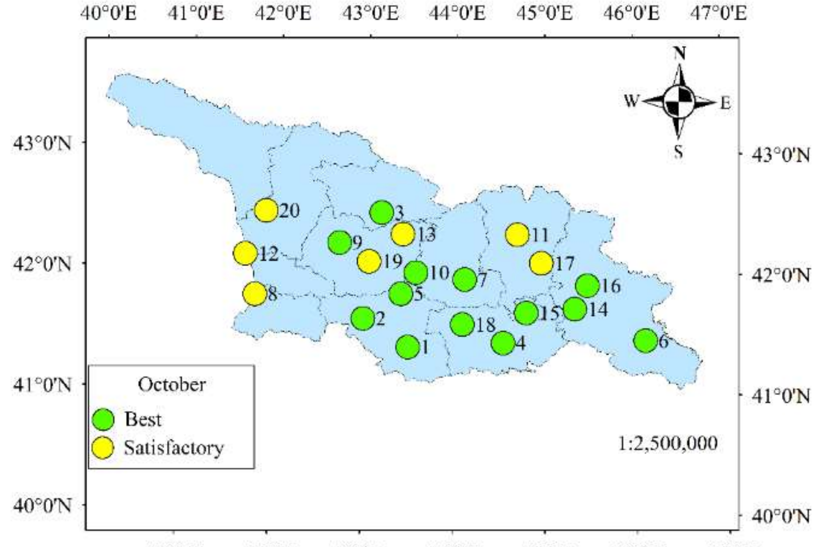

Fig. 10 Outcomes of assessment of modeling mean monthly sums of precipitation in October 1985-2014 by weather stations

The study uses a high-resolution (12 km) regional climate simulation, which provides a more detailed and accurate representation of Georgia's climate compared to lower-resolution simulations used in previous studies. The study uses the RegCM4.7.1 model, a newer version compared to previous simulations. The simulation was conducted with a 12 km horizontal grid spacing, and ERA5 data as boundary conditions, and the results were evaluated against the observation data for Georgia's territory based on correlation, bias, and RMSE (The Root Mean Squared Error). The results showed the slightest discrepancy between observed and modeled average annual temperatures and precipitation in eastern Georgia. The most significant disparities in average annual precipitation were observed along the Black Sea coast and in some high mountain stations in western Georgia [38]. This long-run, high-resolution simulation using ERA5 boundary conditions was the first of its kind for Georgia, and overall, the modeling results were satisfactory, providing a solid basis for using the regional climate model RegCM4.7.1 for modeling temperatures and precipitation in Georgia. This article is a continuation of this research, where a 30-year (1985-2014) simulation has already been discussed, which covers a longer period compared to the previous study, and validation was done using standard deviation. The presented article allows the use of three ranges, with which it is possible to evaluate in more detail for which stations the results - 1-Best, 2-Satisfactory, and 3-Unsatisfactory are modeled, which the previous study does not provide [38].

The insights gained from the study can be applied in various ways to inform climate change projections, adaptation strategies, land use planning, infrastructure design, and natural resource management in Georgia. By providing valuable information on historical climate trends and model performance, the study can help stakeholders develop strategies to address the impacts of climate change and build a more resilient future for the region.

Conducting historical runs and model validation is crucial for ensuring the accuracy and reliability of model simulations. Historical runs allow climate models to simulate past climate conditions, providing a baseline for evaluating their performance. By comparing model outputs with actual historical data, can be assessed the model's ability to accurately capture past climate variability and trends. This is essential for ensuring that the model can provide reliable projections of future climate conditions [5].

According to Yin [47], case study research should have practical implications for addressing real-world problems or informing policy and decision-making. In the case of Georgia's regional climate modeling, the insights gained from this study could be used as a first step for climate change projections for Georgia and for developing climate adaptation strategies, planning land use and infrastructure design, guide natural resource management, and enhance resilience to climate change impacts in the country. Yin, also stresses the importance of understanding the context in which the phenomena occur. In the case of regional climate modeling for Georgia, it's crucial to consider the unique geographical context (location, topography, coastline, etc.). while the use of regional climate models like RegCM4 for projecting future climate changes is valuable, it is essential to conduct historical runs and model validation to ensure the accuracy and reliability of the model simulations.

The study has some important limitations. First of all, the study relies on the RegCM4.7.1 model, which, like all models, has inherent limitations in simulating complex climate processes. This could affect the accuracy of the model's projections. Secondly, the study evaluates only historical monthly mean temperatures and precipitation, which do not capture short-term climate variability or extreme events, potentially limiting the robustness of the model evaluation. Thirdly, the model data was analyzed at discrete points; in particular, the validation was done against 20 meteorological station observation data of Georgia; only for these stations there is a continuous homogeneous series of temperature and precipitation data for the years 1985–2014. This approach and a limited number of stations may not capture all peculiarities of distribution monthly mean temperatures and precipitation over the territory of Georgia, and the validation was conducted based on the standard deviation, not considering other statistical indicators. These limitations could affect the accuracy of the model validation process. Moreover, the study uses a high-resolution (12 km) regional climate simulation, which, while providing detailed information, may still be too coarse to capture localized climate features or small-scale variability. Finally, despite the previous sensitivity experiments, RegCM4.7.1 models' chosen configuration and parameterization may not be optimal for all regions or climate conditions of Georgia. Despite these limitations, the study provides valuable insights into the RegCM4.7.1 model's performance in simulating historical climate conditions in Georgia. This can help improve our understanding of regional climate dynamics and inform climate change adaptation and mitigation strategies.

5. CONCLUSIONS

In Georgia, the average value of the standard deviation of mean monthly air temperatures has an evident annual course with a maximum from January to April, and a minimum in summer and at the beginning of autumn. A similar regime is observed in the annual course of extreme values of standard deviations. In the annual course of the standard deviation of the monthly sums of atmospheric precipitation, 2 maxima are observed in October, November, and January, and a minimum is observed from February to May with significant precipitation. The largest number of weather stations with unsatisfactory modeling outcomes corresponds mainly to months with a minimum standard deviation in their annual course.

A group of weather stations with the best result of data modeling in all months of the year, when the difference between the actual and model data does not exceed the standard deviation value, is highlighted. These are Kutaisi, Gori, Sagarejo, Tbilisi, and Tsalka for air temperature. When modeling precipitation, the number of weather stations with the best modeling result in all months of the year, when the difference between the actual and model data does not exceed the standard deviation, is comparatively greater than when modeling temperature - Akhalkalaki, Akhaltsikhe, Dedoplistskaro, Gori, Sagarejo, Tbilisi, Telavi, and Tianeti.

The results of modeling temperature and precipitation are the best and most satisfactory at the vast majority of stations in all months of the year when the difference between the actual and model data, respectively, does not exceed the standard deviation or fluctuate within St Dev-2St Dev.

The modeling results can generally be considered quite satisfactory, which gives grounds for successfully using the regional climate model RegCM4.7.1 with selected configuration when modeling monthly air temperatures and monthly sums of precipitation in Georgia. Standard deviation is a valuable indicator of variability and can provide insights into the agreement between the model and observed data.

In conclusion, it is recommended that research efforts continue to improve model performance and validation. This includes more sensitivity experiments and using alternative statistical indicators for a more comprehensive model accuracy evaluation.

6. ACKNOWLEDGMENTS

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