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REVIEWING CLIMATE CHANGES MODELING METHODS

V. A. Pepelyaev,[1†] **A. N. Golodnikov,**[1] **and N. A. Golodnikova**[1]

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Abstract. *The authors overview the main approaches to the analysis of climate change. Climate models are based on physical laws and take into account scenarios of greenhouse gas emissions. They are used to analyze the processes in the climate system and predict a possible climate future. The authors focus on the relationship between global climate models (GCMs), regional climate models (RCMs), and downscaling methods. An approach to the analysis and reproduction of climatic changes is also considered, which compared the results of multiple simulations with each other and with observational data.*

Keywords: *climate change, climate models, statistical downscaling, scenarios of greenhouse gas emissions.*

INTRODUCTION

One of the industries most sensitive to climate change is agriculture. Depending on the direction of these changes, the risk of significant yield losses may increase. They lead to a significant increase in food prices, which is a significant threat to food security in Ukraine [1, 2]. The problem of minimizing the risk of yield losses under current climatic conditions is considered in [3, 4]. In these works, the minimization of the risk of losses is ensured by choosing the optimal structure of sown areas using information about weather conditions from past years. Some loss risk minimization methods are described in [5–8] These methods can be used to adapt crop production to future climate change, provided sufficient information is available about the nature of these changes. Currently, this information can only be obtained through quantitative modeling of climate change using climate models. This paper provides an overview of modern approaches and methods of climate change modeling.

1. CLIMATE MODELS

Climate models are the primary tools available for investigating the response of the climate system to greenhouse gas emissions. They are based on physical laws and take into account scenarios of greenhouse gas emissions. Global climate models (GCMs) are used to study the processes that occur in the climate system and predict the possible future climate. Although GCMs are an important tool for generating large-scale statistics in spatial and temporal dimensions, computational limitations currently prevent GCMs from performing global simulations at the high spatial resolution required to obtain useful climate information at regional or local scales.

The results of temperature and precipitation simulations using GCMs are characterized by significant biases that arise as a result of systematic errors in the model. For example, for the numerical integration of complex systems of differential equations on which GCMs are based, it is necessary to have information about the state of the climate system

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[1] V. M. Glushkov Institute of Cybernetics, National Academy of Sciences of Ukraine, Kyiv, Ukraine, †*pepelaev@yahoo.com*. Translated from Kibernetyka ta Systemnyi Analiz, No. 3, May–June, 2023, pp. 48–58. Original article submitted November 22, 2022.

at the initial moment of time, which cannot be determined precisely, because the amount of observational data is small compared to the number of degrees of freedom of the climate system. For its part, the inaccuracy in determining the initial state generates errors in the results of modeling the climate system. This makes it difficult to directly use the results of GCM simulations as direct inputs to more detailed models. In order to eliminate this shortcoming, an ensemble approach is used, which consists of conducting parallel calculations with different combinations of GCMs under the same external influence. To assess the uncertainty caused by the inherent variability of the climate model, ensemble calculations are performed using this model under different initial conditions.

At the current stage of development of climate models, the spatial resolution of GCMs is insufficient to reproduce some climatically significant local processes that could be used as a basis for decision-making on adaptation to climate change. Currently, typical GCM horizontal resolution is 100–300 km, and the best is 50–100 km. This resolution prevents global models from providing an accurate description of extreme events, which are of fundamental importance to users of climate information regarding regional and local impacts of climate variability and change [9, 10]. Theoretically, GCMs are able to provide more detailed information on a regional scale [11], but due to the large amount of computing resources required, they are not used for regional climate modeling. With the advent of new supercomputer platforms and advances in climate modeling, the horizontal resolution of GCMs is expected to improve to 1–2 km [12]. Then, there will be a real opportunity to use GCMs to model small-scale processes like thunderstorms and rain showers.

Due to the fact that for adaptation to climate change it is necessary to have relevant information at the regional and local levels, there is a need to develop climate models with a higher resolution. Regional information can be obtained using regional climate models (RCMs) and downscaling techniques. RCMs are based on physical principles and differ from GCMs in their higher resolution. This makes it possible to reproduce extreme phenomena more realistically with their help. They model a bounded region using GCMs outputs at the lateral and surface boundaries of that region as boundary conditions. This approach allows for higher resolution in the selected area and better representation of important regional climate drivers, such as mountain ranges, land use, and urban effects. These models provide forecasts with much greater detail and a more accurate representation of local extreme events. The horizontal resolution of modern RCMs is 12.5–50.0 km [13].

The transition from global climate models to regional ones is carried out by the method of reducing the scale, which is called “downscaling.” It makes it possible to obtain regional or local climate information from the results of GCMs work [14, 15]. Downscaling methods include dynamic and statistical downscaling. Dynamic downscaling uses RCMs or local models to generate high-resolution climate information at the regional level [16]. For example, a standard method for estimating the future impacts of climate change on hydrology combines the results of GCMs with the results of local hydrological models. In [17], it is proposed to reduce the scale gap between GCMs on the one hand and existing local permafrost models on the other, using RCMs as an intermediate step. Instead of calculating the permafrost index from the RCMs data, the authors used the RCMs only to calculate the boundary conditions for the existing detailed permafrost model.

Dynamic downscaling requires a significant amount of computing resources, which limits the use of this method. In addition, the results obtained with the help of RCMs have a systematic bias, which significantly complicates their direct use for adaptation to climate change. This is explained by the fact that the scales of processes that occur at the regional or local levels and the features of the Earth’s surface are too small. Therefore, they cannot be taken into account in GCMs [18, 19]. To eliminate the error that occurs and overcome the scale gap between the numerical model grid and the desired scale, the RCMs output data is subjected to additional processing using statistical downscaling as a bias correction method [20].

Statistical downscaling uses the statistical relationship between large-scale climate information derived from GCMs or RCMs and local climate information that is based on observations [21]. The idea behind statistical downscaling is to move from a distribution function that describes some large-scale (GCMs) climate variable to an equivalent distribution function at a local scale, which can then be easily generated with local values to produce realistic local-scale time series. In [18], it was emphasized that these two distribution functions are non-trivial and usually do not belong to such a well-known distribution family as the gamma distribution. Furthermore, no assumptions are made about the shape of the relationship being modeled and the family of CDFs, and non-parametric approaches are used. This approach, in particular, was implemented in [22], but only a fixed type of distribution function, namely, the gamma distribution, was used. However, statistical downscaling cannot capture relationships that have historically been absent. In addition, this method cannot be used in regions where there is no connection between large-scale climatic characteristics and local observations [23].

2. ENSEMBLE MODELING METHODS

The main approach to the analysis and reproduction of climate change is to compare the results of multiple simulations with each other and with observational data. Modeling is carried out using separate climate models with agreed boundary conditions and specified rates of greenhouse gas emissions. To implement this approach, the Intergovernmental Panel on Climate Change (IPCC) was established in 1988, and it conducts a systematic analysis of scientific results related to climate change and provides recommendations to world leaders on the development and improvement of climate policy. The IPCC does not perform original research, but rather conducts a periodic systematic review of all relevant published literature. The lead authors of the IPCC reports assess the available information on climate change from published sources, and every six to seven years the IPCC issues reports containing the latest research findings on the drivers of climate change, the analysis of socio-economic impacts, and recommendations for mitigation. The last, sixth, report was published in 2022.

The IPCC reports include, in particular, results obtained within the framework of the Coupled Model Intercomparison Project (CMIP), which was launched in 1995 to study and improve GCMs. This project conducts numerical experiments covering many aspects of climate variability and change and compares GCMs developed by different groups of researchers in different countries around the world both with each other and with observational data. The number of climate centers or consortia carrying out modeling and forecasting of the global climate has increased from 11 in the first CMIP1 project to 19 in CMIP5 and 28 in CMIP6 [24]. These experiments generate a huge amount of information that allows us to better understand past, current, and future climate change.

A selection of model simulations under different initial conditions, which are carried out using models that are different from each other, is called a multi-model ensemble. Differences in initial conditions and model formulation lead to different evolutions of the modeled system. Members of the multimodel ensemble are developed by various organizations that research climate change. They can differ significantly in software design and programming approach, spatial discretization handling, and precise formulation of physical, chemical, and biological processes. The advantages of using a multimodel ensemble are manifested in “the consistently better performance of the multimodel when considering all aspects of forecasts” [25]. By sampling the modeling uncertainties, the ensembles provide a better basis for probabilistic forecasts compared to single-model ensembles that sample only the uncertainty in the initial state. Mutual comparison of GCMs developed by groups of researchers in different countries of the world, both with each other and with observational data, makes it possible to identify the advantages and disadvantages, as well as to estimate the systematic errors of each of them.

Increasing the computing power has made it possible to investigate the internal variability of models and increase the reliability of estimates of climate model responses using large ensembles of initial conditions. With this approach, multiple calculations are performed using one fixed model, starting from many different initial states [24]. Changes in the initial conditions lead to different evolutions for individual implementations of the system as a whole. However, ensembles of initial conditions with a single model cannot capture the same degrees of freedom as an ensemble with several models, because the characteristics of the model significantly affect model behavior [26].

Another common modeling method is the ensemble of perturbed parameters. This method is used to estimate uncertainty based on a single model where individual parameters are changed to reflect the full range of their uncertainty [27–30]. Then, statistical methods are applied to identify, which parameters are the main causes of uncertainty in the entire ensemble. Together, ensemble methods (ensembles of initial conditions, ensembles of perturbed parameters, and multimodel ensembles) enable the investigation of climate model uncertainty arising from internal variability, initial and internal boundary conditions, model formulation, and parameterization [31].

The results of simulations using GCMs are characterized by significant biases that arise due to systematic errors in the model. To solve the problem of systematic displacement, international projects of mutual comparison of dynamic scaling are carried out, for example, the Ensembles-Based Predictions of Climate Changes and Their Impacts (ENSEMBLES) [32, 33]. This project was launched in September 2004. It coordinates the development of an ensemble climate forecasting system for use at a range of time (seasonal, decadal, and longer) and spatial scales (global, regional, and local). This modeling system is designed to construct integrated scenarios of future climate change that will provide a basis for quantifying climate change risk and variability.

The Coordinated Regional Climate Downscaling Experiment (CORDEX) framework was initiated by the World Climate Research Program (WCRP) in 2009 to evaluate and improve regional climate downscaling (RCD) methods. This framework evaluates the performance of a regional climate model using a set of experiments aimed at generating regional climate predictions.

The main goals of CORDEX are as follows [34].

1. Conducting studies of regional and local climatic phenomena using the downscaling method.
2. Evaluating and improving of models and methods of regional climate downscaling.
3. Creating a database of coordinated sets of regional and local climate change projections for all continents.
4. Facilitating the familiarization of wide circles of users of regional climate information with the results obtained within the framework of the CORDEX program, and the exchange of the obtained results.

The CORDEX program coordinates the development related to climate modeling at the regional and national levels, and also stimulates the use of modeling results by end users of climate information around the world [35].

Experiments conducted within CORDEX model both historical and future regional climates under various representative greenhouse gas concentration pathways. At the first stage of the CORDEX program, simulations were carried out using dynamic regional climate models. In recent experiments, the share of empirical and statistical models was increased [36]. The results of the studies under the CORDEX program are used as input data when studying the impact of climate change on human life and livelihoods, as well as for finding ways to adapt to new climate conditions [37].

The region, for which regional downscaling is carried out, is called a "domain." Within the CORDEX program, the following 14 domains are allocated: South America, Central America, North America, Europe (EURO), Africa, South Asia, East Asia, Central Asia, Australasia, the Antarctic, the Arctic, Mediterranean (MED), Middle East, North Africa (MENA), and Southeast Asia (SEA).

The EURO-CORDEX project is the European branch of the CORDEX international program. Its goal is to develop high-resolution climate scenarios for Europe. During the implementation of this project, the efficiency of reproduction of the main spatio-temporal features of the European climate by individual models is investigated. As a benchmark for observations of surface air temperature and precipitation, the data from the E-OBS daily land observation data set in Europe is used [38, 39].

Research within the EURO-CORDEX project is based on dynamic downscaling methods [38, 40–48] and on empirical statistical downscaling methods [49-56]. These scaling approaches, each with its own merits, are mutually complementary.

3. SCENARIOS OF FUTURE GREENHOUSE GAS EMISSIONS

In order to simulate climate changes, climate models must receive information about future greenhouse gas emissions. They are the product of complex dynamic systems that depend on such determining factors as demographic and socio-economic development, as well as technological changes. The dynamics of these emissions is characterized by considerable uncertainty. Scenarios are used to analyze this uncertainty, which are alternative forecasts of possible developments in the future. These scenarios make it possible to analyze the way in which the determinants may affect future emission figures.

In 1992, the IPCC proposed IS92 scenarios for estimating greenhouse gas emissions. These were the first scenarios used in global circulation models to develop climate change scenarios. In 2000, the IPCC published a Special Report on emission scenarios, in which 40 new scenarios (the so-called SRES scenarios) were proposed [55]. For their classification, four different descriptive storylines, called "families" (A1, A2, B1, and B2) were developed. Each storyline represents a different demographic, social, economic, technological, and environmental event. Each scenario is a specific quantitative interpretation of one of four storylines. These scenarios were used to prepare the IPCC Fourth Assessment Report, released in stages during 2007 [56].

The research results presented in the Fifth Assessment Report of the IPCC in 2013 [57] are based on four scenarios of greenhouse gas emissions. Unlike the scenarios used in the Fourth Assessment Report, some of these scenarios also include policy measures to mitigate climate change impacts. These scenarios are called Representative Concentration Pathways (RCPs). They are determined by the approximate total amount of radiation exposure in 2100 compared to 1750 as follows: 2.6 W/m^2 for RCP2.6, 4.5 W/m^2 for RCP4.5, 6.0 W/m^2 for RCP6.0, and 8.5 W/m^2 for RCP8.5. The set of RCP-scenarios includes one emission reduction scenario that assumes a fairly low level of impact (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6.0) and one scenario with very high levels of greenhouse gas emissions (RCP8.5).

TABLE 1. Changes in the Global Surface Temperature for the Selected 20-Year Time Periods and Five New Illustrative Emission Scenarios [58]

Scenario	**2021–2040**		**2041–2060**		**2081–2100**	
	The Best Score (°C)	**The Most Likely Range (°C)**	**The Best Score (°C)**	**The Most Likely Range (°C)**	**The Best Score (°C)**	**The Most Likely Range (°C)**
SSP1-1.9	1.5	1.2–1.7	1.6	1.2–2.0	1.4	1.0–1.8
SSP1-2.6	1.5	1.2–1.8	1.7	1.3–2.2	1.8	1.3–2.4
SSP2-4.5	1.5	1.2–1.8	2.0	1.6–2.5	2.7	2.1–3.5
SSP3-7.0	1.5	1.2–1.8	2.1	1.7–2.6	3.6	2.8–4.6
SSP5-8.5	1.6	1.3–1.9	2.4	1.9–3.0	4.4	3.3–5.7

Climate responses to a wider range of future emissions of greenhouse gases, land use, and air pollutants were examined in the IPCC Sixth Assessment Report (2021) [58] and compared with the IPCC Fifth Assessment Report (2013). This report assesses the climate response to five illustrative scenarios that cover the range of possible future development of anthropogenic climate change drivers. Each set of scenarios corresponds to its own forecast of changes in the climate system. All scenarios start from 2015.

The new scenarios include the following [58]:

- scenarios with high and very high levels of greenhouse gas emissions (SSP3-7.0 and SSP5-8.5) and CO_2 emissions that roughly double from current levels by 2100 and 2050, respectively;
- scenarios with intermediate levels of greenhouse gas emissions (SSP2-4.5) and CO_2 emissions remaining at roughly current levels until mid-century;
- scenarios with very low and low levels of greenhouse gas emissions and CO_2 emissions declining to zero around 2050, followed by different levels of net negative CO_2 emissions (SSP1-1.9 and SSP1-2.6).

The characteristics of the new emission scenarios are given in Table 1.

4. CLIMATE CHANGE RESEARCH IN UKRAINE

The study of climatic changes in Ukraine is described in the works of S. V. Krakovska, N. V. Hnatyuk, T. M. Shpytal, L. V. Palamarchuk, I. P. Shedemenko, A. K. Bilozerova, and other scientists. In particular, a study of projections of changes in average monthly, seasonal, and annual air temperatures for three 20-year periods in the 21st century was conducted for the entire territory of Ukraine and separately for five selected regions [59]. Quantitative scenarios of possible changes in air temperature and humidity relative to the modern control period in the Luhansk region were determined [60]. Possible scenarios of climatic conditions on the territory of the Ternopil region were developed and statistical characteristics of the main climatic indicators i.e., long-term average monthly and annual values of air temperature, precipitation, and relative air humidity, were obtained [61]. In [62], the trend of climatic changes on the territory of Khmelnytskyi region is determined according to the average annual values of temperature and amount of precipitation. In [63], an analysis of the regime of the maximum daily air temperature was carried out based on actual data for periods longer than sixty years, as well as the expected ones for 2021–2050 for three weather stations (Uzhgorod, Kharkiv, and Odesa). For each day of the year, the so-called “absolute temperature threshold” was calculated according to WMO recommendations.

CONCLUSIONS

The review of the climate change modeling methods presented in this paper shows that the state of research on this problem has reached the level of implementation of relevant developments in the economic activity. The development of high-resolution climate scenarios for Europe within the framework of the EURO-CORDEX project significantly reduced the relevance of climate change research at the level of the regions of Ukraine. All the necessary information on this topic with high resolution (12.5–50 km [13]) is contained in the results of the EURO-CORDEX project. Instead, the relevance of research on the impact of climate change on the branches of Ukraine's economy is increasing.

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