N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224-5278
Volume 4, Number 442 (2020), 147 – 155 **https://doi.org/10.32014/2020.2518-170X.95**

UDC 551.582; 551.583
IRSTI 44.01.94; 28.17.23

N. Yunicheva[1], I. Yesserkepova[1], K. Bostanbekov[2], A. Alimova[2], I. Vitkovskaya[1], A. Keylan[3]

[1]Institute of Information and Computational Technologies, Almaty, Kazakhstan;
[2]Satbayev University, Almaty, Kazakhstan;
[3]Tokyo Denki University, Tokyo, Japan.
E-mails: naduni@mail.ru, iyesserkepova@mail.ru, k.bostanbekov@norlist.kz, anic2002@mail.ru, irinas_vit@mail.ru, 20787@ms.dendai.ac.jp

SELECTION OF THE PARAMETERS OF A REGIONAL CLIMATE MODEL BASED ON A COMPARISON WITH OBSERVATIONAL DATA FOR THE "CENTRAL ASIA" DOMAIN

Abstract. The article presents the results of selecting the optimal parameters for the regional climatic WRF-model for the Central Asia domain. Three variants for setting the parameters of the WRF model are considered: 1) WSM6 microphysics in combination with the YSUPBL boundary layer scheme; 2) MYJPBL planetary boundary layer scheme combined with Thompson microphysics; 3) Thompson microphysics with setting of the boundary layer parameters according to the YSUPBL scheme. As data of ground-based observations, global archives of data from the Meteorological Office, United Kingdom (Climatic Research Units) and data from the laboratory of surface hydrology at Princeton University of the United States were used. The results of numerical calculations of the mean annual seasonal variability of surface temperature and precipitation are compared for all selected parameterization schemes for 4 climatic seasons in the Central Asian region. It was shown that the most preferred combination was the YSUPBL scheme with Thompson microphysics.
Key words: climate change, modeling, selection, parameterization, sensitivity, WRF.

Introduction. It is known, that the main methodological basis for solving the problem of forecasting estimates of future climate parameters is numerical modeling of the climate system using global climate models, which are based on global models of the general circulation of the atmosphere and ocean [1-2]. That the improvement of climate models requires the formulation of more accurate models of specific physical processes that determine the dynamics of the climate system for any region

In most cases, the model should be adjusted for a specific region by varying empirical coefficients in the parameterization schemes, as well as using different precipitation parameterization schemes, a planetary boundary layer, etc. Usually, regional model is evaluated by its ability to reproduce fields of precipitation and temperature of the near-surface air.

Regional climate modeling under the CORDEX (COordinated Regional Climate Downscaling EXperiment) program (https://www.cordex.org/) plays an important role, providing projections of the future climate with much greater detail and a more accurate representation of local extremes [3-6]. The higher spatial resolution of the regional model allows us to more adequately reproduce the influence of mountains and the properties of the underlying surface on atmospheric processes [7]. The allocation of their contribution can be considered the main expected result of regional modeling.

The Weather Research and Forecasting (WRF) model is a system for weather forecasting and modeling atmospheric processes, suitable for both operational and research purposes. The system is an effective tool for the development of data assimilation techniques, parameterization of sub-grid scale weather forecast and regional climate modeling [8].

At the present stage, attempts are being made to build regional climate models (RCM) for the territories included in the Central Asia domain and taking into account the specifics of the region. So, in [9] the results of calculating air temperature, atmospheric pressure, and precipitation for the territory of the Tomsk region using the WRF predictive modeling system with various parameterization schemes are presented. For example, in [10] studies were conducted on the selection and adaptation of the optimal convection parametrization scheme in the hydrodynamic mesoscale model WRF for forecasting meteorological values in the territory of Kyrgyzstan. The calculation of the amount of precipitation during the cold period in the Western Urals using the WRF model was carried out [11].

The results of WRF simulation and downscaling of local climate in Central Asia are described in [12]. This work had two goals: (1) achieve better performance of the WRF model in simulating the observed precipitation, daily extreme temperatures in Central Asia, so to create a tool that can be used to improve understanding of weather and climate in Central Asia, and (2) create a high-resolution (20 × 20 km) meteorological dataset for the region for the period 1980–2015. The model initial and boundary conditions are derived from the ERA-Interim reanalysis data.

The model was tested with various parameterization schemes. The calculation results were compared with ground-based observations. The choice of model configuration was determined by the smallest difference in the comparisons. As a result of those tests, microphysics scheme of Thompson [13] and Betts-Miller-Janjic scheme [14] for cumulus parameterization in the model were selected. The PBL parameterization used in the model is the Mellor–Yamada–Janjic scheme [15].

It should be noted that a number of studies are also known on the sensitivity of the WRF model using different parameterization schemes for different parts of the Central Asia domain [16-20].

For Kazakhstan territory by the WRF model calculated a range of meteorological parameters (temperature field of the air near the ground and at altitude of the atmospheric pressure 850 hPa, the total accumulated precipitation and precipitation for scheme convective cloudiness, field of near surface pressure and surface wind) [21].

Methods and Data. The purpose of the numerical experiments in our study is to select a parameterization scheme describing microphysics, a planetary boundary layer, short-wave and long-wave radiation fluxes for the formation of a model that adequately reflects the processes occurring in the atmosphere, on the surface of the earth and water, with their mutual influence and model constraints for the 'Central Asia' domain. In the present study, the selection of parameters was carried out for regional climate WRF model [22].

It is possible to use various options for parameterization with varying degrees of accounting for hydrometeors in the liquid and solid phases and the processes corresponding to them [23-24].

In our study, the focus is on near-surface wind speed, precipitation, and near-surface temperature at a height of 2 meters. To calculate the temporal variability of meteorological elements in the surface and boundary layers, it is possible to use the following schemes for parameterizing:

– The Mellor-Yamada-Janjic (MYJ) parametrization is based on the turbulent kinetic energy equation, the right side of which includes terms depending on vertical gradients of wind and potential temperature that produce turbulent kinetic energy.

– Parametrization of Yonsei University (YSU). The scheme calculates the vertical exchange coefficient for the amount of motion using information on vertical gradients of temperature and wind, calculates a turbulent analogue of the Prandtl number, and determines the coefficient of turbulence for use in the equations of temperature and humidity transfer. The contribution from large vortices is determined depending on the magnitude of convective flows at the upper boundary of the surface layer, which are expressed in terms of the stability functions.

Finally, we consider three different options for specifying the parameters of the WRF model using the WSM6 microphysics is used in combination with the YSU scheme (Exp.1); combination of a planetary boundary scheme layer MYJ PBL combined with Thompson microphysics (Exp.2); in the second variant, the same microphysics is used, but the parameters of the boundary layer are set according to the YSU PBL scheme (Exp.3).

The boundary and initial conditions for the regional climate model were established on the basis of the ERA-Interim reanalysis data set (https://rda.ucar.edu/datasets/) with a 6-hour interval [25], a spatial resolution of 1,5° over the entire Earth's surface, which is about 150 km Central Asian region [26]. The fields of the meteorological parameters listed above are presented at 37 isobaric levels [27]. In each cycle of ERA-Interim reanalysis , the available observational data is combined with the previous forecast model information to calculate the evolution of atmospheric parameters (temperature, wind speed, air humidity, ozone concentration, surface pressure) and the underlying surface (temperature and humidity at a height of 2 meters, humidity and soil temperature, snow). Additionally, two global archives were used as observation data: data from the Meteorological Office, UK (CRU-Climatic Research Units), with a spatial resolution of $0,5^0$ (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.00); data from the laboratory of near-surface hydrology at Princeton University, USA, with a spatial resolution of $0,25^0$ (http://hydrology.princeton.edu/data).

The study area. The entire earth's surface is divided into 14 domains have been defined with a spatial resolution of 0,44x0,44 degrees, which approximately corresponds to 50 km. There are areas of current and future climate research based on regional statistical and dynamic models. The domain must include specific physical processes that are important for the climatology of the selected region, have mesoscale or smaller space-time dimensions, which are not reflected by coarser global models. Another criterion is the additional information obtained by regional models compared to global ones. The domain of Central Asia is defined by the scientific group Science Advisory Team and looks as follows (figure 1).

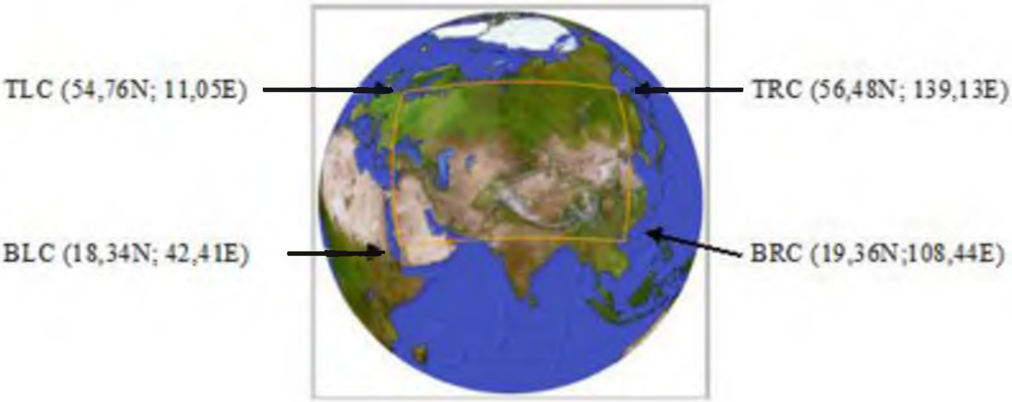

Figure 1 – Domain Central Asia (borrowed from https://www.cordex.org/domains/region-8-central-asia/)

The selected region occupies a vast expanse territory on the earth's surface. It stretches across the territory of Eurasia in the latitudinal direction for almost 5 thousand km, in the meridional direction - more than 1 thousand km. The surface relief varies from high mountains to lowlands lying below sea level. It includes several climatic zones, for example, a territory with a humid and cold continental climate in western Europe and a dry, very cold subboreal climate in the middle and eastern regions of the Siberian plateau; dry mid-latitude desert and steppe with an arid and semi-arid climate in the middle of Central Asia; Himalayas and Tibetan plateau with highland climate. There are areas of the earth's surface, within which there is approximately a homogeneous climate throughout their length.

Results and discussion. The duration of each numerical experiment is 17 years of simulation, which leads to the emergence of numerical instability caused by rounding errors. A simulation interval of 1 month was chosen. The results of numerical experiments for the selection of parameterization schemes of microphysical processes and processes in the boundary layer of the atmosphere are presented in the form of maps of the average annual seasonal variability of surface temperature and precipitation.

The difference between the average annual seasonal variability of surface temperature and precipitation, calculated by the WRF model and observations data from the CRU and Princeton University archives, was analyzed to assess the accuracy of reproducing the climate system parameters by the WRF model for the above parameterization schemes for 4 seasons of the year (period 2000-2016).

Figure 2 shows the field of average monthly surface temperature for July 2015, obtained by the output data model (Exp.1 WSM6+YSU) and interpolated in the spatial grid nodes observation data CRU - Climate Research Units. WRF results are averaged from 3-hour data, CRU data is averaged from average daily data.

As an example, long-term dynamics of average monthly temperatures for CRU and the WRF from January 2006 to December 2015. The data is obtained for the coordinates of the city of Almaty (43° N, 77° E). The correlation between WRF and CRU data for Almaty coordinates is shown in figure 3.

Figure 4 show the comparison results for the surface temperature values, for the autumn season. In the autumn period, there is a positive difference between the calculated and observed temperatures for parameterization schemes 1 and 2, and the use of the parameterization scheme 3 allowed us to obtain the most satisfactory result. The excess of the calculated values of the temperature of the surface layer in comparison with the observed in winter at 2-3°C in the Northern regions of the considered domain, for all numerical experiments with different parameterizations determined by what ERA-Interim reanalysis data already overestimate the temperature of the surface layer for winter. Similar calculations were made for all seasons of the year.

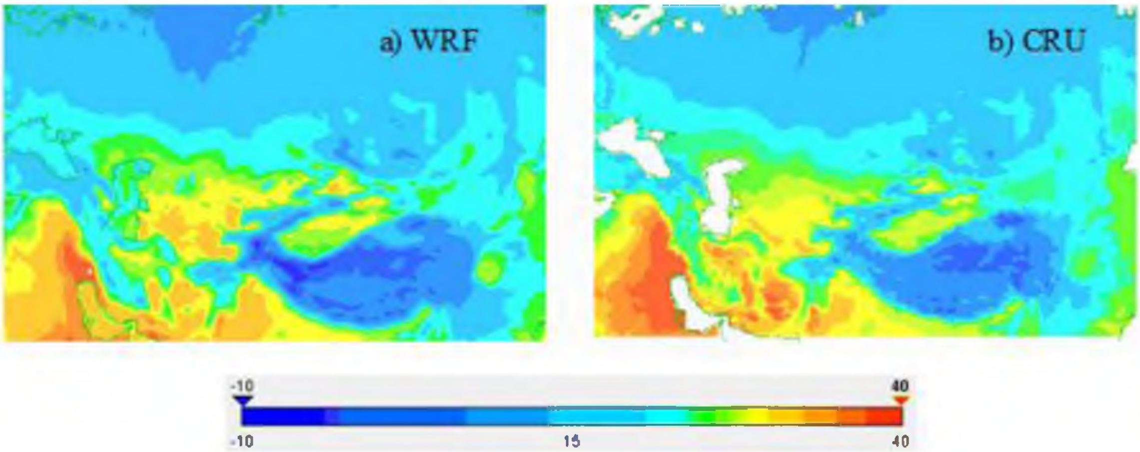

Figure 2 – Average monthly surface temperature for July 2015 according to the calculations (a) and observations (b) (Exp.1 WSM6 + YSU)

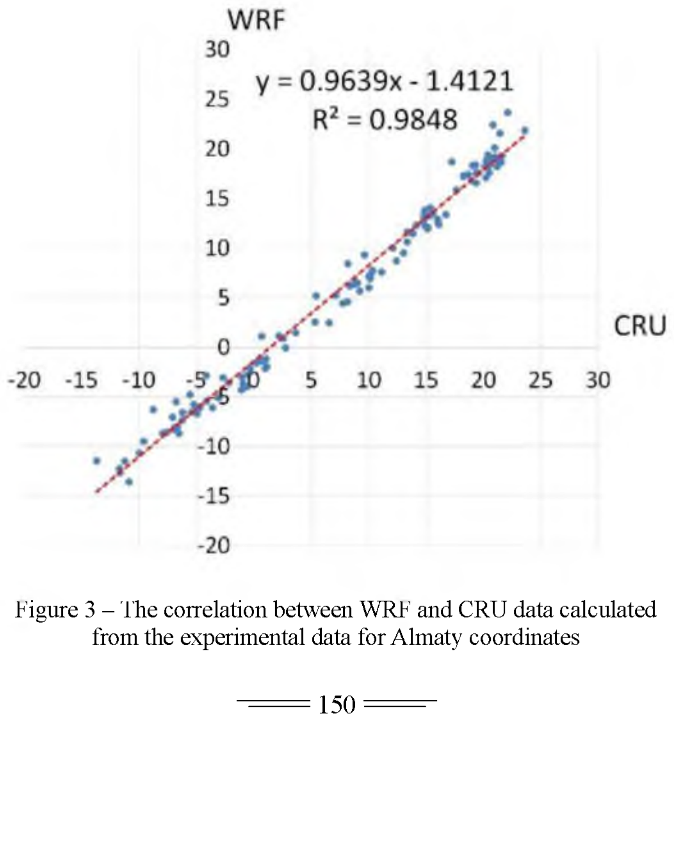

Figure 3 – The correlation between WRF and CRU data calculated from the experimental data for Almaty coordinates

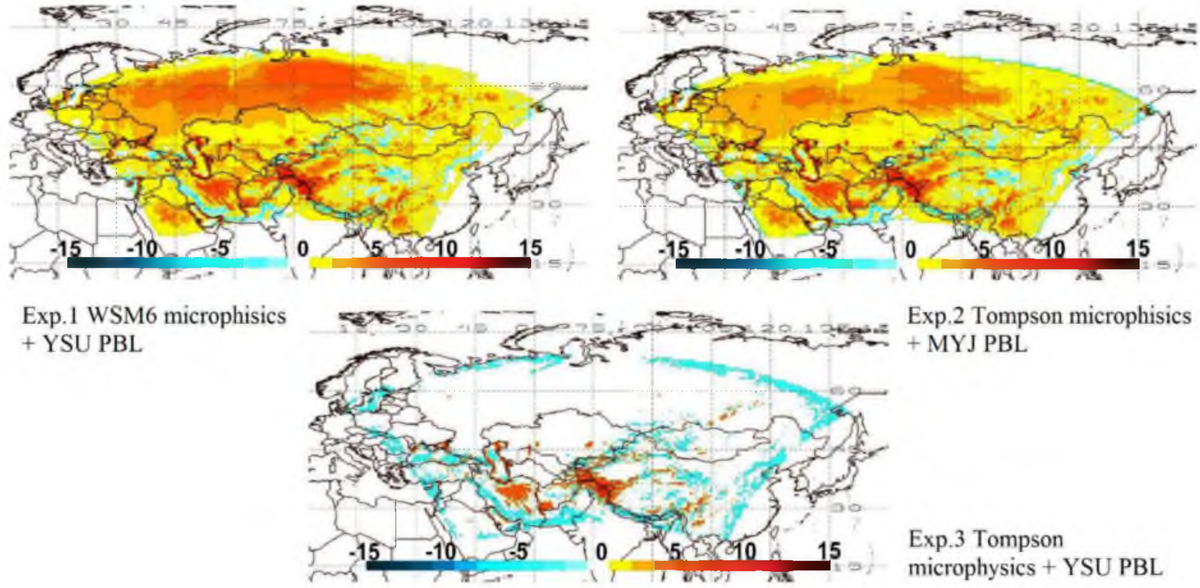

Figure 4 – The difference between the average temperature of CRU and WRF in 2000–2016, the autumn (September, October, November)

In the cold season, the best correspondence between the calculated and observed values is obtained in a numerical experiment using the parameterization scheme 3 (Exp. 3). During the summer period, the best correspondence between model calculations and observational data was obtained using the parameterization scheme 2. Similar comparisons are made between annual precipitation and ground data.

For all seasons, excluding summer, the calculated precipitation values exceeds the observed precipitation for the Western and Northern parts of the study area. Calculations by scheme 3 show better results compared to schemes 1 and 2. In some cases, anomalies occur at the Northern and Eastern borders of the domain, which is probably due to the insufficient width of the relaxation zone. The error of the average annual precipitation values calculated using the regional model does not exceed 1,5 mm/day.

The model produces a significant excess of precipitation in mountainous areas and the Asian monsoon region for autumn, spring, and winter. The opposite situation is observed in the summer. In the summer, precipitation is overestimated by the model for most of the studied domain. Their significant overestimation can be traced in arid and semi-arid regions, as well as in the humid southern parts of the domain. This is due to the fact that mid-latitude cyclones are weaker and less frequent in summer, northern fronts prevail, temperature and pressure gradients decrease over the Euro-Asian continent, and the impact on the South Asian monsoon depression. For the Northern and southern parts, there is also a slight excess of the model calculation data relative to the observed ones.

A comparison of the average long-term seasonal values of the surface air temperature and average annual precipitation according to models and observations for the period 2000-2016 for the entire territory of the studied domain was made using data from the CRU and Princeton University observation archives, ERA-Interim reanalysis and the results of calculations for the WRF RCM (Exp.3), (table).

Average long-term air temperature values and annual precipitation according to models and observations

Models and observations	Average long-term seasonal values surface temperature (^{0}C), (2000-2016)				Mean annual and mean seasonal precipitation (mm/day)			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
WRF (exp 3)	-8,13	5,36	19,51	5,65	1,29	1,57	2,30	1,69
ERA-Interim	-3,44	7,98	20,27	8,61	0,31	0,45	0,82	0,45
CRU	-7,38	6,76	19,52	6,92	0,74	1,09	2,30	1,26
Prinston Un.	-7,68	6,09	19,12	6,70	0,92	1,51	2,02	1,30

As can be seen from Table the regional climate model gives closer air temperature values at the height of 2 m, compared with the observed data, than the results of the ERA-Interim reanalysis for all seasons of the year. The total discrepancy for the domain-averaged long-term air temperature calculated from the model and observations does not exceed 2,0 ^{0}C.

It should be noted that model calculations with the parameterization scheme 3 (exp. 3) correspond better than other parameterization schemes to observational data. It can be seen the regional model data are more consistent with observational data compared to the ERA-Interim set.

The average annual precipitation according to the WSM6 scheme overestimates the data when using the YSU-Thompson scheme, and for the MYJ-Thompson scheme, this value has slight deviations from the YSU-Thompson scheme, which indicates a slight difference when using different parameterization schemes of boundary layer.

Conclusion. We tested the ability of the WRF model to reproduce the observed parameters of the climate system within the Central Asia domain (region 8 of the CORDEX program). A number of numerical experiments were conducted to test various microphysics parametrization schemes and processes occurring in the boundary layer in order to select such a scheme that best reproduces the main characteristics of the climate.

Three combinations of the WRF model schemes were considered, based on the experience of previous regional climate studies: (Exp.1) Thompson microphysics + Mellor-Yamada-Janjic Planetary Boundary Layer (MYJ PBL) parametrization; (Exp.2) Thompson microphysics + Yenssen University Planetary Boundary Layer (YSU PBL) parametrization; (Exp.3) Single Moment 6-class parametrization (WSM6) microphysics + Yenssen University Planetary Boundary Layer (YSU PBL) parametrization.

The assessment of the region's seasonal climatology was performed for the traditional seasons of the year using three parameterization schemes.

The analysis of the difference in surface temperature fields between observations from the CRU archive and calculations using the WRF model with boundary and initial ERA-Interim conditions for different seasons of the year was carried out. Application of the parameterization scheme 3 (Exp.3) it allowed us to get the most satisfactory result.

The difference between average long-term precipitation was compared using simulation data with three parameterization schemes and observation too. Calculations by scheme 3 show better results compared to schemes 1 and 2.

Based on the obtained results, it can be concluded that the simulation data using parameterization scheme for the YSU PBL boundary layer and Thompson microphysics are better than other schemes considered in this study are consistent with observations of precipitation and surface layer temperature.

In conclusion, it should be noted that the WRF numerical regional model with selected parameterization schemes, can be used to simulate future climate projections within the Central Asia domain for various scenarios of greenhouse gases in the atmosphere (RCP (Representative Concentration Pathway) 4.5, RCP 8.5.) [28].

Acknowledgment. This work was done with the support of grant funding for scientific projects of the MES RK No. AP05135848.

Н. Юничева[1], И. Есеркепова[1], К. Бостанбеков[2], А. Алимова[2], И. Витковская[1], A. Keylan[3]

[1]Ақпараттық және есептеуіш технологиялар институты, Алматы, Қазақстан;
[2]Satbayev University, Алматы, Қазақстан;
[3]Токио Денки университеті, Токио, Жапония

«ОРТАЛЫҚ АЗИЯ» ДОМЕНІНЕ АРНАЛҒАН БАҚЫЛАУ ДЕРЕКТЕРІМЕН САЛЫСТЫРУ НЕГІЗІНДЕ АЙМАҚТЫҚ КЛИМАТ МОДЕЛІНІҢ ПАРАМЕТРЛЕРІН ТАҢДАУ

Аннотация. CORDEX бағдарламасы бойынша аймақтық климатты модельдеу болашақтағы климат жағдайына болжам жасауда жаһандық климаттық модельдерге қарағанда анағұрлым дәлдірек және жергілікті экстремалды оқиғаларды нақтырақ көрсетуде маңызды рөл атқарады. Аймақтық модель атмосфералық үдерістерге таулардың және жер бетінің әсерін көрсетеді. Олардың үлесін бөлуді аймақтық модельдеудің күтілетін негізгі нәтижесі деп санауға болады. WRF моделі – зерттеу мақсатында және күнделікті ауа райын болжау мен атмосфералық үрдістерді модельдеу жүйесі.

Мақалада Орталық Азия аймағына арналған WRF аймақтық климат моделінің оңтайлы параметрлерін таңдау нәтижелері келтірілген. Климаттың негізгі сипаттамаларын жеткілікті баяндайтын схеманы таңдау мақсатында шекаралық қабатта жүретін әртүрлі микрофизика мен үдерістердің параметрлендіру схемаларын сынау арқылы жоғары өнімділікті есептеуіш кластерін пайдаланып, бірқатар сандық тәжірибе жүргізілді. Микрофизика және шекаралық қабат схемаларының үш тіркесімі қарастырылды: гидрометеорлардың 5 класын (бұлттағы су, жауын-шашын, бұлттағы мұз, қар және қар түйіршіктері) қолданатын Томпсонның бірреттік микрофизика схемасы атмосфералық шекара қабатының PBL MYJ схемасымен бірге, екінші нұсқада сол микрофизика қолданылады, бірақ шекаралық қабаттың параметрлері PBL YSU схемасын пайдаланады; үшінші нұсқада гидрометеорлардың 6 класы бар WRF Single Moment микрофизика схемасы мен PBL YSU схемасының үйлесуі. Таңдалған аймақтың маусымдық климатологиясы жылдың дәстүрлі жыл мезгілдеріне 2000-2016 жылдар аралығында бағаланды. Аймақтық климат моделі үшін бастапқы және шекаралық шарттар ретінде ERA-Interim реанализ мәліметтері пайдаланылды. Бақылау деректері ретінде екі ғаламдық мұрағат пайдаланылды: Ұлыбритания метеорологиялық бюросының деректері және АҚШ-тың Принстон университетінің жерүсті гидрология зертханасының деректері. Сандық есептеу нәтижелері карта-схема түрінде ұсынылған. Жерүсті қабатының температурасы мен жылдық жауын-шашын өрістерінің бақылау деректерінен айырмашылығы есептелген. Модельдеу нәтижелерін талдау барысында модель климаттық масштабтағы атмосфералық үдерістерді жеткілікті түрде сипаттайды және климаттық жүйенің негізгі параметрлерінің кеңістік-уақыт өзгерісін жақсы көрсетеді. Ерекшелікгі ретінде орографиялық әртектілігі бар аудандар – таулы және биік таулы аудандарды бақылау желісінің сирек кездесуі арқылы түсіндіруге болады. MYJ PBL шекара қабатының және Thompson микрофизикасының параметрлендіру схемалары арқылы алынған модельдеу нәтижелері жауын-шашын мен жер қабаты температурасының бақылау деректерімен сәйкестігі зерттеуімізде қарастырылған басқа схемаларға қарағанда үздік екендігі анықталды.

Таңдалған параметрлендіру схемаларын пайдаланып, WRF сандық климаттық моделін атмосферадағы көшет газ шоғырлануының түрлі сценарийлері үшін Орта Азия аймағында болашақтағы климат болжамын модельдеу үшін қолдануға болатындығын атап өткен жөн.

Түйін сөздер: климат өзгерісі, модельдеу, таңдау, параметрлендіру, сезімталдық, WRF.

Н. Юничева[1], И. Есеркепова[1], К. Бостанбеков[2], А. Алимова[2], И. Витковская[1], А. Keylan[3]

[1]Институт информационных и вычислительных технологий, Алматы, Казахстан;
[2]Satbayev University, Алматы, Казахстан;
[3]Токио Денки университет, Токио, Япония

ВЫБОР ПАРАМЕТРОВ РЕГИОНАЛЬНОЙ МОДЕЛИ КЛИМАТА НА ОСНОВЕ СРАВНЕНИЯ С ДАННЫМИ НАБЛЮДЕНИЙ ДЛЯ ДОМЕНА «ЦЕНТРАЛЬНАЯ АЗИЯ»

Аннотация. Моделирование регионального климата в рамках программы CORDEX играет важную роль, обеспечивая прогнозы будущего климата с большей детализацией и более точным представлением локальных экстремальных явлений, чем глобальные климатические модели. В региональной модели воспроизводится влияние гор и свойств подстилающей поверхности на атмосферные процессы. Распределение их вклада можно считать основным ожидаемым результатом регионального моделирования. Модель WRF – система прогнозирования погоды и моделирования атмосферных процессов, подходящая как для оперативных, так и для исследовательских целей.

В статье представлены результаты выбора оптимальных параметров региональной климатической WRF-модели для региона Центральной Азии. Проведен ряд численных экспериментов на высокопроизводительном вычислительном кластере для тестирования различных схем параметризации микрофизики и процессов, происходящих в пограничном слое с целью выбора такой схемы, которая наилучшим образом воспроизводит основные характеристики климата. Рассмотрены три комбинации схем микрофизики и пограничного слоя: одномоментная схема микрофизики Томпсона, использующая 5 классов гидрометеоров (вода в облаках, осадки, лед в облаках, снег и снежная крупа) в сочетании со схемой пограничного слоя атмосферы PBL MYJ; во втором варианте используется та же микрофизика, но параметры пограничного слоя устанавливаются в соответствии со схемой PBL YSU; в третьем варианте микрофизика схема WRF Single Moment с 6 классами гидрометеоров в сочетании со схемой YSU. Оценка сезонной климатологии выбранного региона выполнена для традиционных сезонов года за период 2000–2016 гг. В качестве начальных и граничных условий для региональной модели климата были использованы данные ERA-Interim реанализа. В качестве данных наблюдений использовались два глобальных архива: данные из Метеорологического бюро Великобритании и данные лаборатории приповерхностной гидрологии Принстонского университета США. Результаты численного расчета представлены в виде карта-схем. Рассчитаны разности полей температур приземного слоя и годовых сумм осадков с данными наблюдений. Из анализа результатов моделирования следует, что модель адекватно описывает атмосферные процессы климатического масштаба и хорошо воспроизводит пространственно-временные вариации основных параметров климатической системы. Исключение составляют районы с орографическими неоднородностями – горные и высокогорные районы, что можно объяснить редкостью наблюдательной сети. Определено, что данные моделирования с использованием схем параметризации для пограничного слоя MYJ PBL и микрофизики Thompson лучше, чем другие, рассмотренные в настоящем исследовании, согласуются с данными наблюдений за осадками и температурой приземного слоя.

Следует отметить, что численная климатическая модель WRF с подобранными схемами параметризации может быть использована для моделирования проекций будущего климата на территории домена Центральная Азия для различных сценариев содержания парниковых газов в атмосфере.

Ключевые слова: изменение климата, моделирование, выбор, параметризация, чувствительность, WRF.

Information about authors:

Yunicheva N.R, Candidate of Engineering Sciences, Associate Professor of VAK (Higher Certification Commission), Institute of Information and Computational Technologies; naduni@mail.ru; https://orcid.org/0000-0001-6351-3450

Eserkepova I.B., Candidate of Geographical Sciences, Institute of Information and Computational Technologies; iyesserkepova@mail.ru; https://orcid.org/0000-0003-2408-1602

Bostanbekov K.A., PhD of computer and software. Satbayev University; k.bostanbekov@norlist.kz; https://orcid.org/0000-0003-2869-772X

Alimova A.N., PhD, Satbayev University; anic2002@mail.ru; https://orcid.org/0000-0002-5155-2417

Vitkovskaya I.S., PhD, Institute of Information and Computational Technologies; irinas_vit@mail.ru; https://orcid.org/0000-0001-7758-2975

Alimhan Keylan, Doctor of Science, Tokyo Denki University; 20787@ms.dendai.ac.jp; https://orcid.org/0000-0003-0766-2229

REFERENCES

[1] Bruyère C.L., Done J.M., Holland G.J., Fredrick S. (2014) Bias Corrections of Global Models for Regional Climate Simulations of High-Impact Weather, Climate Dynamics, 43: 1847-1856. DOI:10.1007/s00382-013-2011-6

[2] Sherstyukov B.G., Salugashvili R.S. (2010) New trends in climate change in the Northern Hemisphere in the recent decade. Proceedings of the All-Russian Research Institute of Hydrometeorological Information - World Data Center, 175: 43-51 (in Russ.).

[3] Cardoso R.M., Soares P.MM., Lima D.CA., Miranda P.MA. (2019) Mean and extreme temperatures in a warming climate: EURO CORDEX and WRF regional climate high-resolution projections for Portugal, Climate Dynamics, 52: 129-157.

[4] Fita L., Polcher J., Giannaros T.M., Lorenz T., Milovac J., Sofiadis G., Katragkou E., Bastin S. (2019) CORDEX-WRF v1.3: development of a module for the Weather Research and Forecasting (WRF) model to support the CORDEX community. Geoscientific Model Devolepment, 12: 1029-1066. DOI:10.5194/gmd-12-1029-2019.

[5] Kang H. (2014) Regional Downscaling Experiments for CORDEX-East Asia. The 7th ICTP workshop on Theory and Use of Regional Climate Models. Trieste, Italy. 26 p.

[6] Tang J., Wang S., Niu X., Hui P., Zong P., Wang X. (2017) Impact of spectral nudging on regional climate simulation over CORDEX East Asia using WRF. Climate Dynamics, 48: 2339-2357. DOI:10,1007 /s00382-016-3208-2

[7] Adilbektegi G.A., Mustafayev J.S., Uvatayeva T.K., Dulatbekova Z.N., Mosiej J. (2019) A new approach to the evaluation of bioclimatic potential of landscapes on the example of Northern Kazakhstan. News of the national academy of sciences of the republic of Kazakhstan, Series of geology and technical sciences, 5 (437): 16-25. DOI:10.32014/2019.2518-170X.121

[8] Michalakes J., Dudhia J., Gill D., Henderson T., Klemp J., Skamarock W., Wang W. (2005) The Weather Research and Forecast Model: Software Architecture and Performance. Use of High Performance Computing in Meteorology, 156-168. DOI:10.1142/9789812701831_0012

[9] Kizhner L., Nakhtigalova D., Bart A. (2012) Using the WRF predictive model for weather research in the Tomsk region. Tomsk State University Journal. 358: 219-224 (in Russ).

[10] Isaev E.K. (2014) Hydrodynamic modeling of atmospheric processes in Kyrgyzstan. Bulletin of the Kyrgyz-Russian Slavic University, 14 (7): 49-53. (in Russ.).

[11] Shikhov A.N., Sviyazov E.M. (2015) Estimation of precipitation amount during the cold period in the Western Urals using the WRF model. Geographical Bulletin, 3: 67-73. (in Russ.). DOI: 10.17072/2079-7877-2015-3-67-73

[12] Qiu Y., Hu Q., Zhanga C. (2017) WRF simulation and downscaling of local climate in Central Asia. International Journal of Climatology, 37: 513-528. DOI:10.1002/joc.5018

[13] Thompson G., Field P.R., Rasmussen R.M., Hall W.D. (2008) Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization. Monthly Weather Review, 136: 5095-5115. DOI: 10.1175/2008MWR2387.1

[14] Janjic Z.I. (1994) The step-mountain eta coordinate model: Further developments of the convection, viscous sublayer, and turbulence closure schemes. Monthly Weather Review, 122: 927-945. DOI: 10.1175/1520-0493(1994)122<0927

[15] Janjic Z.I. (2001) Nonsingular implementation of the Mellor–Yamada level 2.5 scheme in the NCEP Mesomodel. National Centers for Environmental Prediction, Office Note 437: 61.

[16] Awan N.K., Truhetz H., Gobiet A. (2011) Parameterization-induced error characteristics of MM5 and WRF operated in climate mode over the Alpine region: an ensemble-based analysis. Journal of Climate, 24: 3107-3123. DOI: 10.1175/2011JCLI3674.1

[17] Borge R., Alexandrov V., Jose del Vas J., Lumbreras J., and Rodriguez E. (2008) A comprehensive sensitivity analysis of the WRF model for air quality applications over the Iberian Peninsula. Atmospheric Environment, 42: 8560-8574. DOI: 10.1016/j.atmosenv.2008.08.032

[18] Evans J., Ekström M., Ji F. (2012) Evaluating the performance of a WRF physics ensemble over South-East Australia. Climate Dynamics, 39: 1241-1258. DOI 10.1007/s00382-011-1244-5

[19] Gao Y., Xu J., Chen D. (2015) Evaluation of WRF mesoscale climate simulations over the Tibetan Plateau during 1979–2011. Journal Climate, 28: 2823-2841. DOI: 10.1175/JCLI-D-14-00300.1

[20] García-Díez M., Fernández J., Fita L., Yagüe C. (2013) Seasonal dependence of WRF model biases and sensitivity to PBL schemes over Europe. Quarterly Journal of the Royal Meteorological Society, 139: 501-514. DOI: 10.1002/qj.1976

[21] Iskalieva M. (2012) First steps of numerical weather forecasts in Kazakhstan. Report International scientific conference on regional problems of Hydrometeorology and Environmental monitoring, Kazan, Russia. 23 p. (in Russ.).

[22] Hong S.Y., Lim J.O.J. (2006) The WRF Single-Moment 6-Class Microphysics Scheme (WSM6). Journal of the Korean Meteorological Society, 42: 129-151.

[23] Takle E.S., Gutowski W.J., Arritt R.W., Pan Z., Anderson C.J., Ramos da Silva R., … Roads J.O. (1999) Project to Intercompare Regional Climate Simulations (PIRCS): Description and initial results. Journal of Geophysical Research Atmospheres, 104 (D16): 19443-19461.

[24] Schneider U., Finger P., Meyer-Christoffer A., Rustemeier E., Ziese M., Becker A. (2017) Evaluating the Hydrological Cycle over Land Use of the Global Precipitation Climatology Center (GPCC). Atmosphere, 8 (3): 52. DOI: 10.3390/atmos8030052

[25] Simmons A., Uppala S., Dee D., Kobayashi S. (2007) ERA-Interim: New ECMWF reanalysis products from 1989 onwards. ECMWF Newsletter, 110: 25-35.

[26] Bostanbekov K.B., Yunicheva N.R., Alimova A.N. (2019) Procedure for the selection of optimal parameters of numerical regional climatic model (RCM) for the domain «Central Asia». Proceedings of the 2nd International Conference on Sustainable Science and Technology (ICSuSaT-2019), Istanbul, Turkey. 46 p.

[27] Dee D.P., Uppala S.M., Simmons A.J., Berrisford P., Poli P., and co-authors (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137: 553-597. DOI:10.1002/qj.828

[28] Bruyère C.L., Monaghan A.J., Steinhoff D.F., Yates D. (2015) Bias-Corrected CMIP5 CESM Data in WRF/MPAS Intermediate File Format. NCAR/TN-515+STR, 27. doi:10.5065/D6445JJ7