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What SSP Global Climate Change Scenario is the Caspian Sea Region Following? Part 1: Air Temperature Analysis

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The paper's aim is to study the impact of global and regional climate change on the state of the Caspian Sea. Determining the most probable climate scenarios for different coastal zones is an important step in predicting the change in the Caspian Sea level and developing plans for the region's adaptation to future climate change. This study assessed the Shared Socioeconomic Pathways (SSP) climate scenarios obtained using the CMIP6 global climate models (GCMs) by comparing the simulated data with actual measurements of surface air temperature (tas) at 72 weather stations in a 200-km buffer zone of the Caspian Sea. The analysis covered the period from 2015 to 2025. The research focuses on air temperature as the most reliably predicted parameter. The study used four main SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) calculated based on six climate models (AWI-CM-1-1-MR, CMCC-CM2-SR5, CNRM-CM6-1-HR, EC-Earth3, MPI-ESM1-2-HR and INM-CM5-0). The quality of the modeling was assessed using a number of indicators: mean error (ME), correlation coefficient (r), coefficient of determination (R^2), root mean square error (RMSE), Nash–Sutcliffe efficiency (NSE) and Kling–Gupta efficiency (KGE). The results showed a high degree of agreement between the models and observations for temperature, with correlation coefficients ranging from 0.85 to 0.96. However, systematic biases are observed (from −12.9 to +6.5 °C), with modeled data generally overestimated for lowland areas and underestimated for mountainous areas. The choice of the "best" SSP scenario varies depending on the metric used: based on RMSE and NSE, the most consistent with the actual mean temperature data (2015–2025) is the SSP5-8.5 scenario, while based on KGE, the SSP3-7.0 scenario better reproduces the variability and structure of the time series.

Keywords: Caspian Sea, air temperature, weather stations, SSP, CMIP6, global climate models.

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Research Article

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Introduction

Due to global and regional climate changes in recent decades, the issue of the current and future state of the Caspian Sea has acquired the status of special attention [*Kostianoy and Pesic*, 2024]. The issue of the sea level decline in the Caspian Sea is especially acute, since the sea is the most important transport artery for the riparian countries. In recent years, the cargo turnover of the Caspian Sea ports has increased significantly. The decrease in the level of the Caspian Sea sometimes does not allow loading ships to full draft, which leads to economic losses. Dredging often has a temporary effect, or solves the problem partially, since the decline in the Caspian Sea level has been ongoing for 30 years at an average rate of about 10 cm per year [*Kostianoy et al.*, 2025].

In case of negative climate development scenarios and a further sea level decrease, it may be necessary to move the port infrastructure and to construct offshore terminals in the future, first of all, this concerns the shallow Northern Caspian. The high probability of a significant drop in sea level puts the shallow northern part of the Caspian Sea and the Kara-Bogaz-Gol Bay at serious risk of drying out. In particular, some forecasts show that with a drop in the level of 5.0–7.5 m, all ports in the Caspian Sea will become shallow [*Hoseini et al.*, 2025], which will lead to the collapse of the entire transport system in the Caspian Sea. By the end of the 21st century the coastline will retreat from several to tens of kilometers, and in the Kazakh part of the Northern Caspian, with a sea level drop of 10 m, the coastline will retreat up to 200 km from the modern coast, ports and cities with catastrophic socio-economic and environmental consequences for all Caspian countries [*Court et al.*, 2025].

We would like to highlight the high level of uncertainties in the Caspian Sea level forecasts, which depend on the scenario under which the climate change in the Caspian region will occur. For example, *Hoseini et al.* [2025] provide the following probabilistic median estimates (25–75 percentile) of the Caspian Sea level changes in 2100 relative to 2021 in their study: +0.3 m (−12.2 … +10.2 m) for the low greenhouse gas emissions scenario, −1.8 m (−6.7 … +3.1 m) for the medium emissions scenario, −3.3 m (−9.3 … +2 m) for the medium and high emissions scenario, and −4.4 m (−11.0 … +1.6 m) for the high emissions scenario. The most pessimistic forecasts show that by the end of the 21st century the Caspian Sea level could drop by another 21 m under the worse climate development scenario in the region [*Kostianoy et al.*, 2025]. Thus, one of the most important tasks is not only to choose the best climate model that will allow the most realistic calculation of the water balance and level of the Caspian Sea, but also to establish according to which scenario climate change is occurring in the Caspian.

Since the Caspian Sea has no direct connection with the World Ocean, the level of the Caspian Sea is constantly affected by various factors, including global and regional climate change. An increase in air and land temperature leads to an increase in the rate of evaporation from the watershed area and sea surface, as well as a decrease in runoff from the rivers flowing into the Caspian Sea. The main component of the incoming part of the Caspian Sea water balance is the runoff of rivers, which is 80% determined by the runoff of the Volga, the outgoing part is primarily associated with evaporation from the sea surface [*Kostianoy et al.*, 2025].

The Caspian Sea is a southern sea with an annual stable ice cover in the northern part of the sea. Each winter, the water area of the Northern Caspian is partially covered by stable ice, while in the Middle Caspian ice is observed only in coastal areas and only in severe winters. The duration of the cold period in the north-eastern part of the Northern Caspian is up to 5 months, and in the northwestern part – a month less [*Lavrova et al.*, 2022; *Zonn et al.*, 2010]. Evaporation from the sea surface, in particular, depends on the sea surface temperature (SST) and air temperature, as well as on the area of ice cover in the Northern Caspian. A decrease in the ice area is reflected in the water balance of the sea in winter, and can be a factor exacerbating the drop in the Caspian Sea level [*Kostianoy et al.*, 2025]. Thus, air temperature is one of the most important parameters which indirectly enters in the equation of the Caspian Sea water balance and from the other hand this is one of the parameters that is best reproduced in climate models and atmospheric reanalyses.

The IPCC (Intergovernmental Panel on Climate Change) reports pay special attention to adaptation to future climate change [*IPCC*, 2023]. In the Caspian Region, due to climate change, the primary problem is sea level decline. To adapt to the upcoming transformations, it is useful to have an idea of the strength and direction of future climate change. To identify future climate change trends, Global Climate Models (GCMs) are widely used at present. These models are developed by leading climate research centers from different countries. The World Climate Research Programme (WCRP) coordinates the Coupled Model Intercomparison Project (CMIP), which brings together a wide range of global climate models (GCMs). An important part of CMIP is to make the multi-model output publicly available in a standardized format for analysis by the wider climate community and users [*Eyring et al.*, 2016]. Standardized CMIP model output is distributed through the Earth System Grid Federation (ESGF). CMIP6 is the most recent phase of the project, aligned with the preparation of the Sixth Assessment Report of the IPCC [*IPCC*, 2023]. Compared to previous phases, CMIP6 includes more advanced and sophisticated climate models.

When modelling future climate, it is important to take into account not only physical processes in the atmosphere and ocean, but also the trajectories of social, economic and energy development. In this regard, scenarios that take into account socio-economic factors were introduced into CMIP6. This is implemented through the use of Shared Socioeconomic Pathways (SSP) – a set of agreed socio-economic trajectories describing possible paths of human development until the end of the 21st century [*O'Neill et al.*, 2016; *Riahi et al.*, 2017; *Semenov and Gladilshchikova*, 2022]. SSP form the basis for modelling future climate change, as they determine the dynamics of demographic processes, economic growth, the level of urbanization, the energy structure and technological progress. Each trajectory reflects different societal development strategies – from a sustainable low-carbon future to scenarios of intensive use of fossil fuels. When combined with climate models, SSPs allow us to assess a wide range of potential climate change impacts and the effectiveness of mitigation and adaptation measures.

These trajectories are generated using Integrated Assessment Models (IAM), which combine demographic, economic, and energy projections to calculate emissions of key greenhouse gases and aerosols (CO_2, CH_4, N_2O, etc.). The resulting emission scenarios are converted into atmospheric gas concentrations and radiative forcing, which are then used as input data in the CMIP6 Global Climate Models. This approach ensures consistency between socio-economic assumptions and physical climate modeling, allowing for a more comprehensive assessment of the future development of the climate system. The climate model calculates the spatial distribution of future climate parameters (air temperature, precipitation, etc.) on a regular grid from 2015 to 2100. The CMIP6 modeling results are available to researchers in NetCDF file format for various scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5). However, some scenarios may be missing for individual models.

Evaluation of SSP scenarios is of great practical importance, since many management decisions are made based on modeled climate trajectories. Forecast data on climate parameters are used to analyze various trends, for example, to predict the future level of the Caspian Sea. However, the agreement between model estimates (from 2015 to the present) and actual measurements is often not verified. Sometimes, reanalysis data and other gridded products can be used to verify scenarios. Their advantage is their ease of use, since raster operations in GIS applications allow for quick results. However, it should be taken into account that such products contain their own uncertainty, which is likely to be unevenly distributed in space, especially in areas where weather stations are sparsely located. Additional distortions are introduced by differences in spatial resolution. For most climate models, it is about 1°, while for reanalyses it is usually 0.25–0.5°. Moreover, the boundaries of gridded cells may not coincide for different products, which complicates their direct comparison. Within one pixel there may be areas with significantly different relief and altitude, which also affects climate parameters. The most reliable source of information remains discrete observations at weather stations, allowing manual assessment of how well the model data reproduces climate conditions in specific locations.

Air temperature is one of the key climate factors. At the same time, surface air temperature is considered the most reliably predictable parameter compared to precipitation, wind and other variables. Our preliminary assessments of SSP scenarios for the Caspian Sea region based on several global climate models confirmed this. SSP scenarios include climate change calculations starting from 2015, and already based on the results of the first decade, preliminary conclusions can be made about the quality of these scenarios, as well as about the most likely trajectory of the climate system development.

This study aims to assess four main SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) obtained using six different climate models for the Caspian Sea Region by comparing modeled data on surface air temperature with actual measurements at 72 weather stations located in a 200-km buffer zone of the Caspian Sea. In this case, attention is focused exclusively on temperature as the most significant and best predicted climate parameter.

Data and Methods

A selection of climate models from the CMIP6 project was carried out. The criteria for selecting models were the presence of surface air temperature (`tas`), a complete set of the four most common main scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5), and high spatial resolution. The following models were suitable for these conditions: CNRM-CM6-1 HR, MPI-ESM1-2-HR, EC-Earth3, CMCC-CM2-SR5, AWI-CM-1-1-MR. All models were selected in the basic version with the first implementation, first initialization, first physical scheme and first forcing (`r1i1p1f1`) with the exception of CNRM-CM6-1 HR, which is available only in the version with the second forcing (`r1i1p1f2`). Within the framework of CMIP6, Russian scientific centers presented several models, the main one being INM-CM5-0, developed by the Institute of Numerical Mathematics of the Russian Academy of Sciences (INM RAS, Moscow). It has a slightly higher spatial resolution, but was developed by a country that is part of the Caspian region, so it was also included in the study. Table 1 shows the spatial characteristics of the models used.

Table 1. Characteristics of the climate models used

Model	Spatial resolution, °	Spatial resolution, km	Grid type	Country/Organization
AWI-CM-1-1-MR	0.9272 × 0.9375	∼103 × ∼85	gn	Germany (Alfred Wegener Institute)
CMCC-CM2-SR5	0.9424 × 1.25	∼105 × ∼114	gn	Italy (Centro Euro-Mediterraneo sui Cambiamenti Climatici)
CNRM-CM6-1-HR	0.4951 × 0.5000	∼55 × ∼46	gr	France (Centre National de Recherches Météorologiques)
EC-Earth3	0.6959 × 0.7031	∼77 × ∼64	gr	EC (Earth Consortium)
MPI-ESM1-2-HR	0.9272 × 0.9375	∼103 × ∼85	gr1	Germany (Max Planck Institute for Meteorology)
INM-CM5-0	1.5 × 2.0	∼167 × ∼182	gr1	Russia (Institute of Numerical Mathematics RAS)

To find meteorological data for the Caspian Sea region, open sources of meteorological information were analyzed, as a result, data from the archives of All-Russian Research Institute of Hydrometeorological Information – World Data Center (VNIIGMI-WDC) [*VNIIGMI-WDC*, 2024], National Centers for Environmental Information (NCEI) [*National Centers for Environmental Information (NCEI)*, 2024] and weather archive RP5 [*Raspisaniye Pogodi Ltd*, 2004] were used to fill the database.

NCEI has large data series, but the data has gaps, both long-term and periodic by day and time of observations. The RP5 resource contains high-quality data, but they start from 2005. VNIIGMI WDC provides high-quality and comprehensive data, but only for weather stations on the territory of the Russian Federation. Data from local meteorological services of other states of the Caspian region were not publicly available at the time of writing this paper. In order to assess climate changes in air temperature in the Caspian Sea region, data from 72 weather stations in a 200-kilometer buffer zone from the coastline were analyzed (Figure 1). Observation data from weather and hydrological stations and posts are among the main sources of reliable information when assessing changes in climate parameters and the climate as a whole.

In this paper, we considered only the surface air temperature at a height of 2 meters above the surface (tas), which is calculated taking into account the average relief height for each pixel. We studied the correspondence of weather stations data for this parameter with the forecasts for four SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) of each of the selected models. In the work, we used monthly average values of the models, and the weather stations data were averaged to monthly averages by processing urgent observations. The analysis covered the period from 2015 to 2025, i.e. the first ten years envisaged in the SSP scenarios.

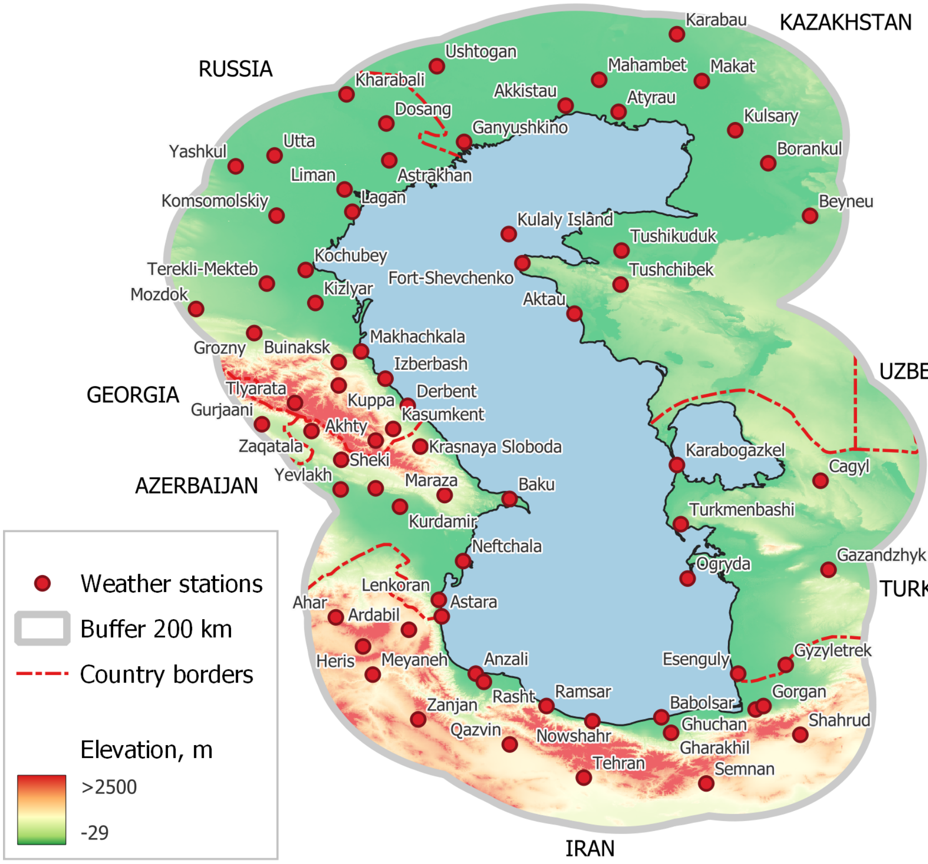

Figure 1. Location of weather stations in the 200-kilometer buffer zone from the coastline of the Caspian Sea (names of weather stations are given according to RP5 weather archive).

In this study, monthly mean station data were compared with monthly values from SSP scenarios. The following metrics were used to assess the agreement between observed and modeled data: mean error (ME), mean absolute error (MAE), root mean square error (RMSE), correlation coefficient (r), coefficient of determination (R^2), standard deviation of the differences (SD), Nash–Sutcliffe efficiency coefficient (NSE), and Kling–Gupta efficiency coefficient (KGE). It should be noted that this study did not aim to validate the GCMs themselves using weather station data. We limited ourselves to validating the SSP scenarios obtained using GCMs, since the number of weather stations with high-quality and long-term observation series available in the public domain was limited.

Results

When comparing simulated and observed surface air temperature (tas) data, the correlation coefficient for all scenarios and models was at least 0.85. The average values of the correlation coefficient for all SSP scenarios for individual models ranged from 0.93 to 0.96. This indicates a high degree of agreement between the models and observations, indicating good quality of air temperature reproduction. It should be noted that when assessing other climate parameters, the agreement between models and observations is generally lower.

Despite the high correlation, the models may have a mean bias. For all SSP scenarios and all models, the mean error (ME) ranged from −12.9 to +6.5 °C. The mean errors (ME) for all SSP scenarios for individual models were: AWI-CM-1-1-MR – +1.69 °C, CMCC-CM2-SR5 – +0.63 °C, CNRM-CM6-1-HR – −2.28 °C, EC-Earth3 – +0.18 °C, INM-CM5-0 – +0.03 °C, and MPI-ESM1-2-HR – +0.71 °C. AWI-CM-1-1-MR shows the largest positive bias, while INM-CM5-0 is closest to observations. CNRM-CM6-1-HR has a pronounced negative bias, indicating a systematic underestimation of air temperature.

The largest ME deviations are observed at weather stations in mountainous areas (see Figure 1 for location). In general, the region shows a tendency for models to underestimate temperature with increasing altitude above sea level. Figure 2 shows the ME values for the moderate scenario SSP2-4.5. The smallest average bias relative to weather stations at low altitudes is demonstrated by the CNRM-CM6-1-HR model, however, it shows significant underestimations for mountainous areas. At the same time, the Russian INM-CM5-0 model, despite its lower spatial resolution, showed good results within the region with variable relief, demonstrating relatively small and balanced deviations for both mountain and lowland weather stations.

The coefficient of determination was calculated using the r^2_score function, so R^2 may differ from r^2, as it reflects not only the correlation but also systematic errors (e.g., ME or amplitude differences). Thus, even with high correlations, significant biases can result in low or negative R^2 values. The coefficient of determination (R^2) for some mountain weather stations, as well as two Iranian weather stations (Ramsar and Gorgan), located almost at sea level, takes negative values (up to -1.59) with the CNRM-CM6-1-HR model scenarios. All these stations have high bias (ME) relative to this model. The highest R^2 values (up to 0.95) are also observed when evaluating the CNRM-CM6-1-HR model. It shows good performance in the northwestern, northern, northeastern and eastern sectors of the allocated 200-kilometer buffer zone at altitudes close to sea level. The standard deviation of the differences (SD) varied from 1.9 to 6.6 °C with an average value of 3.0 °C. The highest average SD value for all SSP scenarios was shown by the CMCC-CM2-SR5 model – 3.5 °C, while for the other models it was about 2.9 °C. No pronounced spatial dependence was observed.

The main metrics for selecting the best scenario were RMSE, NSE and KGE. For each weather station, the most suitable SSP scenario was selected from each GCM we used. Three metrics were used to assess the quality of modeling and select the best scenario: RMSE, NSE and KGE. RMSE (root mean square error) shows the average value of the model deviation from observations in physical units, which makes it clear and easy to interpret. Nash–Sutcliffe efficiency coefficient (NSE) [*Nash and Sutcliffe*, 1970] evaluates how well the model reproduces the variation of observed data compared to their mean value, while it is a dimensionless metric and is traditionally used in hydrological and climatic studies. Kling–Gupta efficiency coefficient (KGE) [*Gupta et al.*, 2009] is a comprehensive assessment that takes into account correlation, amplitude, and model bias relative to observations, allowing for a more comprehensive characterization of the quality of time series reproduction.

While NSE remains one of the most popular and recognized metrics, KGE has become widespread in recent years due to its ability to simultaneously account for several aspects of modeling quality. Using these three metrics together allows for consideration of both the absolute magnitude of errors and the ability of the model to correctly convey the dynamics and variability of the parameter under study.

The analysis showed that the selection of the best scenario by RMSE and NSE coincides in 100% of cases, since both metrics reflect the accuracy of reproduction of average values and errors. To visualize the selection of the best SSP scenario, the RMSE metric was chosen (Figure 3), since it shows the average value of the model error relative to observations in understandable physical units (the lower the RMSE, the better the model), and not in relative or dimensionless quantities like NSE. In Figure 3, the values for the best SSP scenario are given as signatures (in accordance with the color gradation).

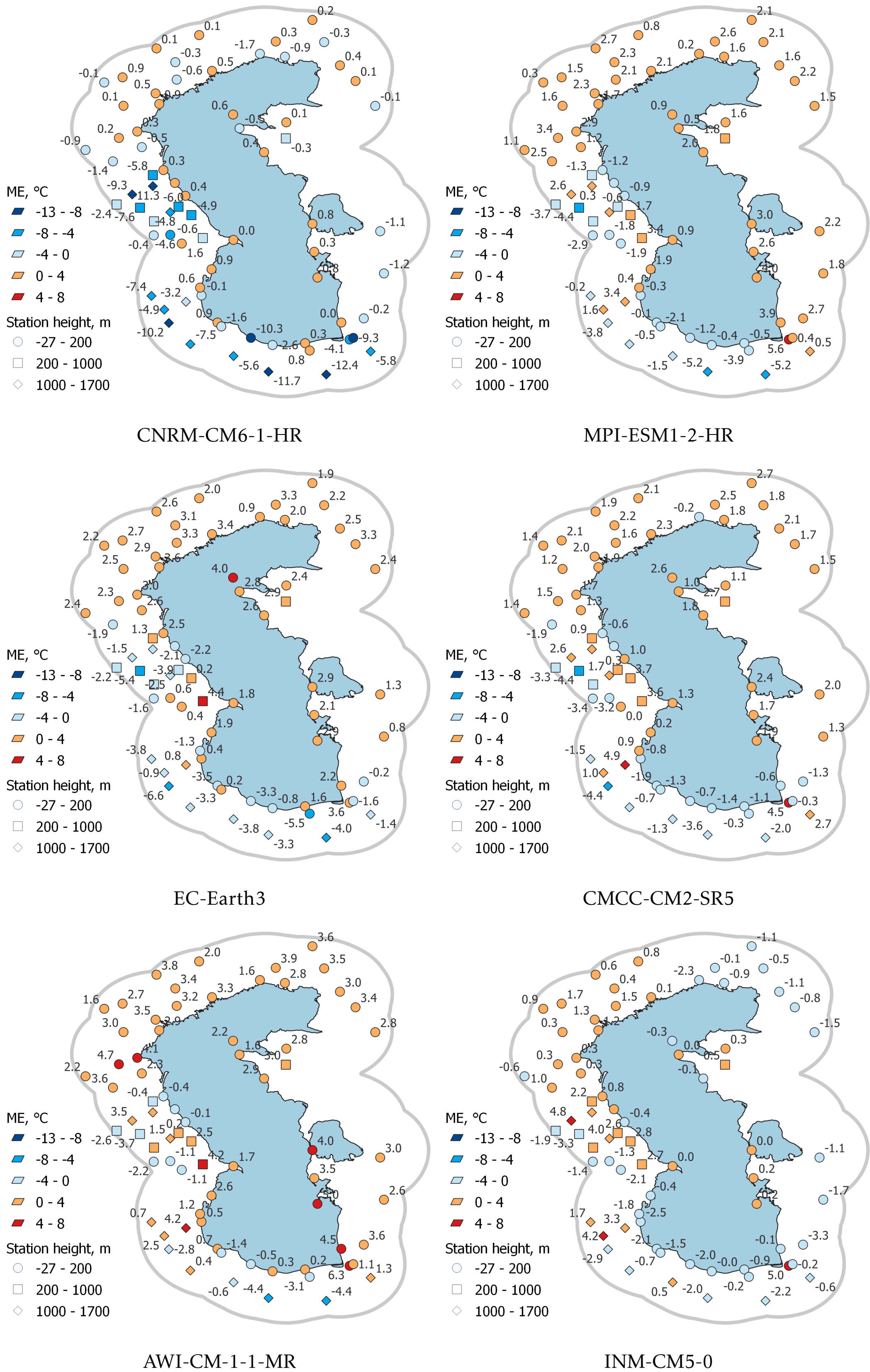

Figure 2. Mean error (°C) of the measurement difference (ME) for the medium (moderate) scenario SSP2-4.5

Using KGE, a different scenario is determined more often than with RMSE and NSE, since this metric additionally takes into account the bias, variation, and correlation of the time series. RMSE and NSE mainly evaluate absolute errors, while KGE evaluates the consistency of the dynamics between the model and observations. The agreement between the RMSE/NSE and KGE metrics for the selected most representative scenario was only 44–64%, depending on the model. The results of selecting the best SSP scenario based on KGE are presented in Figure 4.

Table 2 shows the results of identifying the best SSP scenarios for each model using the RMSE/NSE and KGE metrics. The final selection was based on the mode of the scenario distribution. The values for the multi-model analysis are also presented.

Table 2. Best-performing SSP scenarios by metrics (2015–2025)

Climate Model	Best Scenario by RMSE/NSE	Best Scenario by KGE
CNRM-CM6-1-HR	SSP2-4.5	SSP3-7.0 / SSP2-4.5
MPI-ESM1-2-HR	SSP2-4.5	SSP5-8.5
EC-Earth3	SSP1-2.6	SSP5-8.5
CMCC-CM2-SR5	SSP3-7.0	SSP3-7.0
AWI-CM-1-1-MR	SSP1-2.6	SSP3-7.0
INM-CM5-0	SSP5-8.5	SSP3-7.0
All	SSP5-8.5	SSP3-7.0

The results of the multi-model analysis of air temperature values showed that for the Caspian Sea Region in the period from 2015 to 2025, on average, the most consistent with the actual data at weather stations (based on RMSE and NSE) is the SSP5-8.5 scenario. At the same time, the SSP3-7.0 scenario better reproduces the variability and structure of the time series (based on KGE). At the same time, we would like to once again emphasize that there are significant spatial differences within the region, especially due to the diversity of the relief. Also, a significant part of the region, namely the Caspian Sea itself, does not have regular meteorological observations, which is a factor of significant uncertainty.

Conclusions

Since 1995, the Caspian Sea level has been falling, reaching −29.4 m abs this year, which is the minimum for the last 400 years. This is a concern for experts, the population, decision-makers and politicians of all Caspian countries, since most forecasts of changes in the Caspian Sea level are very pessimistic. A further decrease in the level by 2 m will lead to a complete desiccation of the Kara-Bogaz-Gol Bay, a decrease in the level by 5.0–7.5 m will lead to the shallowing of all ports in the Caspian, and a decrease in the level by 15–20 m will lead to the complete drying up of the Northern Caspian, with catastrophic environmental and socio-economic consequences for the entire Caspian Region. Unfortunately, it will not be possible to make accurate forecasts of sea level changes until the end of the 21st century for various reasons, in particular, since they vary greatly depending on the SSP scenarios of global climate change. Therefore, if we can determine the scenario according to which the regional climate in the Caspian changes, we will be able to significantly narrow the range of probabilistic estimates of future sea level changes.

In our article we posed the question – What SSP climate change scenario is the Caspian Sea Region following? We tried to answer this question with the help of six CMIP6 Global Climate Models which provide forecasts since 2015 to 2100 according to four main SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5). To do this, in the present study we have compared the forecasted air temperature with records at 72 weather stations in the 200 km buffer zone around the Caspian Sea in the time period from 2015 to 2025, and we could come to the following conclusions.

The models that have been used (AWI-CM-1-1-MR, CMCC-CM2-SR5, CNRM-CM6-1-HR, EC-Earth3, MPI-ESM1-2-HR and INM-CM5-0) do not predict surface air temperature (tas) changes equally well for the entire Caspian Sea Region. The tas variable does not fully account for relief changes. In most cases, the modeled surface air temperature data are overestimated for flat areas and underestimated for mountainous areas.

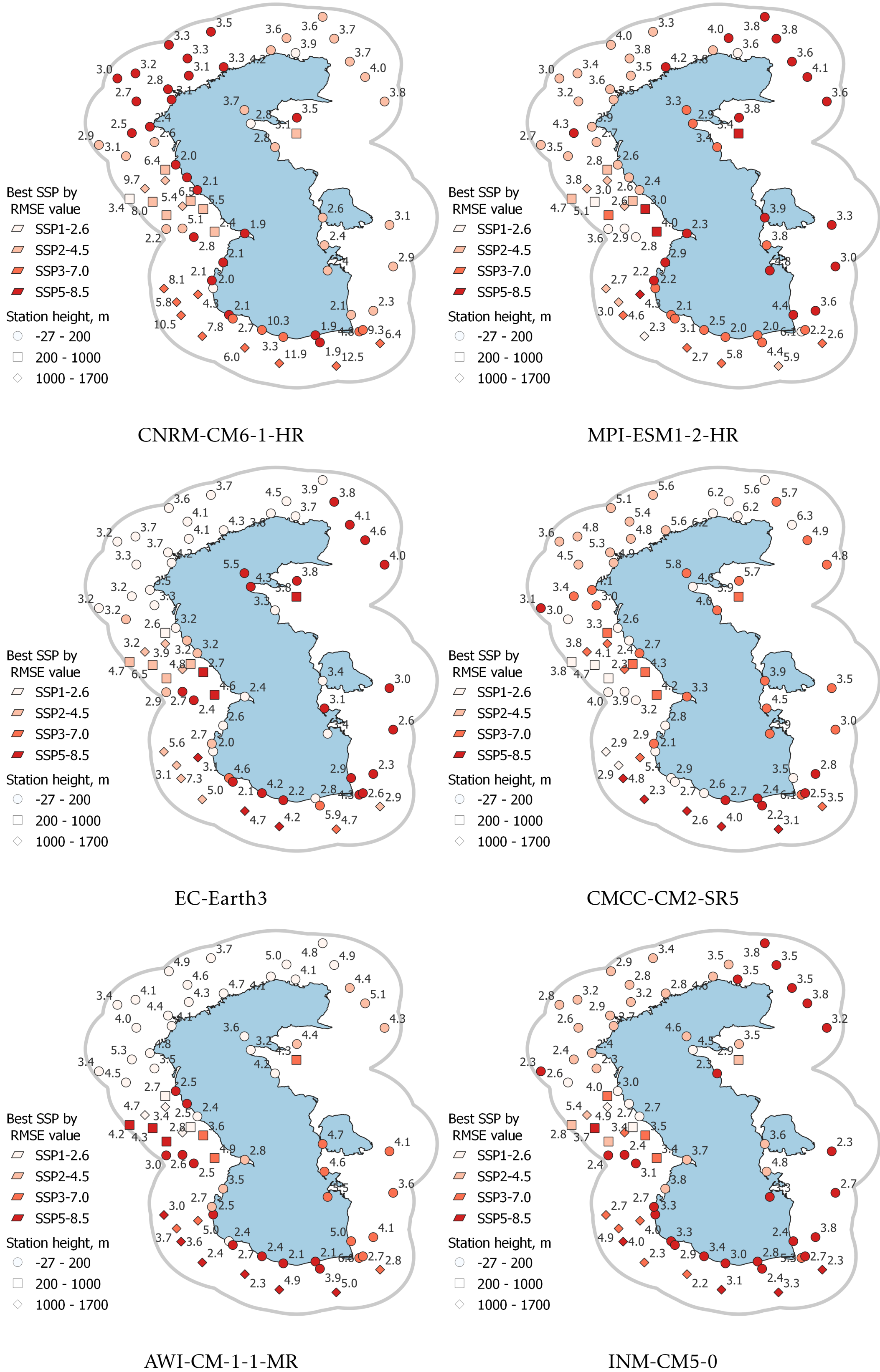

Figure 3. The most suitable scenario is determined by comparing RMSE (the numerical designation shows the RMSE value (°C) in for the most suitable scenario).

Despite the high correlation (0.93–0.96), the models may have a significant mean bias. For all SSP scenarios and all models, the mean error (ME) ranged from −12.9 to +6.5 °C. The

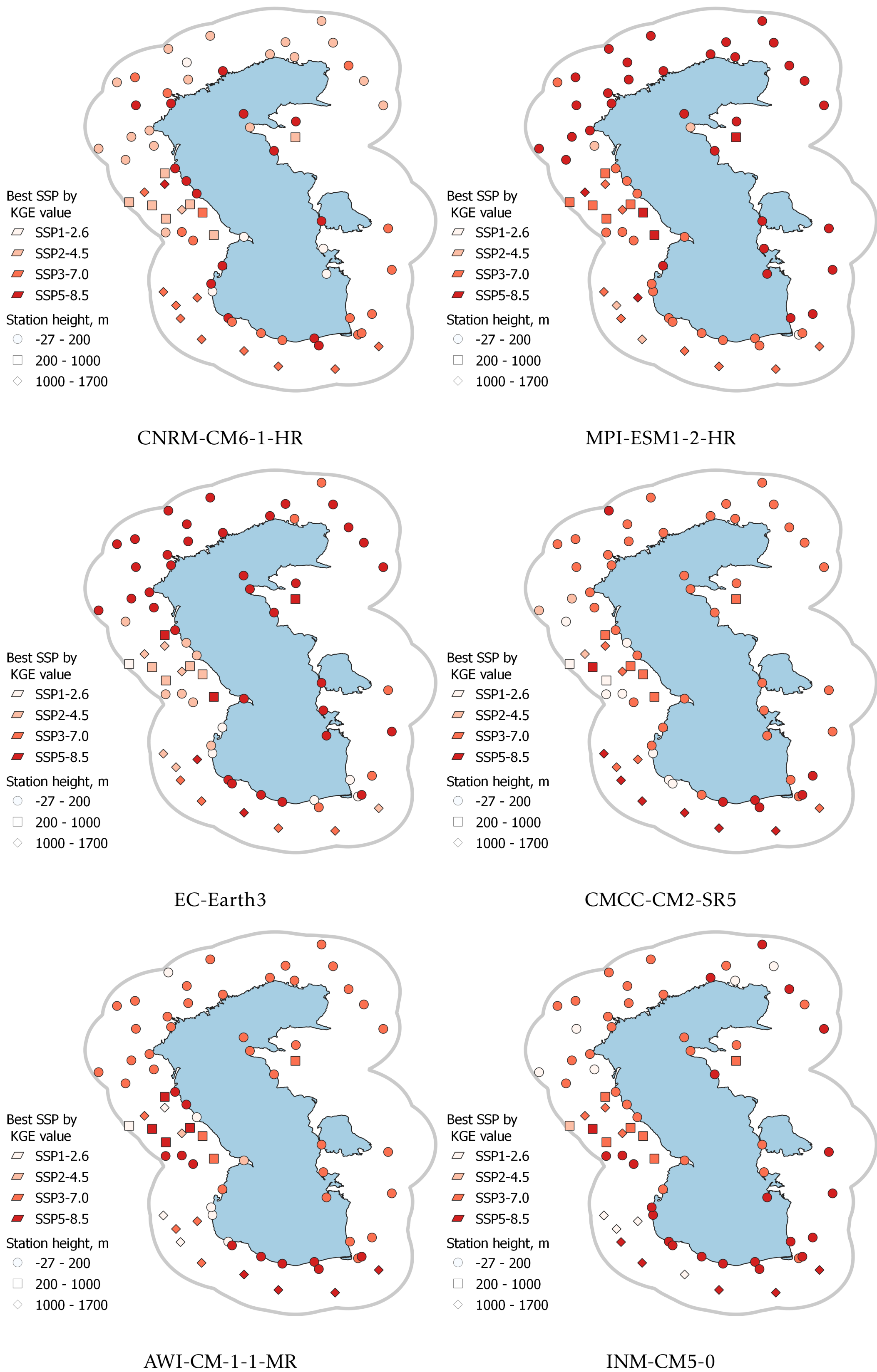

Figure 4. The most suitable scenario determined by comparing KGE.

ME for all SSP scenarios for individual models were: AWI-CM-1-1-MR – +1.69 °C, CMCC-CM2-SR5 – +0.63 °C, CNRM-CM6-1-HR – −2.28 °C, EC-Earth3 – +0.18 °C, INM-CM5-0 – +0.03 °C, and MPI-ESM1-2-HR – +0.71 °C. AWI-CM-1-1-MR shows the largest positive bias, while INM-CM5-0 is closest to observations. CNRM-CM6-1-HR has a pronounced negative bias, indicating a systematic underestimation of air temperature. The largest ME deviations are observed at weather stations in mountainous areas. The CNRM-CM6-1-HR model has the smallest average bias between the model and meteorological data for sea-level (coastal) weather stations, and it also has the maximum bias for mountainous regions. Despite the small size of the studied region compared to the model resolution, the Russian INM-CM5-0 model demonstrated good results for the entire region covered.

We could not establish a single SSP scenario which fits better the Caspian Sea Region. From one hand the Caspian Sea Region is very small in comparison with the globe, but from the other hand it was large enough to statistically correctly identify different scenarios in different areas of the Caspian Region. Thus, when determining climate change pathways (SSP) and assessing the performance of existing climate models in a 200-kilometer buffer zone, it is probably necessary to divide the region into approximately the following sectors: (1) Astrakhan Region, Republic of Kalmykia (Russia), northern part of the Republic of Dagestan (Russia), and the coastal zone of the western coast; (2) The Republic of Chechnya (Russia), the southern part of the Republic of Dagestan, Azerbaijan (beyond the coastal zones), and Georgia; (3) Iran; (4)Turkmenistan, Kazakhstan and Uzbekistan.

Despite the significant divergence of the SSP scenarios in the long-term dynamics, for some weather stations, it is noted that in the studied time period, some scenarios can be very close. It is quite often observed that at the moment SSP1-2.6 and SSP5-8.5 can be very close. This indicates a divergence lag and emphasizes the importance of observations in the middle of the 21st century.

The selection of the best scenario based on RMSE and NSE coincides, whereas the KGE metric often identifies a different scenario. This difference arises because RMSE and NSE primarily emphasize absolute errors, while KGE also accounts for bias, variability, and correlation. The analysis showed that for the Caspian Sea Region during 2015–2025, the scenario most consistent with observed air temperature data at weather stations, according to RMSE and NSE, is SSP5-8.5, representing the worst global climate change scenario. In contrast, according to the KGE metric, the most suitable scenario is SSP3-7.0, which better captures the variability and temporal structure of the observations.

Our preliminary estimates of other climate parameters (precipitation, evaporation, wind) showed poor agreement with the weather station data. A more in-depth analysis will be given in our subsequent studies. These parameters are necessary for assessing the Caspian Sea water balance, and forecasts of the Caspian Sea level. And even taking into account the use of a multi-model ensemble and making corrections based on the calculation of bias between the modeled data and the data based on actual measurements, as done in the work [*Hoseini et al.*, 2025], it can be assumed that the estimates of the future Caspian Sea level based on the SSP scenarios may have significant distortions.

Besides, we can add the following uncertainties that can have a significant impact on the accuracy of the Caspian Sea regional climate change, water balance, and sea level forecasts:

- The present analysis was done for the 200 km coastal zone of the Caspian Sea, but due to a lack of in-situ measurements over the aquatoria of the Caspian Sea, which is 390,000 km^2 large, we cannot provide any conclusions concerning the reliability of global climate models over the sea and the division of the sea according to the SSP scenarios.
- We are not sure that our findings will remain the same when we will take additional decades to the present 2015–2025 time period under study.
- We are not sure that the characteristics of the SSP scenarios in terms of the dynamics of demographic processes, economic growth, the level of urbanization, the energy structure and technological progress will remain the same in the next 75 years as defined in the IPCC Sixth Assessment Report on climate change in 2021. Theoretically, SSPs can jump from one to another one in the coming decades.

- It is evident, that regional climate change in the Caspian Sea Region is adjusted to the global climate change in a certain way in the 2015–2025 time period under our study. But we are not sure that the mechanism of this adjustment will remain the same in the next 75 years, and that new GCM models will show different forecasts in the future.

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