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Investigating the effect of height difference correction between reanalysis grid points and observation stations on the accuracy of ERA5 2m temperature and pressure data

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Abstract

Temperature and surface pressure are among the critical variables in various meteorological and climatic applications. Reanalysis products have become valuable sources of temperature and pressure data in recent years and have garnered much attention. Due to the elevation difference between reanalysis grid points and ground stations, surface pressure and 2m temperature derived from reanalysis products exhibit noticeable biases. In this study, using 10 years of measured data from 202 synoptic stations in Iran, the impact of elevation correction on the accuracy of ERA5 Land (ERA5L) pressure and 2m temperature data was investigated. Three different models were used for elevation correction. A comparison of error statistics before and after elevation correction revealed that in most stations the accuracy of ERA5L temperature and pressure data are improved after elevation correction. The results indicate that after data calibration, the average bias and Root Mean Square Error (RMSE) of surface pressure in the region improved by 96% and 66%, respectively. Compared to surface pressure, the positive impact of elevation correction on ERA5L temperature was less pronounced, with average bias and RMSE improving by 68% and 13%, respectively. Furthermore, for the elevation calibration of ERA5L pressure, the three used models were compared. A comparison of error statistics across all stations demonstrated that the performance of the three models did not show significant differences in the Iran region.

Keywords: 2m temperature, surface pressure, reanalysis grid point elevation, ERA5L

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1 Introduction

Surface meteorological variables such as temperature and pressure play a significant role in various meteorological and environmental applications, including the investigation of climate and hydrological changes, numerical weather prediction and climate modeling. Utilizing accurate values of surface meteorological variables leads to more precise predictions in hydrological models. On the other hand, for calculating evapotranspiration as one of the essential parameters in environmental and agricultural studies, surface meteorological parameters are employed (Singh and Woolhiser, 2002; Ruffault et al., 2017; Pelosi et al., 2020).

Surface pressure at the GNSS antenna height is the primary parameter used to calculate the hydrostatic delay of satellite signals. Additionally, corrections for receiver clock and estimated station height in GNSS observation processing are interrelated with the tropospheric zenith delay parameter (Rothacher, 2002).

Parameters such as temperature and surface pressure are consistently essential for determining water vapor content using GNSS meteorology. The electromagnetic signals transmitted from satellites experience delays when passing through the Earth's atmosphere because of interactions with electrons in the ionospheric layer and neutral atoms in the tropospheric layer (Hofman-Wellenhof et al., 2008). More than 99% of the ionospheric delay effect on signals can be mitigated through the combination of measurements at two different frequencies (Xu, 2007). The tropospheric delay of GPS signals consists of two parts, dry and wet. By employing the Saastamoinen model (Saastamoinen, 1972), the dry part can be computed using precise pressure observations at the station (Davis et al., 1985; Böhm et al., 2013). To obtain precipitable water vapor values using GNSS observation processing, after obtaining the wet part of tropospheric delay, the need for the atmospheric mean temperature arises. Bevis et al. (1992) demonstrated that a linear function of surface temperature can accurately provide the atmospheric mean temperature. Therefore, access to temperature at GNSS stations is essential when calculating PWV.

In general, using accurate pressure observations at stations is recommended for calculating ZHD. However, not all GNSS stations are equipped with pressure and temperature sensors. The lack of access to meteorological sensors at all GNSS stations limits the study and monitoring of spatio-temporal variations of water vapor in many locations (Huang et al., 2023). In such cases, the use of empirical models like GMF, GPT, GPT2, GPT2w, and several others is recommended as alternatives (Lagler et al., 2013; Li et al., 2020). In many studies, empirical models have been utilized to obtain the required temperature and pressure information in the meteorological process using GNSS, as they can be applied without the need for meteorological sensors in each location.

Pressure at a specific location can be measured either using airborne or ground-based instruments such as radiosondes. However, worldwide radiosonde observations are not universally consistent because of the need for extensive calibration efforts (Su et al., 2021). On the other hand, empirical models in estimating surface meteorological parameters do not account for daily and short-term variations.

Reanalysis data serve as another valuable source of weather data, providing various atmospheric parameters over a wide spatio-temporal range across the globe. Among these parameters, 2m temperature and pressure are crucial variables in meteorology, including in GNSS meteorology studies. Therefore, many researchers utilize reanalysis data as auxiliary and valuable resources in studying water vapor using GNSS (Zhang et al., 2019). Additionally, reanalysis data are extensively employed in various meteorological research studies (Parracho et al., 2018).

The reanalysis data are available to users for free and in standard formats. These weather data sources provide meteorological variables with diverse spatio-temporal resolutions over long-term time intervals on a global or local scale (Sheffield et al., 2006). This type of weather data source offers a precise description of past weather conditions, derived from a combination of ground-based and atmospheric observations integrated into physical models (Soci et al., 2016).

With the advancement of computational tools, data assimilation methods, Numerical Weather Prediction (NWP) models, and improvements in remote sensing methods for atmospheric and surface observations in recent years, the quality of reanalysis data has been enhanced (Paredes et al., 2018). In March 2017, the most advanced ECMWF reanalysis product called ERA5 was released, covering the period from 1940 to present. Compared to its predecessor, ERA5 incorporates a more advanced four-dimensional data assimilation system and utilizes more data sources. Furthermore, ERA5 provides finer spatial resolution of about 30 kilometers and hourly temporal resolution of atmospheric variables at 139 different pressure levels (Tarek et al., 2020). Following ERA5, in 2019, ERA5-Land (ERA5L) was introduced as the land component of ERA5 with improved spatial resolution (around 11 kilometers). This enhancement was aimed at supporting ground-based applications such as GNSS meteorology and surface studies (Baker et al., 2021).

Huai et al. (2021) investigated the relationship between the height difference of stations and the corresponding grid height in reanalysis products. They found that as the height difference increases, the temperature estimation of ERA5 becomes less accurate compared to observational values. Sam-Khaniani and Mohammadi (2022) reported a correlation of around 70% between the bias values of ERA5L temperature and the height difference between the grid and the station location in the Iran region. Their study indicated a strong relationship between the negative bias values and Root Mean Square Error (RMSE) in 2m temperature and surface pressure of ERA5L and the height difference.

The importance of pressure and 2m temperature reanalysis data in different applications and the presence of significant errors in this reanalysis products, which depend on the difference in the height of the grid point and the station, encourage the authors to investigate the correction of ERA5L 2m temperature and pressure data over Iran. On the other hand, the notable errors present in reanalysis products, especially for 2m temperature and pressure, which are dependent on the height difference between the reanalysis grid and the station, have prompted the need for corrections. In this study, the authors aim to address this by using developed methods by Berg (1948) and Su et al. (2021) to examine the impact of the height difference between reanalysis grid heights and ground-based station heights.

Specifically, the authors plan to investigate the amount of the effect of elevation corrections using above-mentioned methods on the accuracy of surface pressure and temperature parameters in ERA5L reanalysis compared to actual observations. This assessment will be carried out at 202 synoptic stations distributed throughout the country, covering the period from

2010 to 2019. The goal is to analyze and quantify the improvements achieved from the correction process in enhancing the accuracy of reanalysis data against real observational data. This study reflects the endeavor to enhance the reliability and usefulness of reanalysis data for various applications by addressing the issues related to the height differences between reanalysis grids and ground-based stations.

2 Data and study area

2-1 Study area

In this study, the effect of vertical calibration on ERA5L surface pressure and temperature data is examined in the region of Iran. This country is located within the geographic latitudes of 25 to 40 degrees north and longitudes of 44 to 64 degrees east. The Caspian Sea is located on the northern border of this region, and the Persian Gulf and the Oman Sea are located on the south (Fig. 1). As shown in Fig. 1, the elevation variations in the study area range from a few meters below mean sea level along the Caspian Sea coast to over 5600 meters higher in the Alborz Mountain range. Also, the study area includes the Alborz Mountain range in the north and the Zagros Mountain range in the west. The central part of Iran includes the deserts of Kavir and Lut, characterized by dry and semi-arid climates. Due to the elevation variations and climatic diversity in this region, 202 stations distributed throughout the area have been selected for the statistical evaluation of vertical correction methods for ERA5L pressure and temperature data, as indicated by the blue dots in Fig. 1.

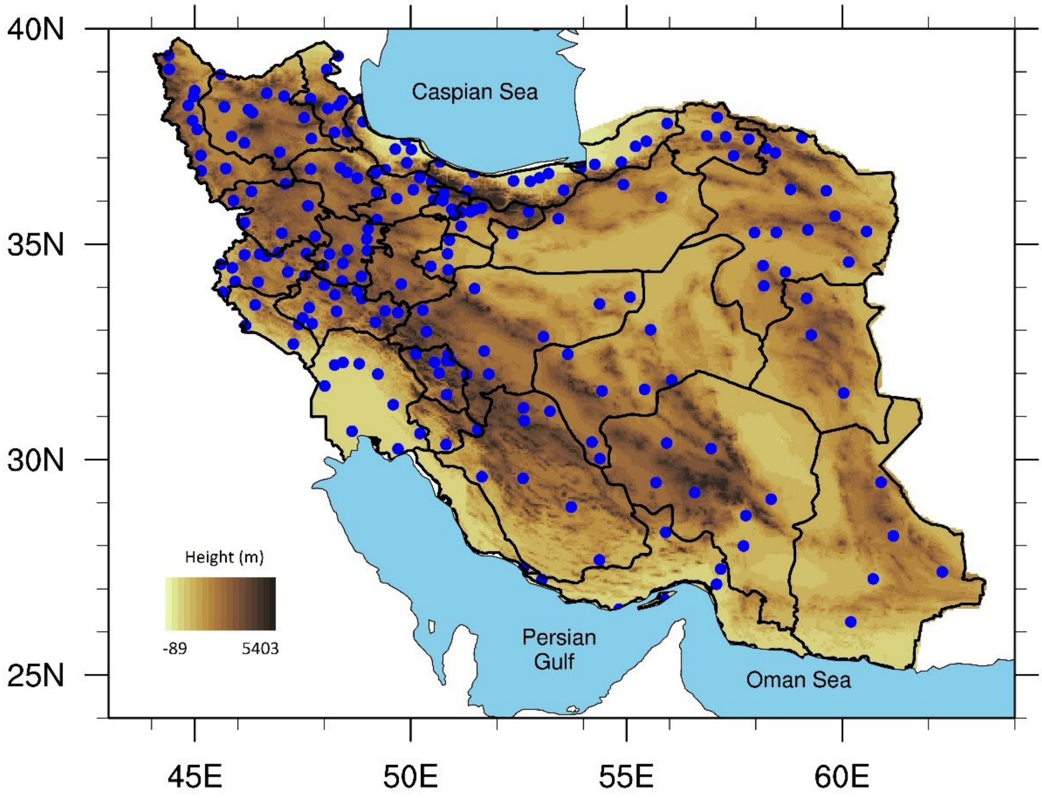


Figure 1. Locations of synoptic stations used in this study along with topographic map of Iran.

2-2 Data

To assess the significance of vertical calibration for temperature and surface pressure data obtained from ERA5L reanalysis products, observations from 202 meteorological stations distributed across the study area are utilized as local reference measurements. The measurements of temperature and pressure at these meteorological stations, with a spatial resolution of 3 hours, have been collected from the Iran Meteorological Organization between the years 2010 and 2019. The selected stations in this study are characterized by having observations available for the majority of the 10-year study period, including both daily and nightly observations.

ERA5L is produced through a single simulation without considering the atmospheric module of the integrated ECMWF forecasting system. It provides meteorological variables at 137 pressure levels from the surface to 0.01 hPa. The key advantage of ERA5L over ERA5 is its improved spatial resolution of up to 9 kilometers. Temporally, it maintains a resolution of 1 hour similar to ERA5, although ocean fields are masked.

In this study, 10 years of 2m temperature and surface pressure data from ERA-L reanalysis within the study area were obtained from the website https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-ERA5L?tab=form in grib format. By performing bilinear interpolation at the selected station locations, hourly temperature and surface pressure values were extracted from the reanalysis data. Furthermore, stations were selected where the height of the ground in their location is greater than the height of the corresponding grid point of reanalysis. This selection is made based on previous research, as vertical calibration has been recommended for reanalysis products under such conditions (Wang et al, 2016). Subsequently, to assess the statistical performance against meteorological observations, the 1-hour reanalysis products were separated at the times corresponding to ground-based measurements. In other words, the 3-hourly time series of reanalyzed pressure and temperature for the entire duration of 10 years were prepared for all stations, allowing for comparison with actual measurements.

3 Methodology

In this section, technical details and required conditions for the vertical corrections of temperature and pressure in ERA5L products will be addressed.

3-1 Geodetic height conversion to geopotential height

The surface meteorological data and GNSS (Global Navigation Satellite System) data in the study area are referenced to the geodetic height system which is defined based on the distance from the ellipsoidal surface. On the other hand, the geopotential height system has been employed for reanalysis data such as ERA5L. While the geoid-based and geopotential height systems have negligible differences, the distinction between the geopotential height system and the geodetic height system could potentially have a significant impact on the vertical corrections of temperature and pressure data from grid points to the desired station height. Hence, prior to evaluating and utilizing reanalysis 2m temperature and pressure data, it is necessary to unify the vertical height system between the two datasets: reanalysis data and ground measurements. This alignment is essential to ensure accurate vertical corrections from grid points to the intended station height (Wang et al., 2016; Huang et al., 2023).

Vedel (2000) proposed a two-step transformation of elevation from the WGS84 ellipsoidal height to the geopotential height. In the first step, the ellipsoidal height needs to be converted to orthometric height, which is the height above the geoid surface:

$$H = h - N \quad (1)$$

where h is the geodetic height of the station, H is the orthometric height of the station, and N is the geoid height above the ellipsoid at the location of station. The geoid height N at the specific point can be calculated using the EGM2008 model, and by subtracting it from the geodetic height in Eq. (1), the orthometric height is obtained. The next step involves converting the orthometric height to the geopotential height H_g using the following equations (Vedel, 2000):

$$H_g = \frac{\gamma_s(\varphi)}{\gamma_{45^\circ}} \cdot \left[\frac{R(\varphi).H}{R(\varphi)+H}\right] \qquad (2)$$

where $\gamma_s(\varphi)$ is the normal gravity on the rotated ellipsoidal surface at latitude φ, $R(\varphi)$ is the effective radius of the Earth at the considered geodetic latitude, and γ_{45° is the normal gravity on the ellipsoidal surface at a 45-degree latitude. The value of γ_{45° is assumed to be 9.80665 m/s^2. Additionally, the values of $\gamma_s(\varphi)$ and $R(\varphi)$ can be calculated using Eqs. (3) and (4):

$$\gamma_s(\varphi)=9.780325.\left[\frac{1+0.00193185.\sin(\varphi)^2}{1-0.00669435.\sin(\varphi)^2}\right]^{0.5} \qquad (3)$$

$$R(\varphi) = \frac{6378.137}{1.006803 - 0.006706.\sin(\varphi)^2} \qquad (4)$$

If the transformation between geopotential and geodetic heights is not performed, calculating the mean atmospheric temperature from reanalysis data may introduce errors up to 0.5 Kelvin (Wang et al., 2016).

3-2 Extrapolation of reanalysis data at the height of the surface station

Once the height system of the ground-based meteorological data is unified with the height system of the reanalysis grid points, it is essential to perform vertical corrections between the reanalysis grid points and the ground station elevation. If the geopotential height of the reanalysis grid points is higher than the geopotential height of the ground station, vertical corrections are necessary for the pressure and temperature values (Wang et al., 2016):

$$T_s = T_{grid} - \Delta(H_s - H_{grid}) \qquad (5)$$

$$P_s = P_{grid}\left(\frac{T_{grid} - \Delta(H_s - H_{grid})}{T_{grid}}\right)^{\frac{g.M}{R.\Delta}} \qquad (6)$$

where $\Delta = 0.0065\, {}^{Kelvin}/_{m}$ is the standard lapse rate of temperature, H_s is the station height, $M = 0.0289644\, {}^{Kg}/_{mol}$ is the molar mass of dry air, $R = 8.31432\left[\frac{N.m}{mol.Kelvin}\right]$ is the universal gas constant, and g is the gravitational parameter which can be calculated using Eq. (7):

$$g = 9.8063\left\{1 - 10^{-7}\left(\frac{H_s + H_{grid}}{2}\right)[1 - 0.0026373\cos(2\varphi) + 5.9 * 10^{-6}\cos(2\varphi)^2]\right\} \qquad (7)$$

Wang et al. (2016) compared the reanalysis pressure values from ERA-Interim with observational values at 20 stations. They estimated the range of RMSE variations in reanalyzed pressure to be between 0.35 and 2.17 millibars. As a result of their analysis, ZHD at the stations yielded an RMSE ranging from a minimum of 1.19 millimeters to a maximum of 5.09 millimeters. In general, their study found that the average RMSE of reanalyzed pressure data and ZHD was 0.91 millibars and 2.29 millimeters, respectively, across the 20 stations. This level of accuracy for ZHD leads to an error of approximately 0.37 millimeters in the calculation of GNSS PWV.

To correct pressure from the elevation of reanalysis grids to the station elevation, Berg (1948) introduced a model (Eq. 8) that relies on the pressure at the grid point and the difference between the grid elevation and the ground elevation. This model doesn't depend on temperature, making it faster to implement compared to Eq. (6). However, as the elevation difference between the reanalysis grid point and the observational station increases, the correction error becomes higher.

$$P_s = P_{grid}.\left(1 - 0.0000226.(H_s - H_{grid})\right)^{5.225} \qquad (8)$$

Su et al. (2021) conducted a study that aimed to optimize the Berg model. Eqs. (9) and (10) represent the two proposed models which are the optimized versions of the Berg model:

$$P_s = P_{grid}.\left(1 - 0.0000226.\left(H_s - H_{grid}\right)\right)^{5.225} + k_1 \ ,$$
$$k_1 = \left(H_s - H_{grid}\right).\left[-3.886 * 10^{-6} * \varphi^2 + 1.57 * 10^{-5} * \varphi + 5.128 * 10^{-3}\right] \qquad (9)$$
$$P_s = P_{grid}.\left(1 - 0.0000226.\left(H_s - H_{grid}\right)\right)^{5.225} + k_2 \ ,$$
$$k_2 = \left(H_s - H_{grid}\right).\left[-3.974 * 10^{-9} * \varphi^2 + 1.642 * 10^{-8} * \varphi + 5.308 * 10^{-6}\right] + 1 \qquad (10)$$

where k_1 and k_2 are correction terms added to the Berg model. The initial results of the present study demonstrated that for all studied stations, the correction values calculated using Eqs. (6) and (8) had differences close to zero.

Henceforth, the corrected values of ERA5L temperature using Eq. (5) are denoted as $T_{calibrated}$, and the Eqs. (6), (9), and (10), which can be regarded as three models for transferring reanalysis pressure values from the grid point to the surface station height, are referred to as $P_{calibrated}^{model1}$, $P_{calibrated}^{model2}$ and $P_{calibrated}^{model3}$, respectively.

3-3 Statistical evaluation

Here, first, the reanalysis values and real observations of temperature and surface pressure at each station from 2010 to 2019 are prepared. After unifying the elevation systems of the reanalysis and observations, using Eqs. (5) and (8) to (10), the ERA5L reanalysis data are extrapolated from the grid point height to the ground station elevation. To assess the impact of the applied corrections on the accuracy of the reanalysis data, using a 10-year comparison of synoptic station data within the country and Eqs. (11) to (13) the values of Mean Error (ME), RMSE, and correlation coefficient (R) were calculated:

$$ME = \frac{1}{N_y}\sum_{i=1}^{N_y}\left(y_i^{ERA5L} - y_i^{obs}\right) \qquad (11)$$

$$RMSE = \sqrt{\frac{1}{N_y}\sum_{i=1}^{N_y}\left(y_i^{ERA5L} - y_i^{obs}\right)^2} \qquad (12)$$

$$R = \frac{\sum_{i=1}^{N_y}\left(y_i^{ERA5L} - y_m^{ERA5L}\right)\sum_{i=1}^{N_y}\left(y_i^{obs} - y_m^{obs}\right)}{\sqrt{\sum_{i=1}^{N_y}\left(y_i^{ERA5L} - y_m^{ERA5L}\right)^2}\sqrt{\sum_{i=1}^{N_y}\left(y_i^{obs} - y_m^{obs}\right)^2}} \qquad (13)$$

where N_y represents the total number of 3-hourly data points in the time series of variable y for each station. Additionally, y_i^{ERA5L} and y_i^{obs} denote the *i*th values of the time series of variable y extracted from ERA5L products and surface measurements, respectively. It's worth noting that y_i^{ERA5L} both before and after elevation corrections, will be compared with the actual observations. In Eq. (13), the average of the time series values of the meteorological variable y at the specified station is denoted as y_m^{ERA5L} and y_m^{obs}, corresponding to ERA5L and surface measurements, respectively.

4 Results and discussions

4-1 ERA5L pressure elevation correction

After preparing the 10-year time series of observed temperature and pressure values for all studied stations and their corresponding ERA5L reanalysis values, elevation calibration was performed using the equations provided in section 3. Elevation correction for reanalysis 2m temperature was accomplished using Eq. (5). Also, for elevation correction of ERA5L pressure data, three models [Eqs. (6), (9), and (10)] were utilized.

Among all the stations, four arbitrary stations were selected across the entire region to visually depict the effect of elevation correction on ERA5L pressure data. In Fig. 2, stations with varying elevation differences (between the grid and the station) were chosen, and the annual mean observed pressure (black graph), pressure corrected using the first model (blue graph), the second model (green graph), and the third model (yellow graph) are displayed for each station from 2010 to 2019.

In Fig. 2, the annual mean ERA5L pressure values without elevation correction are indicated in red color. By comparing the red and black graphs at each of the four stations, the negative bias of ERA5L pressure compared to actual measurements is clearly evident. After applying elevation correction to the reanalysis pressure values, the annual mean reanalysis values (blue, green, and yellow graphs) become closer to the measured values (black graph). In other words, elevation correction for reanalysis pressure leads to a reduction in bias in ERA5L pressure products. Moreover, based on Fig. 2, it can be easily observed that different elevation correction models had a similar impact on these four stations. The two models proposed by Su et al. (2021) (green and yellow graphs) had almost identical effects in all four stations, as their graphs completely overlap. Fig. 3 illustrates the effect of elevation correction on improving the accuracy of ERA5L reanalysis pressure data in all stations based on the RMSE and ME statistics. The horizontal axis of Fig. 3 represents the station numbers in ascending order of the elevation difference between the ERA5L grid and the ground station. In other words, station number 1 corresponds to the station with the smallest elevation difference between the ERA5L grid and the surface station. The absolute differences of the error statistics of reanalysis pressure before and after elevation correction are shown on the vertical axis of Fig. 3. Based on this figure, in most stations the bias and RMSE values before elevation correction are higher than these values after correction. Positive values of the changes in ME and RMSE in each station indicate an improvement in accuracy after applying elevation corrections, while negative values indicate a decrease in accuracy.

Considering the ascending trend of the graphs in Fig. 3, the extent of improvement in the accuracy of reanalysis pressure data after elevation correction increases with the elevation difference between the grid and the ground surface. The negative values in Fig. 3 indicate that in some stations, the accuracy of reanalysis data decreases after applying correction on the ERA5L pressure data. However, it's important to note that the amount of accuracy reduction in these stations is not significantly large compared to the initial accuracy of ERA5L pressure data before elevation correction.

The variations in error statistics for ERA5L pressure data after applying corrections, as presented in Fig. 2, were calculated based on 10 years of data for all station. In Fig. 4, the average error statistics for ERA5L pressure data across all study points are shown annually. According to the results, the average ME of ERA5L pressure data in the Iran region before and after elevation correction is approximately -16 hPa and -2 hPa, respectively. Applying elevation corrections to pressure data extracted from reanalysis grids reduces the bias of ERA5L pressure by an average of 14 hPa. Moreover, relatively speaking, the Berg model has performed slightly better in reducing the bias of reanalysis pressure across the entire study region compared to the two other models. However, based on the numerical results in Fig. 4, the performance of all three models in correcting reanalyzed pressure can be considered quite similar. Furthermore, on average, the RMSE of ERA5L pressure

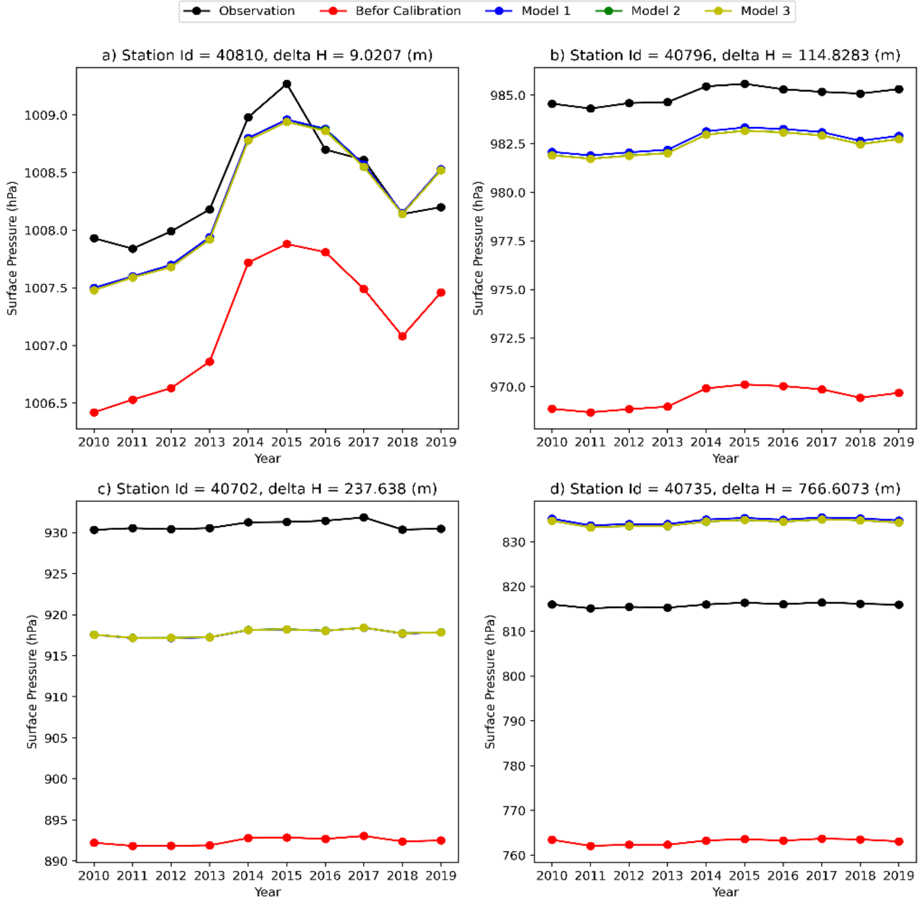
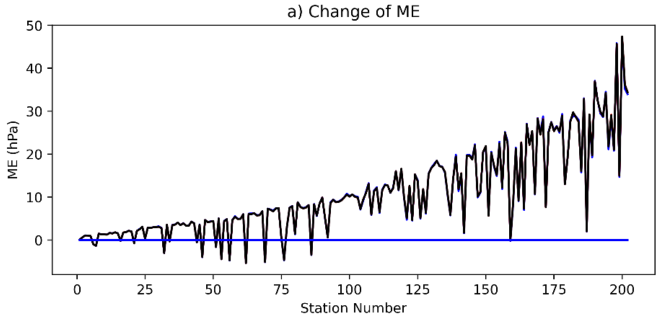


Figure 2. Annual average surface pressure in four arbitrary stations of the study area. Actual observation values, reanalysis without height correction, with height correction using the first model, second model and third model are shown in black, red, blue, green and yellow colors, respectively.


a) Change of ME

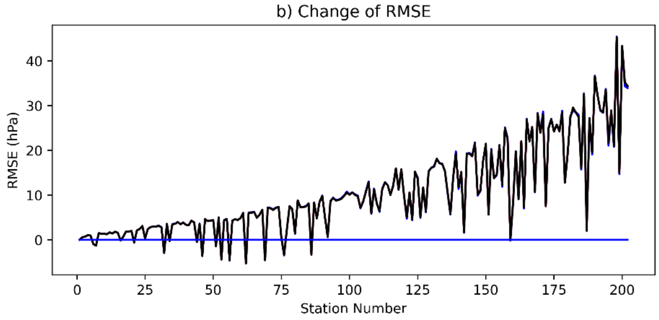

b) Change of RMSE

Figure 3. Absolute difference of error metrics for uncorrected ERA5L pressure data from corresponding values after elevation correction in various stations. On the horizontal axis, stations are sorted in increasing order of the elevation difference between the reanalysis grid and the ground station.

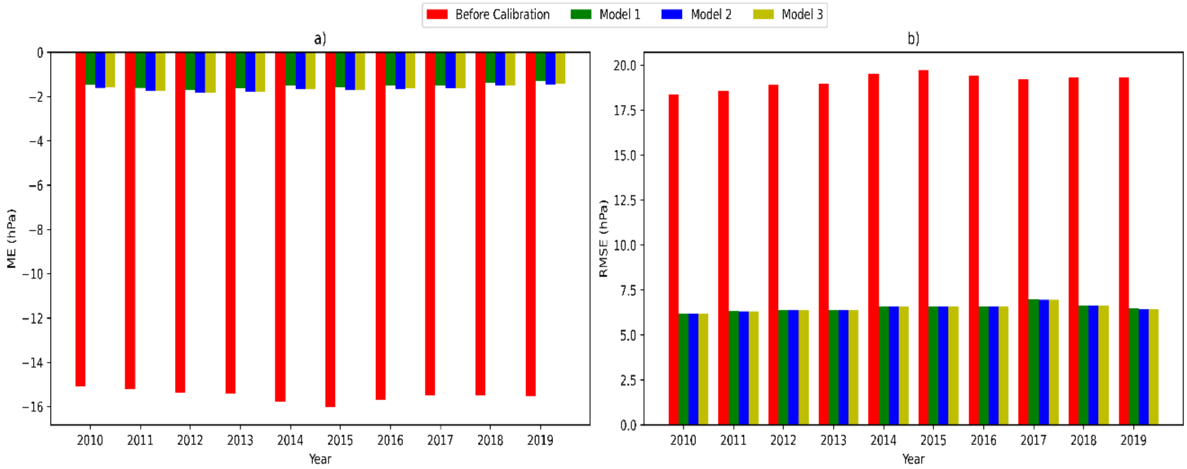


Figure 4. Annual mean bias and RMSE of ERA5L pressure data before elevation correction (red), after correction using model 1 (green), model 2 (blue), and model 3 (yellow).

data in different years is estimated to be around 19 hPa, which is reduced to approximately 6 hPa after applying elevation corrections.

In addition to examining error statistics before and after elevation correction of ERA5L pressure products for different years and stations, the effect of elevation correction can also be compared spatially among different station locations. Figs. 5 and 6 depict the spatial distribution of bias and RMSE of ERA5L pressure before and after applying the three elevation correction models in the study area.

Based on Figs. 5 and 6, the results of elevation correction using all three studied models are consistent across all stations. In a significant number of stations located in the northern and western parts of the study area, ERA5L pressure exhibited a pronounced negative bias compared to actual observations before elevation correction. As shown in Fig. 5, after calibration, the magnitude of bias has decreased in most stations. The spatial distribution of RMSE of reanalysis pressure in Fig. 6 indicates that RMSE has decreased in stations that had a significant negative bias in Fig. 5 after applying elevation correction.

4-1 ERA5L temperature elevation correction

After the elevation correction of ERA5L temperature data in the study area, the annual average values of observed temperature (black graph), ERA5L temperature before correction (red graph), and temperature after elevation correction (blue graph) in four selected stations are presented in Fig. 7. The elevation differences between the reanalysis grid and the ground surface in these four stations are 9.02, 114.82, 237.63, and 766.60 meters, respectively. As observed in Fig. 7, with an increase in the elevation difference between the reanalysis grid and the ground station, the proximity of the corrected reanalysis temperature to the actual observations becomes closer. Additionally, at the station with a smaller elevation difference, elevation correction did not exhibit any positive effect.

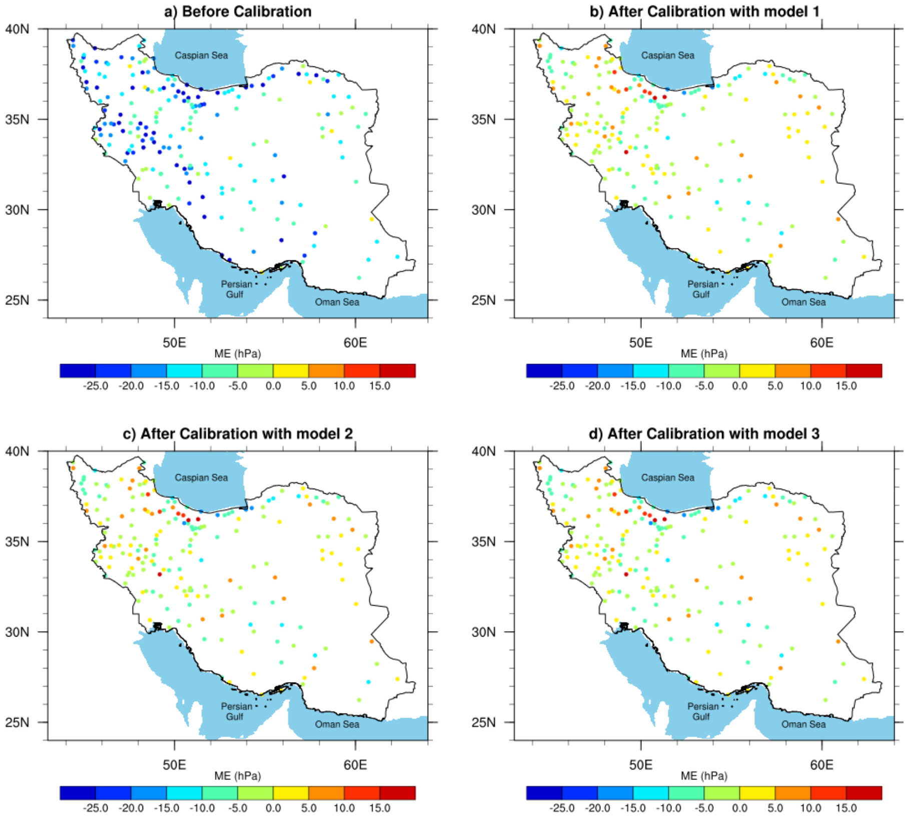


Figure 5. Spatial distribution of mean bias of ERA5L pressure before and after applying three elevation correction models in the study area.

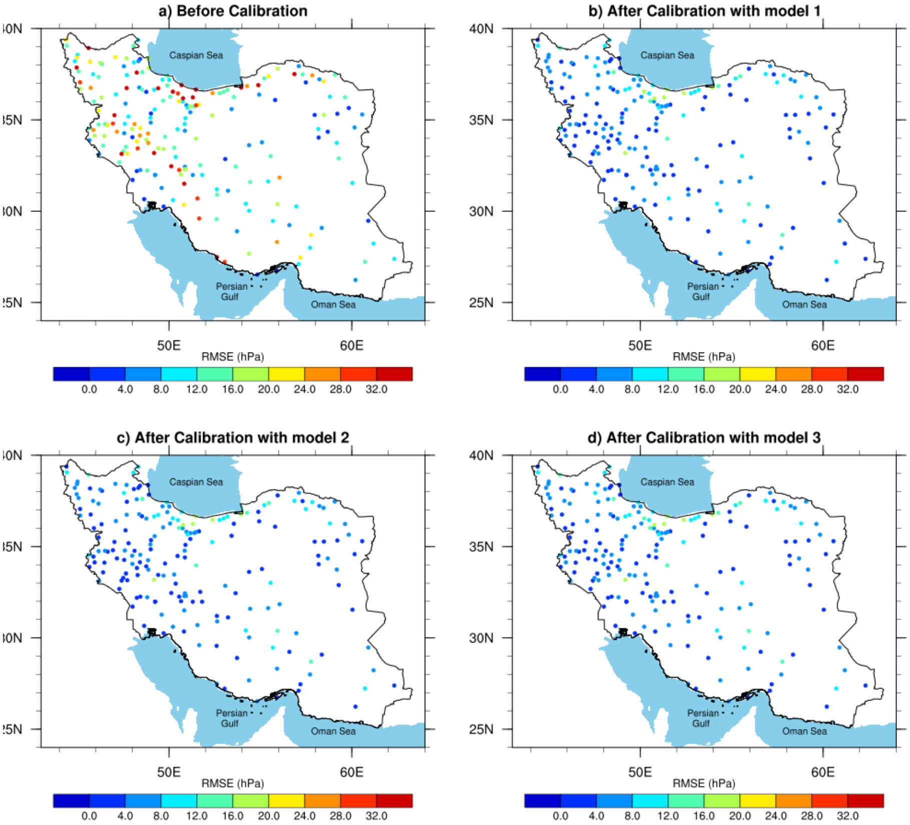


Figure 6. Spatial distribution of mean RMSE of ERA5L pressure before and after applying three elevation correction models in the study area.

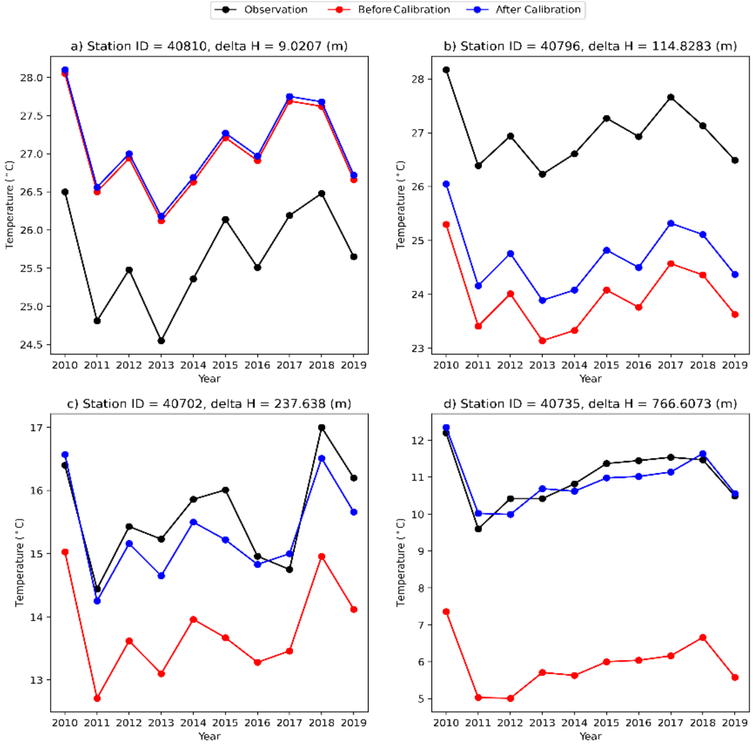


Figure 7. Annual average 2m temperature in four arbitrary stations of the study area. Actual observation values, reanalysis without height correction, with height correction using the first model, second model and third model are shown in black, red, blue, green and yellow colors, respectively.

Fig. 7 has been plotted for only four arbitrarily selected stations. Therefore, to comprehend the extent of the elevation correction's impact on the accuracy of ERA5L temperature data, Fig. 8, similar to Fig. 3, illustrates the absolute differences of ME and RMSE statistics of reanalysis temperature data before and after elevation correction for all stations.

In most stations, the bias of ERA5L temperature data before elevation correction has been higher. Regarding the ME variation graph in Fig. 8, at stations with higher elevation differences the improvement in bias after elevation corrections of reanalysis temperature is more prominent. In fewer than 10% of the stations, elevation correction has resulted in an increased bias in ERA5L temperature. The increase in the absolute value of bias, observed in some stations after reanalysis, has mostly been within the range of less than 1 degree Celsius. Furthermore, after elevation correction, the RMSE of ERA5L temperature data has been reduced up to 2.5 degrees Celsius. In Fig. 9, the average error statistics for all study points for ERA5L temperature data are presented annually. According to the results, the average ME of ERA5L temperature data in the Iran region before and after elevation correction is approximately -1.5°C and -0.5°C, respectively. On average, elevation correction has led to a reduction of around 1 degree Celsius in ERA5L temperature across the entire study region for almost all years. Based on Fig. 9, the decrease in RMSE of ERA5L temperature data after elevation correction is estimated to be around 0.5 degrees Celsius on average across all years.

The average RMSE and bias of ERA5L surface pressure and 2m temperature in all stations of the study area before and after elevation correction for gridded reanalysis data are calculated and provided in Tables 1 and 2. According to the results, elevation correction of ERA5L pressure data leads to an average reduction of bias and RMSE by 14 hPa and 12.6 hPa, respectively. Additionally, the bias of ERA5L temperature decreases from an average of -1.31°C to -0.42°C after elevation correction. Therefore, elevation correction of pressure and temperature reanalysis data can play a crucial role in enhancing the accuracy of these products before their utilization.

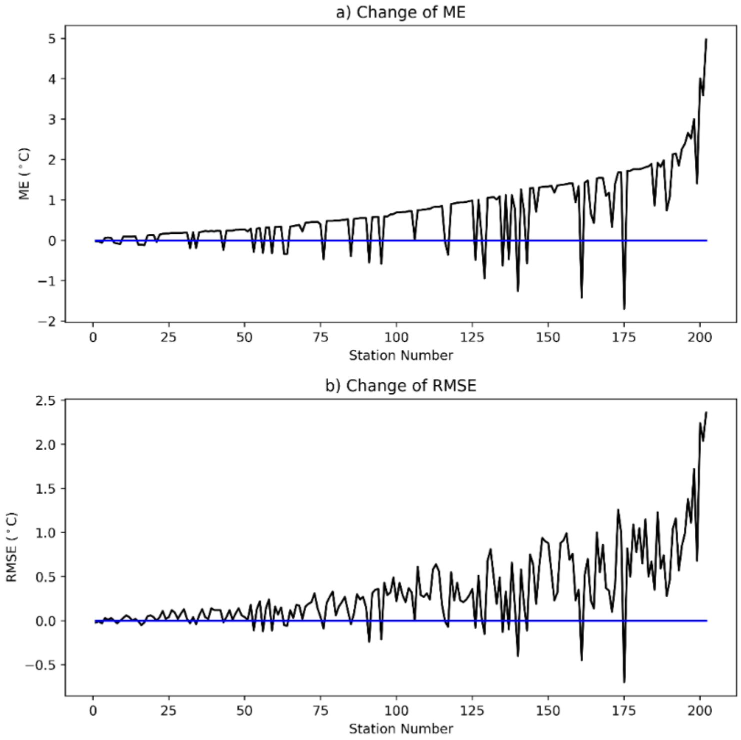


Figure 8. Absolute difference of error metrics for uncorrected ERA5L temperature data from corresponding values after elevation correction in various stations. On the horizontal axis, stations are sorted in increasing order of the elevation difference between the reanalysis grid and the ground station.

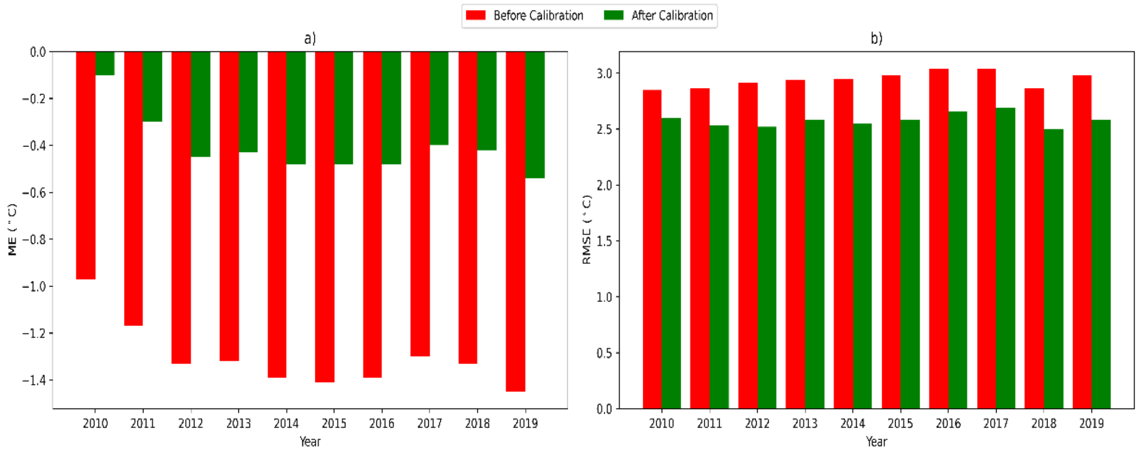


Figure 9. Annual mean bias and RMSE of ERA5L pressure data before (red) and after (green) elevation correction.

To investigate the spatial impact of elevation correction on the accuracy of ERA5L temperature in the study region, Figs. 10 and 11 illustrate the spatial distribution of bias and RMSE of ERA5L temperature data before and after elevation correction in the study area. According to the results presented in Fig. 10, after elevation correction of ERA5L temperature products, the negative bias values of temperature, which reach below -4°C in some stations, become closer to zero. The red-colored points in Fig. 11a indicate the locations with the highest RMSE values of ERA5L temperature in the region. As observed in Fig. 11b, the size of RMSE values decreases after elevation correction.

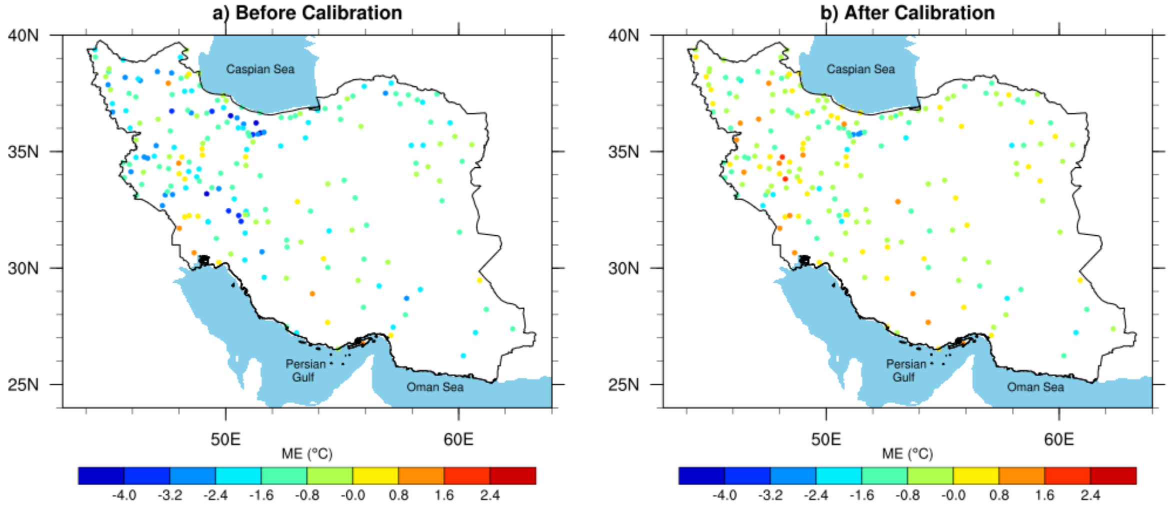


Figure 10. Spatial distribution of mean bias of ERA5L temperature before and after applying elevation correction in the study area.

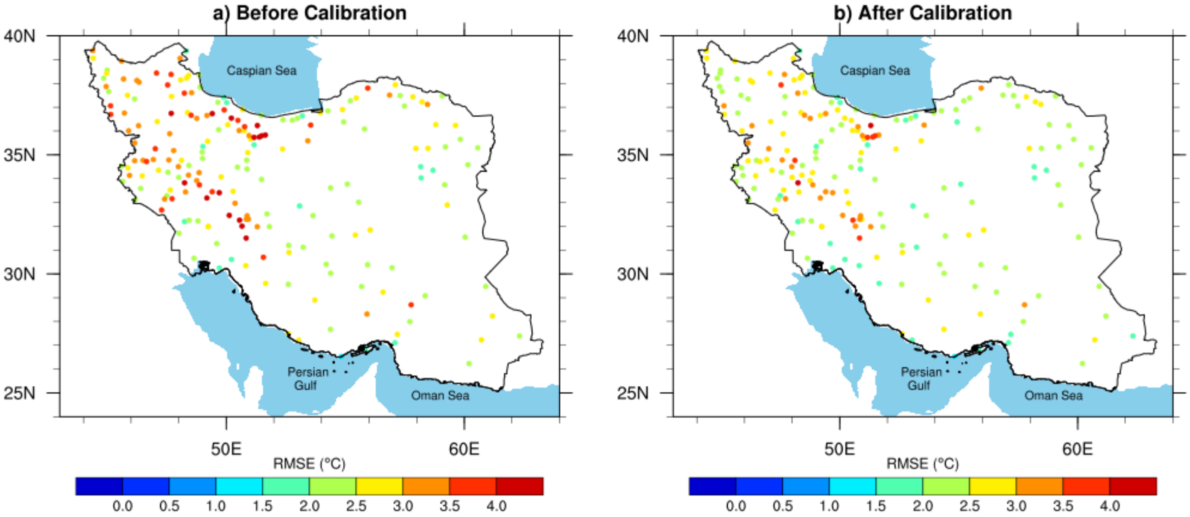


Figure 11. Spatial distribution of mean RMSE of ERA5L temperature before and after applying elevation correction in the study area.

Table 1. Mean error (hPa) of ERA5L surface pressure before and after elevation correction compared to surface observations.

statistics	before calibration	calibration with model 1	calibration with model 2	calibration with model 3
ME	-15.53	-1.51	-1.65	-1.64
RMSE	19.17	6.53	6.52	6.52

Table 2. Mean error (C) of ERA5L 2m temperature before and after elevation correction compared to surface observations.

statistics	before calibration	after calibration
ME	-1.31	-0.42
RMSE	2.94	2.58

5 Conclusions

Gridded reanalysis products have become a valuable data source in regions with limited ground-based weather stations. In recent years, through the integration of various satellite and ground-based observational sources into numerical weather models, these products have been capable of providing weather parameters with high spatio-temporal resolution. ERA5L is one of the latest reanalysis products that offers hourly 2m temperature and pressure values at a spatial resolution of around kilometers.

Before utilizing reanalysis data, it is crucial to assess their accuracy within the study area. Previous studies have shown that the elevation difference between grid points and surface stations significantly affects the bias of surface pressure and 2m temperature reanalysis data. Therefore, in this study, the elevation calibration effect on ERA5L pressure and temperature data in the Iranian region was investigated using 10 years of measurements collected from 202 stations.

Three correction models provided by Su et al. (2021) and Berg (1948) were compared in terms of their effectiveness in correcting ERA5L pressure across the entire study area. Initially, the bias and RMSE of ERA5L pressure data were compared before and after elevation correction. The analysis of error variations revealed that elevation correction generally enhances the accuracy of ERA5L pressure data in most stations. Furthermore, the greater the elevation difference between grid points and surface stations, the more significant the improvement. The findings of the study also demonstrated that elevation correction had a notable impact on improving the accuracy of ERA5L temperature data. However, the improvement observed in ERA5L pressure data was more pronounced compared to ERA5L temperature data. Also, the results indicated that all three models led to similar improvements in the accuracy of ERA5L pressure data in most stations.

In general, after applying elevation correction, the bias and RMSE of reanalysis pressure data decreased by approximately 14 and 12.6 hPa, respectively, across the entire region. Additionally, with elevation correction, the average bias and RMSE of ERA5L temperature data decreased from -1.31 and 2.94 to -0.42 and 2.58 degrees Celsius, respectively. The results of this study highlight the essential nature of elevation correction for 2m temperature and pressure reanalysis data before utilizing them in various meteorological and geodetic studies. Neglecting this correction can lead to inaccurate outcomes in the study area.

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