DEU FMD 26(76) (2024) 9-21

Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Dergisi
Dokuz Eylul University Faculty of Engineering Journal of Science and Engineering
Elektronik/Online ISSN: 2547-958X

RESEARCH ARTICLE / ARAŞTIRMA MAKALESI

Evaluation of ERA5 and MERRA-2 Reanalysis Datasets over the Aegean Region, Türkiye

ERA5 ve MERRA-2 Yeniden Analiz Veri Setlerinin Ege Bölgesi Genelinde Değerlendirilmesi

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Abstract

Reanalysis products are among the most-used datasets in the atmospheric sciences since they comprehensively describe the observed climate at sub-daily intervals in a region. Two reanalysis datasets, namely, the fifth generation of European Centre for Medium-range Weather Forecast (ECMWF) atmospheric reanalysis of global climate (ERA5) and Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2), were evaluated for the representation of air temperature at 2 m, mean sea level pressure and wind speed over the Aegean Region of Türkiye during the period 1963–2020. Hourly reanalysis data were compared with observations in 19 meteorological stations in the region. Several statistical parameters, such as root mean square error (RMSE), correlation coefficient (R), and mean bias error (MBE), were used to evaluate the performances of the datasets. The results indicated that air temperature and mean sea level pressure are generally better represented by the MERRA-2 reanalysis in the region, whereas the ERA5 reanalysis dataset better represents wind speed. MERRA-2 had lower RMSE and slightly better performance at 11 stations with high R (>0.98) for mean sea level pressure. The MERRA-2 reanalysis dataset had a high overall R (>0.94) for air temperature and performed better at 12 stations. The overall regional R-value for the ERA5 wind speed dataset was 0.58, and ERA5 showed better performance at 13 individual stations for wind speed. Our results guide which reanalysis dataset better represents the regional climate characteristics for selected parameters.

Keywords: *Reanalysis, MERRA-2, ERA5, air temperature, sea level pressure, wind speed*

Öz

Yeniden analiz verileri, bir bölgedeki iklim verisini saatlik bazda tanımladıkları için atmosfer bilimlerinde en yaygın kullanılan veri setleri arasında yer almaktadır. Bu çalışmada beşinci nesil Avrupa Orta Menzilli Hava Tahmini Merkezi (ECMWF) küresel iklimin atmosferik yeniden analizi (ERA5) ve Araştırma ve Uygulamalar için Modern Çağ Retrospektif Analizi, sürüm 2 (MERRA2) olmak üzere iki yeniden analiz veri seti, 1963–2020 döneminde Türkiye'nin Ege Bölgesi'nde yerden 2 m yükseklikte hava sıcaklığı, ortalama deniz seviyesi basıncı ve rüzgar hızı parametreleri için değerlendirilmiştir. Saatlik yeniden analiz verileri bölgede bulunan 20 meteoroloji istasyonundan elde edilen gözlemlerle karşılaştırılmıştır. Veri kümelerinin performanslarını değerlendirmek için ortalama hataların karekökü (RMSE), korelasyon katsayısı (R) ve ortalama sapma hatası (MBE) gibi çeşitli istatistiksel parametreler kullanılmıştır. Sonuçlar, hava sıcaklığının ve ortalama deniz seviyesi basıncının, bölgedeki MERRA-2 yeniden analiz verileri ile daha iyi temsil edildiğini, buna karşın ERA5 yeniden analiz verileri ile rüzgar hızının daha başarılı temsil edildiğini göstermiştir. Ortalama deniz seviyesi basıncı için daha yüksek R değerine (>0,98) ve daha düşük RMSE değerine sahip olan MERRA-2, 11 istasyonda daha iyi performans göstermiştir. Hava sıcaklığı için genel olarak yüksek bir R değerine (>0,94) sahip olan MERRA-2 yeniden analiz veri seti, 12 istasyonda daha iyi performans göstermiştir. Bölgedeki rüzgar hızı için ERA5 veri setinin genel R değeri 0,58 olup ERA5 ile rüzgar hızı için 13 istasyonda daha başarılı bir performans elde edilmiştir. Çalışma sonucunda elde edilen bulgular, seçilen parametrelerde hangi veri setinin bölgeyi daha iyi temsil ettiğini göstermesi açısından bir kılavuz niteliği taşımaktadır.

Anahtar Kelimeler: *Yeniden analiz, MERRA-2, ERA5, hava sıcaklığı, ortalama deniz seviyesi basıncı, rüzgar hızı*

1. Introduction

Reanalysis datasets are widely used in many fields, providing data for past climates without any temporal or spatial gaps. Meteorological reanalysis datasets are products of data assimilation systems consisting of observational data and dynamic models. These datasets differ in data assimilation methods, time coverage, and source. Two primary datasets released by ECMWF and NASA, ERA5 [1] and MERRA-2 [2], have been used widely in the literature. ERA5 uses a 4D-VAR data assimilation model with Integrated Forecast System cycle version 41r2 (2016) model with reduced Gaussian grids, and MERRA-2 uses 3DVAR with Goddard Earth Observing System Model 5.12.4 (2015) atmospheric data assimilation system with cubed-sphere horizontal discretization. It is known that biases originate from models, data assimilation processes, and observational data systems. Therefore, the uncertainty of reanalysis data could decrease the reliability of climate change research and air quality modeling studies. Thus, the reanalysis datasets should be compared with long-term observational data

DOI:10.21205/deufmd.2024267602
Atıf şekli / How to cite:
Tulger Kara, G., Elbir, T. (2024). Evaluation of ERA5 and MERRA-2 Reanalysis Datasets over the Aegean Region, Türkiye. DEUFMD, 26(76), 9-21.

Geliş Tarihi / Received: 15.03.2022
Kabul Tarihi / Accepted: 24.01.2023

in multiple regional and global stations to identify their applicability.

Reanalysis datasets were used in many studies focusing on pollution monitoring [3-7], extreme event forecasts [8,9], evaluation of renewable energy [10], wind power modeling [11], impact assessment of volcanos [12], etc. Chen et al. (2019) and Karami (2019) identified parameter base variations between different datasets in the same study area [8,13]. The accuracy of the reanalysis datasets was discussed both globally regionally. The quality of the reanalysis data was compared with observational data in different geographic scales and time intervals (annually, seasonally, or hourly). Miao et al. (2020) conducted a comparative analysis in Northern Hemisphere (North America, Europe, and Asia) [14]. It was found that the estimation accuracy of reanalysis datasets varies according to the region for wind speed and wind power density. Sharmar and Markina (2020) validated different datasets (ERA5, MERRA2, ERA-Interim, and CFSRv2) by comparing them with the observational data for wind-wave hindcasts based on reanalyses and wind speed parameters [15]. ERA5 had the lowest bias for both variables, and MERRA-2 had a relatively lower bias except for the equatorial and tropical regions. Olauson (2018) compared the estimation performance of ERA5 and MERRA-2 for wind speed in five different wind turbines and found that ERA5 performed better than MERRA-2 [16]. Wang et al. (2019) compared different Arctic sea ice datasets and found biases between buoy and reanalysis data seasonally [17]. The accuracy of the reanalysis datasets could change seasonally as well as spatially. Jiang et al. (2020) evaluated ERA5 estimations for total, direct, and diffuse solar radiations in China [18]. They indicated that rainy and cloudy weather affects the accuracy of the dataset, even its estimations correlated well with ground-level measurements. Other regional studies examined the accuracy of the datasets and suggested the best datasets for their regions [19-21].

The Turkish State Meteorological Service (TSMS) automatically produces hourly data at 861 observation stations in Türkiye [22]. While it is an extensive observation network, the absence of stations in some rural regions or the lack of data in the existing stations is a common problem. Therefore, the use of reanalysis datasets is a necessity. However, limited studies compared the reanalysis datasets in Türkiye [23,24]. Tan (2019) compared the datasets for the ravinsonde data in the eight selected cities in Türkiye [23]. Yanbolu et al. (used ERA-20C, ERA-20CM, and CERA-20C wind speed parameters as input to a wave model and compared model results for the stations at the coastal region of the Black Sea for wave heights and average wave periods [24]. Yilmaz (2022) evaluated air temperature obtained from ERA5 with observed meteorological data and found that the dataset is reliable over Türkiye [25].

This study evaluated hourly meteorological data of air temperature at 2 m, mean sea level pressure, and wind speed from ERA5 and MERRA-2 at 20 observation stations in Western Türkiye since these parameters are critical in weather forecasting, air quality modeling, and environmental impact assessment studies in the region.

2. Materials and Methods

2.1. Study area

The Aegean region in the western part of Türkiye covers 26°20′E-30°20′E longitudes and 36°50′N-39°60′N latitudes in the Mediterranean region (Figure 1). This region is complicated with several major cities with a total population of 10.7 million, many industrial plants including a refinery, a petrochemical plant, iron-steels plants, etc., an international port, several coastal sites with high tourism potential, and large agricultural areas. Air quality problems widely occur in the region due to industrialization, urbanization, and increased fuel consumption in residential areas and industrial plants [26-29].

Mediterranean climate typically appears in a large part of the Aegean Region. Summers are hot and dry; winters are warm and rainy. Snowfall and frost are rare in the coastal zone. In high places, winters are snowy and cold. The average temperature of the coldest month, January, is 6.3°C, the average temperature of the warmest month, July, is 26°C, and the average annual precipitation is 592.2 mm [30].

2.2. Observational data

TSMS operates automatic meteorological stations in the national monitoring network. Automated stations became more common after their first establishment in the country in the 2000s [31]. TSMS has 25 automatic meteorological stations available in NOAA database for the Aegean region. However, 5 stations were mandatorily omitted due to substantial missing data in this study. Finally, the hourly data were obtained from 19 meteorological stations within the scope of this study. The hourly air temperature at 2 m (T2M, °C), mean sea level pressure (MSLP, hPa), and wind speed (WS, m/s) from the ERA5 and MERRA-2 datasets were compared with hourly observations in all individual stations.

Observations were obtained from the global Integrated Surface Database (ISD) of the National Oceanic and Atmospheric Administration (NOAA) (www.ncdc.noaa.gov/isd) using the worldmet package of R-Studio [32]. ISD consists of data gathered from observational data networks around the world. It provides climatological data in various parameters such as wind speed, temperature, sea level pressure, dew point, cloud cover data, and precipitation due to the observation extent of each station [33]. The coordinates of the stations, observation periods, and data periods are given in Table 1.

2.3. Reanalysis Data

The fifth generation of the European Centre for Medium-range Weather Forecast (ECMWF) atmospheric reanalysis of global climate (ERA5) dataset has been produced globally at a spatial resolution of 0.25° x 0.25° (approximately 31 km) on an hourly basis since 1979 [34]. Earlier datasets produced by ECMWF are ERA-20C (1900-2010), ERA-20CM (1899-2010), CERA-20C (1901-2010), CERA-SAT (2008-2016), ERA-40 (1961- 2001) and ERA-Interim (1989-2008) [34-36].

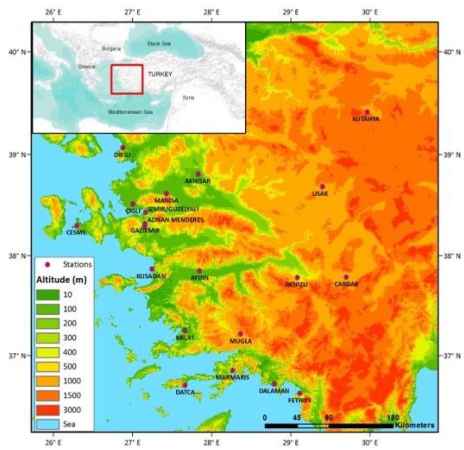

Figure 1. Map of the study area, including the selected meteorological stations.

Table 1. List of the stations used in this study

Stations	Latitude (ºN)	Longitude (ºE)	Altitude (m)	Observation Period (Years)			Data Availability (%)		
				MSLP	T2M	WS	MSLP	T2M	WS
Adnan Menderes A.	38.292	27.157	126	1989-2020	1987-2020	1987-2020	48	99	91
Akhisar	38.809	27.834	80	1979-2020	1979-2020	1979-2020	79	100	78
Aydin	37.840	27.838	56	1989-2020	1983-2020	1983-2020	81	100	86
Cardak	37.786	29.701	852	2016-2020	2010-2020	2010-2020	15	100	79
Cesme	38.300	26.372	5	2013-2020	2013-2020	2013-2020	100	100	99
Cigli	38.513	27.010	5	2014-2020	1979-2020	1979-2020	35	100	83
Dalaman	36.713	28.793	7	2003-2020	1991-2020	1991-2020	24	99	96
Datca	36.708	27.692	28	2008-2020	2008-2020	2008-2020	100	100	99
Denizli	37.762	29.092	425	1998-2020	1998-2020	1998-2020	97	100	89
Dikili	39.067	26.883	3	2012-2020	2012-2020	2012-2020	33	100	98
Fethiye	36.627	29.124	3	2008-2020	2008-2020	2008-2020	100	100	96
Izmir/ Guzelyali	38.395	27.082	29	2008-2020	2008-2020	2008-2020	52	100	90
Kusadasi	37.859	27.265	22	2008-2020	2008-2020	2008-2020	100	100	99
Kutahya	39.417	29.989	969	2006-2020	2003-2020	2006-2020	92	100	89
Manisa	38.617	27.433	71	no data	2008-2020	2008-2020	100	100	100
Marmaris	36.839	28.245	16	2015-2020	2008-2020	2008-2020	60	100	96
Milas Bodrum	37.250	27.667	6	2014-2020	2005-2020	2009-2020	15	100	86
Mugla	37.217	28.367	646	1979-2020	1979-2020	1979-2020	82	100	89
Usak	38.671	29.404	919	1979-2020	1979-2020	1979-2020	71	100	86

MERRA-2 is an hourly dataset produced by NASA at a horizontal resolution of 0.625° × 0.5° (approximately 50 km) since 1980 [37]. This dataset includes data at 72 pressure levels reaching up to 0.01 hPa in height. Although it is fundamentally the same as the previously produced MERRA dataset, it has more accurate predictions with the latest updates [2,38,39].

ERA5 datasets are archived in "C3S Climate Data Store," and raw files are in two optional file formats, NetCDF or GRIB. The ERA5 hourly data on single levels dataset was used. MERRA-2 datasets are archived in "MDISC" managed by NASA GES (Goddard Earth Sciences). MERRA-2, 2d, 1-Hourly, Time-Averaged, Single-Level, Assimilation, Single-Level Diagnostics V5.12.4 (M2T1NXSLV 5.12.4) were downloaded by using GNU Wget-tool in NetCDF-4 file format [1, 38].

The NetCDF and NetCDF-4 file formats for ERA5 and MERRA-2 datasets, respectively, were preferred in the study. Time series were extracted from the data files by using MATLAB R2020b. Finally, time series of observations from meteorological stations and reanalysis datasets were paired at each station for further processes by using the R dplyr package [40]. A summary of the parameters used in the study is given in Table 2.

TSMS adjusted the pressure observed at the station, predicating on sea level, to eliminate the altitude factor. Therefore, the mean sea level pressure parameter was preferred over surface pressure for both reanalysis datasets. The temperature at 2 m above the land surface and the wind speed calculated from the eastward (u) and northward (v) wind components at 10 m above the land surface were used as coherent with the observed data. Thus, no adjustments were needed for these two parameters. Wind speed was calculated from u and v components by the rWind package in RStudio [41].

Table 2. Characteristics of the parameters derived from each dataset

	Spatial Resolution	File Format	Meteorological Parameter		
			Temperature	Mean Sea Level Pressure	Wind Speed
ERA5 dataset (hourly data on single levels dataset)	0.25° x 0.25° (31 km)	NetCDF	t2m	msl	u10 v10
MERRA-2 dataset (2d,1-Hourly, Time-Averaged, Single-Level, Assimilation, Single-Level Diagnostics V5.12.4 (M2T1NXSLV 5.12.4))	0.625° × 0.5° (approximately 50 km)	NetCDF-4	T2M	SLP	U10M V10M

2.4. Methodology

In the reanalysis datasets, data is available at the discrete grid points located at the intersections of longitudes and latitudes. Station coordinates do not exist precisely on these grid points and generally stay somewhere in the "grid boxes". There are two approaches to overcoming this limitation in the literature [19, 23, 42]. The first method suggests interpolating the coordinates and the values [19, 23]. The second method is to get values on the coordinates of the nearest grid point to the station [42]. A point-based comparison method was preferred in this study. As Sheridan et al. (2020) stated, the nearest grid point method generally gives better performance than interpolation method [43]. The values at the nearest grid points of the reanalysis dataset to the station coordinates were compared. The nearest latitudes (min LTT) and longitudes (min LGG) and also the distance between nearest points were calculated using the Haversine formula (Equation 1) [44, 45]. These values are given in Table 3.

$$d = 2R_d \sin^{-1} \sqrt{sin^2\left(\frac{\varphi_1-\varphi_2}{2}\right) + \cos(\varphi_1)\cos(\varphi_2)\, sin^2\left(\frac{\phi_1-\Phi_2}{2}\right)} \quad (1)$$

where;

d: distance between two locations (km)
R_d: Earth's average radius (~6.371 km)
φ_1 : Latitude of location 1 (rad)
φ_2: Latitude of location 2 (rad)
ϕ_1: Longitude of location 1 (rad)
ϕ_2: Longitude of location 2 (rad)

Table 3. Distances between the meteorological stations and the nearest grid points in the reanalysis datasets

Stations	MERRA-2			ERA5		
	min LTT	min LGG	Distance (km)	min LTT	min LGG	Distance (km)
Adnan Menderes A.	38.5	26.88	33.8	38.25	27.25	9.4
Akhisar	39	28.13	32.9	39	27.75	9.8
Aydin	38	28.13	29.4	37.75	27.75	14.2
Cardak	38.5	26.88	35.5	38.5	27	5.9
Cesme	38	29.38	22.7	37.75	29	7.1
Cigli	38.5	26.88	11.9	38.5	27	1.7
Dalaman	37	28.13	24	37.25	28.25	5.6
Datca	38.5	29.38	26.8	38.75	29	9.3
Denizli	38	29.38	35.2	37.75	29	8.2
Dikili	38.5	26.25	7.7	38.25	27	12.6
Fethiye	36.5	28.75	26.5	36.75	28.75	16.7
Izmir/Guzelyali	36.5	27.50	26.5	36.75	27.75	10.4
Kusadasi	39	26.88	26.5	39	27	13
Kutahya	36.5	29.38	9.7	36.75	29	9.6
Manisa	38	27.50	14.3	37.75	27.25	14.3
Marmaris	39.5	30.00	20.9	39	29	11.2
Milas Bodrum	38.5	27.50	31.5	38.5	27.5	7.3
Mugla	37	28.13	32.3	36.75	28.25	10.9
Usak	37.5	27.50	20.5	37.25	27.75	11.4

2.5. Statistical Indicators

The correlation coefficient (R) was used to decide which reanalysis dataset gives the best results compared with observational data. If R is closer to ±1, this indicates a strong positive or negative relationship with the reanalysis and observation data. Conversely, the two datasets are not correlated if the R-value is close to zero. R was calculated by using Equation 2 [46]:

$$R = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2][n\sum y^2-(\sum y)^2]}} \quad (2)$$

where;

R: the correlation coefficient
n: number of the given dataset
x: observed datasets
y: reanalysis data.

Mean bias error (MBE) indicates the average bias in the reanalysis data and the direction of the bias. A positive MBE means an overestimation, and a negative MBE indicates an underestimation of the observed data. MBE was calculated by Equation 3 [47]:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(\widetilde{y_i} - y_i) \quad (3)$$

where;

n : number of the given data
(y_i)̃: reanalysis data
y_i : observed data

The Root Mean Square Error (RMSE) is another statistical indicator to evaluate how accurately the reanalysis data predicts the observed data. RMSE indicates the quality of the prediction model effectively. RMSE was calculated using Equation 4 [47].

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_{obs,i} - x_{model,i}\right)^2} \quad (4)$$

where;

n: number of the given dataset
x_(obs,i) : observation data
x_(model,i) : reanalysis data

Statistical analysis, visualization, and data processing were studied using the R Openair package [48].

3. Results and Discussions

3.1. Spatial characteristics of parameters

General statistics of the parameters are given in Table 4 and Figure 2. The mean air temperature in the study area was 17.6 °C. The minimum hourly temperature was at the Cardak station (-24.0 °C) at 852 m above sea level, and the highest was at the Aydin station (56.4 °C). The minimum annual average temperature was 13.1°C at the Usak station, and the highest annual average temperature was 21.9 °C at the Datca station.

The overall yearly average mean sea level pressure in the study area is 1014 hPA. The minimum hourly value of MSLP was 1012.9 hPA at the Datca station, and the highest was 1014.9 hPA at the Kutahya station. The minimum annual average of MSLP was at the Marmaris station (914.9 hPa), and the highest was also at the Marmaris station (1080.2 hPa).

The average wind speed in the study area was 2.8 m/s. The minimum hourly wind speed was near zero for all stations, and the highest hourly wind speed was 61 m/s at the Manisa station. The minimum annual average wind speed is 1.3 m/s at the Manisa, Denizli, and Fethiye stations, and the highest annual average wind speed was 5.1 m/s at the Adnan Menderes Airport station.

No mean sea level pressure data were available at the Manisa Station. Nevertheless, this station was included only for evaluating temperature and wind speed parameters.

3.2. Comparative analysis of reanalysis data

In this study, two reanalysis datasets were compared with observed data and also each other. According to comparative statistics, the overall R-value for the reanalysis datasets and observed data varied between 0.86-0.96 for T2M, 0.95-0.99 for MSLP, and 0.08-0.70 for WS. The R-values for comparing two reanalysis datasets were 0.94-0.99 for T2M, 0.97-0.99 for MSLP, and 0.69-0.9 for WS. The R-values for all parameters are given in Table 5.

3.2.1 Mean Sea Level Pressure

The reanalysis datasets represented mean sea level pressure quite well (Figure 3), similar to Graham et al. (2019) results [49]. The overall R-value for the region was 0.98 for both MERRA-2 and ERA5, in line with Fredriksen (2018) [50]. MERRA-2 had a higher RMSE (1.398 hPa) and also a higher MBE (0.4526 hPa) than ERA5 (RMSE=1.355 hPa, MBE=0.1359 hPa). Both datasets mostly overestimated the MSLP. Datasets were estimated more accurately at a range of 1000-1030 hPa

Table 4. Characteristics of meteorological parameters in the study area

Stations	T2M (°C)			MSLP (hPa)			WS (m/s)		
	min	max	mean±sd	min	max	mean±sd	min	max	mean±sd
Adnan Menderes A.	-8.5	43.0	17.1±9.0	978.2	1038.4	1014.3±6.2	0.0	33.4	5.1±2.95
Akhisar	-10.4	44.7	16.9±9.6	973.2	1043.6	1014.8±6.4	0.0	39.6	2.7±2.06
Aydin	-4.6	56.4	18.3±9.0	977.8	1077.0	1013.8±6.1	0.0	42.2	1.8±1.28
Cardak	-24.0	40.0	13.7±9.6	990.8	1037.5	1013.9±6.6	0.0	23.1	3.7±2.02
Cesme	-2.2	36.5	19.7±6.9	991.3	1037.2	1014.2±6.1	0.0	10.8	2.5±1.48
Cigli	-7.0	44.0	17.3±8.6	987.1	1039.7	1014.2±5.8	0.0	45.3	4.5±2.62
Dalaman	-3.0	44.0	18.5±7.3	979.4	1034.0	1013.1±5.9	0.0	41.2	3.7±2.16
Datca	-1.0	41.9	21.9±6.7	987.0	1038.4	1012.9±5.7	0.0	24.7	3.8±2.84
Denizli	-9.8	43.8	17.6±9.2	981.6	1066.0	1013.6±6.5	0.0	44.8	1.3±0.92
Dikili	-7.0	44.0	17.5±7.7	984.2	1073.4	1014.4±6.2	0.0	46.3	2.5±1.61
Fethiye	-1.4	43.5	20.7±7.9	986.1	1032.6	1013.0±5.9	0.0	10.8	1.3±0.99
Izmir/Guzelyali	-6.3	41.0	18.9±8.0	987.1	1038.4	1014.1±5.9	0.0	24.7	3.8±2.64
Kusadasi	-4.0	39.5	18.9±7.1	991.6	1045.9	1014.0±5.9	0.0	15.4	2.1±1.43
Kutahya	-19.9	39.6	13.4±9.4	990.1	1042.8	1014.9±7.2	0.0	7.7	1.5±0.99
Manisa	-6.4	43.7	17.4±9.2	n.a.	n.a.	n.a.	0.0	61.0	1.3±0.95
Marmaris	-8.8	43.3	19.9±7.8	914.9	1080.2	1013.0±5.9	0.0	40.1	1.7±1.11
Milas Bodrum	-5.0	44.0	18.3±8.4	988.9	1033.7	1013.6±5.8	0.0	20.1	3.4±2.27
Mugla	-8.9	42.2	15.7±9.3	979.9	1071.9	1013.5±6.0	0.0	41.7	2.1±1.36
Usak	-19.9	39.6	13.1±9.4	980.3	1040.2	1014.1±6.3	0.0	43.2	2.2±1.58

n.a.: not available

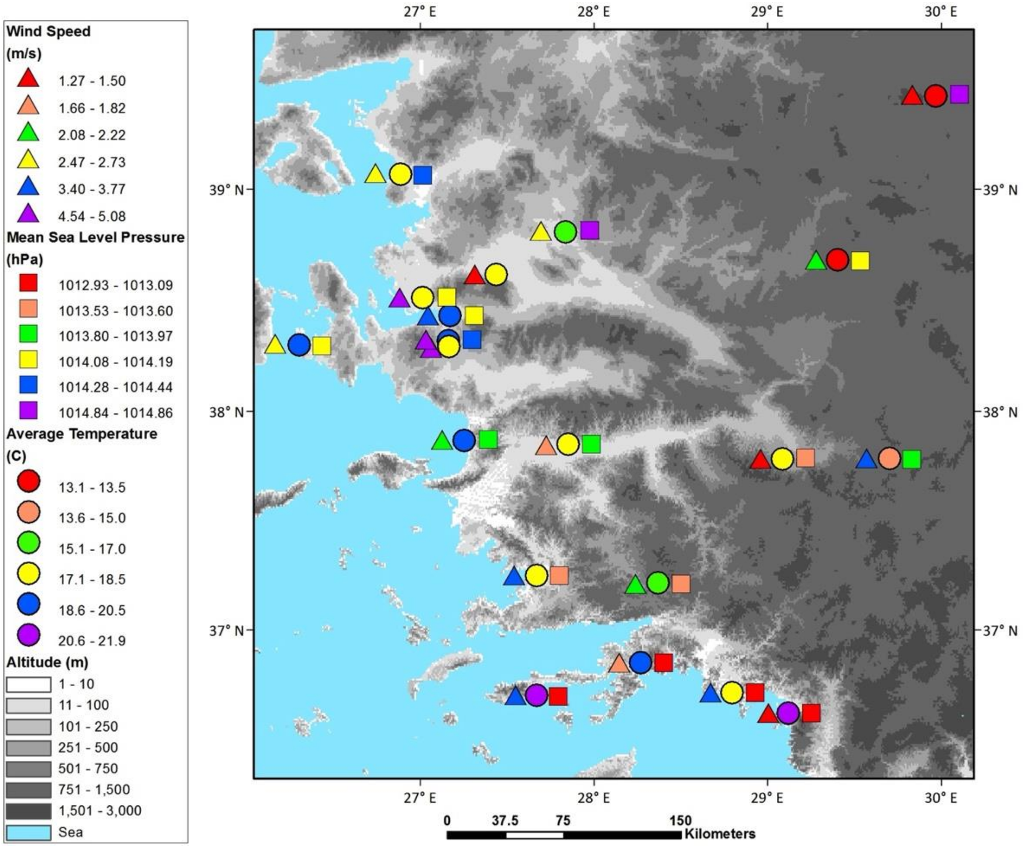

Figure 2. Long-term mean values of meteorological parameters in the stations for 25 years

Table 5. Correlation coefficients of reanalysis datasets vs. observed data

Stations	ERA5 vs. TSMS			MERRA-2 vs. TSMS			ERA5 vs. MERRA-2		
	T2M	MSLP	WS	T2M	MSLP	WS	T2M	MSLP	WS
Adnan Menderes Airport	0.92	0.99	0.68	0.94	0.99	0.67	0.97	0.99	0.77
Akhisar	0.93	0.98	0.66	0.96	0.98	0.61	0.96	0.99	0.75
Aydin	0.93	0.99	0.38	0.96	0.98	0.30	0.97	0.99	0.69
Cardak	0.89	0.96	0.51	0.92	0.96	0.54	0.96	0.97	0.72
Cesme	0.93	0.98	0.70	0.93	0.99	0.70	0.99	0.99	0.90
Cigli	0.91	0.99	0.68	0.93	0.99	0.60	0.97	0.99	0.87
Dalaman	0.89	0.99	0.67	0.86	0.99	0.45	0.97	0.99	0.70
Datca	0.94	0.98	0.66	0.95	0.98	0.67	0.97	0.99	0.81
Denizli	0.93	0.97	0.49	0.96	0.97	0.45	0.96	0.98	0.66
Dikili	0.94	0.98	0.14	0.94	0.97	0.08	0.98	0.99	0.90
Fethiye	0.92	0.99	0.52	0.95	0.98	0.51	0.96	0.99	0.70
Izmir/Guzelyali	0.94	0.99	0.58	0.96	0.99	0.56	0.97	0.99	0.82
Kusadasi	0.94	0.98	0.60	0.94	0.99	0.59	0.96	0.99	0.84
Kutahya	0.93	0.96	0.65	0.95	0.95	0.56	0.97	0.97	0.83
Manisa	0.95	n.a.	0.58	0.96	n.a.	0.51	0.97	0.99	0.82
Marmaris	0.91	0.99	0.58	0.94	0.99	0.54	0.94	0.99	0.76
Milas Bodrum	0.90	0.99	0.67	0.90	0.99	0.43	0.97	0.99	0.75
Mugla	0.95	0.98	0.51	0.96	0.98	0.49	0.98	0.99	0.79
Usak	0.92	0.96	0.53	0.95	0.97	0.46	0.97	0.97	0.83

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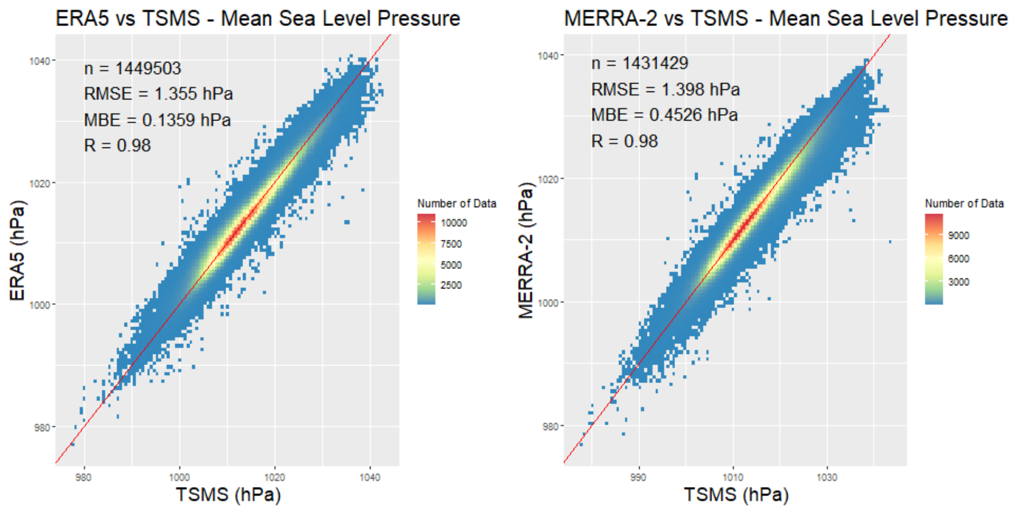

Figure 3. Density scattered plots showing comparative statistics for MSLP

The comparison of TSMS and the reanalysis datasets for MSLP is given in Figure 4. Both reanalysis datasets were in good agreement with the observational data. The R-values were equal to or higher than 0.98 in most stations. The lowest R-values were obtained at the highest altitudes and the stations located in the interior of Western Türkiye; Usak station (919 m) in a transition zone between the Mediterranean and temperate climate zones, Kutahya station (969 m) situated in an area dominated by mountains and plateaus, and Cardak (852 m) station located at the mountain ridge. The highest RMSE was 2.521 hPa for the MERRA-2 dataset in the Kutahya Station. Both ERA5 and MERRA-2 had minimal biases generally.

MERRA-2 performed slightly better than ERA5 in the coastal areas for estimating MSLP. Both datasets had the highest correlations at 13 stations having lower altitudes (3-126 m), whereas the lowest correlation and highest RMSE were observed for stations at higher altitudes (425-1000 m). However, the correlation coefficient was the same with MERRA-2 (0.98). ERA5 performed better than MERRA-2 since it has a lower bias and RMSE for MSLP.

ERA5 overestimated the MSLP data in five stations. These stations were generally located in the interior of the region; Denizli (425 m above sea level), Kutahya, Mugla (646 m above sea level), and Usak, except Dikili, which was located on the northwestern coast of Türkiye (3 m above sea level). The other 13 stations, located mostly in coastal areas with lower altitudes, were underestimated except for Cardak, situated at high altitudes, Akhisar (80 m), Manisa (71 m), and Aydin (56 m), located interior of the region. ERA5 underestimated the MSLP at the lower levels at all stations except the Kutahya and Cardak stations. However, estimations followed the trend line significantly; it was underestimated at higher levels and overestimated at lower levels. Three stations are located nearly 1000 m higher, and the lowest accuracy was at these stations. Therefore, as the altitude increases, estimation accuracy gets lower. The RMSE values were in the range of 0.941 - 2.291 hPa.

The MERRA-2 dataset showed a good performance. The lowest correlations were at the Kutahya (0.95) and Cardak (0.96) stations. The Kutahya station is 9.7 km away, and the Cardak station is 35.5 km away from the nearest grid points of MERRA-2. The MERRA-2 dataset generally underestimated MSLP. The MSLP values were overestimated at the Datca (28 m above sea level) and Dikili stations in the coastal areas. The RMSE values were in the range of 0.873-2.521 hPa. MERRA-2 had a lower RMSE than ERA5 at 11 stations.

There was a significant agreement between the two reanalysis datasets. Comparison of the datasets with each other showed that MERRA-2 overestimated MSLP at 60% of the stations. The lowest correlation was 0.97 at the Cardak, Kutahya, and Usak stations. The R-value was the highest in all stations, with 0.99, except for the Denizli station (0.98).

3.2.2 Air Temperature

The overall R-value for MERRA-2 was 0.92, which can also be seen in Gupta et al. (2020) and Graham et al. (2019) [49,51]. Similarly, it was 0.91 for ERA5 for T2M, which is consistent with Yilmaz (2022) and Graham et al. (2019) findings [25, 49].

Results indicate a strong correlation between the reanalysis datasets and the observed data (Figure 5). Although MERRA-2 had a higher MBE (0.341 °C) than ERA5 (MBE=0.2712 °C), ERA5 had a higher overall RMSE (3.678 °C) than MERRA-2 (3.633 °C).

Correlations between the reanalysis datasets and observations were significant for all stations (Figure 6). The ERA5 dataset had an R-value ranging from 0.89 to 0.95. The lowest correlation (0.89) was obtained at the Dalaman station located on the southwestern coast of the study area. The Dalaman station is located 5.6 km far away from the grid point. Although this station is one of the closest stations to the grid points, it still had the lowest correlation. The Cigli station (5 m above sea level), located on flat terrain in northern Izmir, is the closest station (1.7 km away), and its R-value was 0.91 for ERA5. The highest RMSE was at the Manisa station with 6.45 °C, and the lowest RMSE was at the Kusadasi station (22 m below sea level) on the southern coast of Izmir with a value of 2.56 °C. The ERA5 dataset showed a strong correlation higher than 0.9 for seventeen stations. ERA5 underestimated at 60% of the stations.

The MERRA-2 dataset had an R-value ranging between 0.86 (Dalaman) and 0.96 (Akhisar, Aydin, Denizli, İzmir/Guzelyali, Manisa, Muğla), respectively. The Dalaman station in the coastal area is 24.0 km away. Other stations are mostly in inner areas, except Izmir/Guzelyali station. The furthest station is Cardak which had an R-value of 0.92. The shortest distance is 7.5 km at the Dikili station, with an R-value of 0.94. Ninety-five percent of the stations had an R-value of more than 0.9, indicating a good correlation between the two datasets. MERRA-2 underestimated 80% of the stations, and the lowest RMSE was at the Dikili station, with a value of 2.569 °C. MERRA2 had the highest correlations in terrestrial areas with higher altitudes and lower correlations in coastal regions with the highest RMSE value. MERRA-2 had lower RMSE than ERA5 at 12 stations for temperature estimations.

There was a significant correlation between the two reanalysis datasets for the temperature at all stations. The R-value changed between 0.94 and 0.99. Only the correlation at the Marmaris station (16 m below sea level), on the southwestern coast of Türkiye, was lower than 0.95. Still, there was a strong correlation. There was almost a perfect match between the two datasets at the Cesme station (5 m below sea level), west of Izmir. MERRA-2 tended to underestimate 70% of the stations.

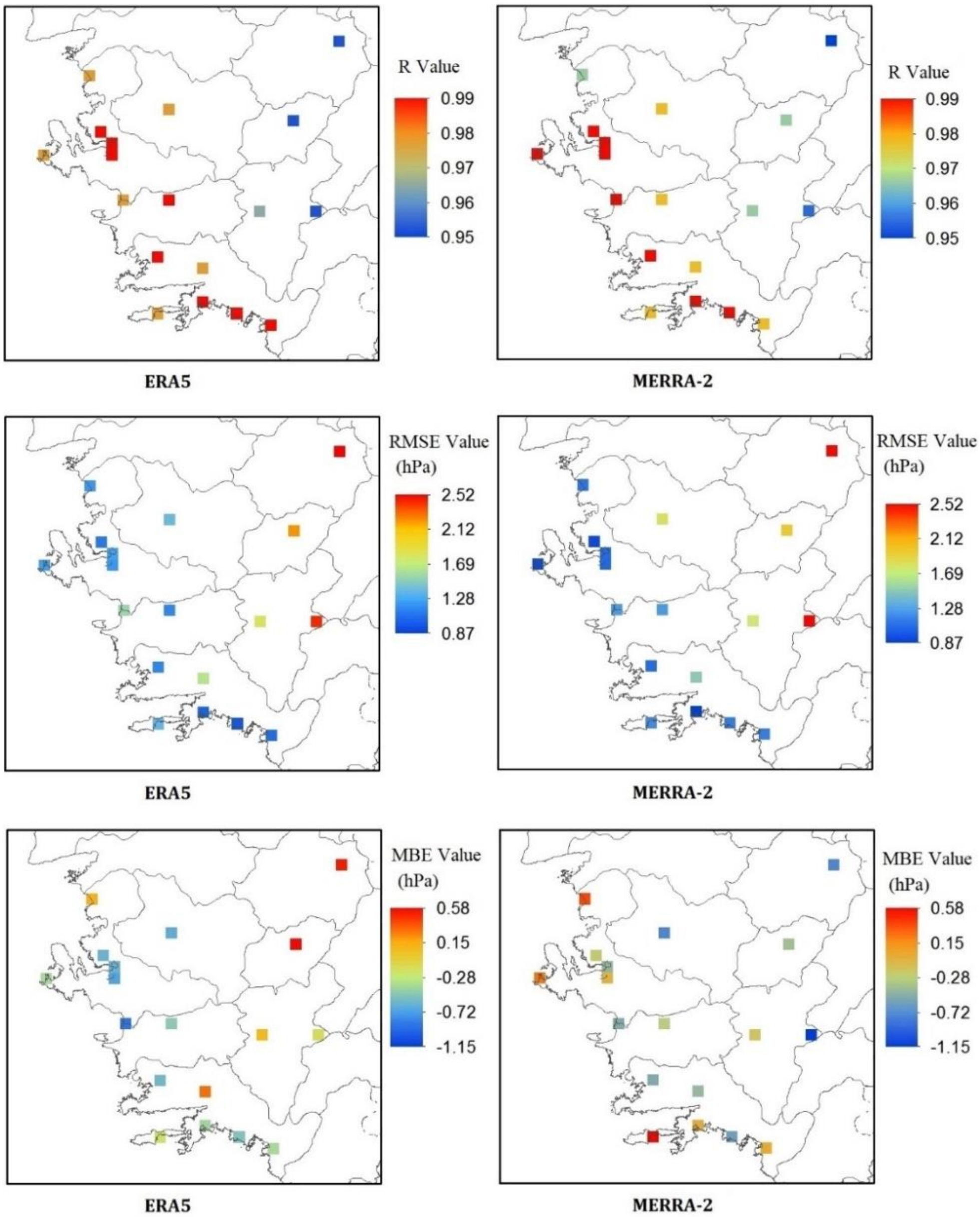

Figure 4. Estimation performance of the ERA5 dataset (on the left) and the MERRA-2 dataset (on the right) for MSLP

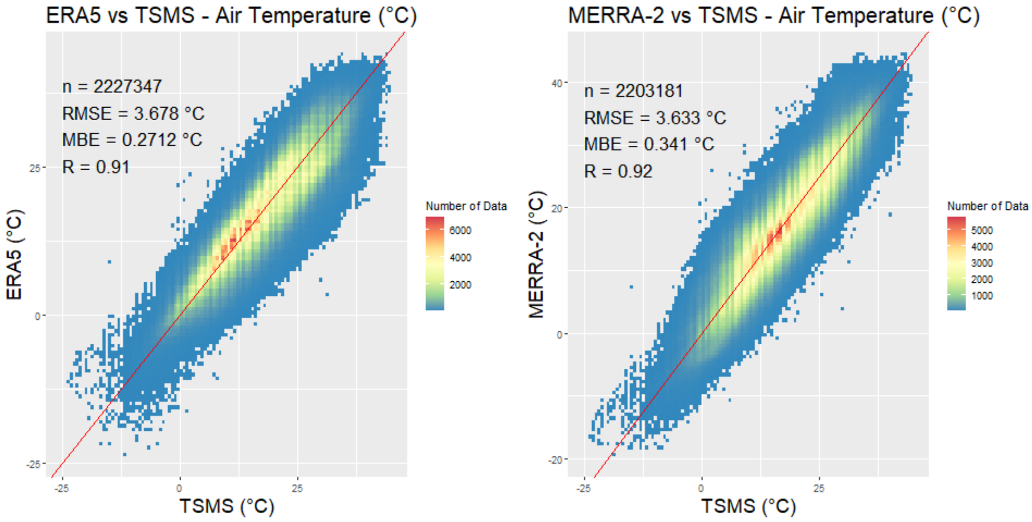

Figure 5. Density scattered plots showing comparative statistics for T2M

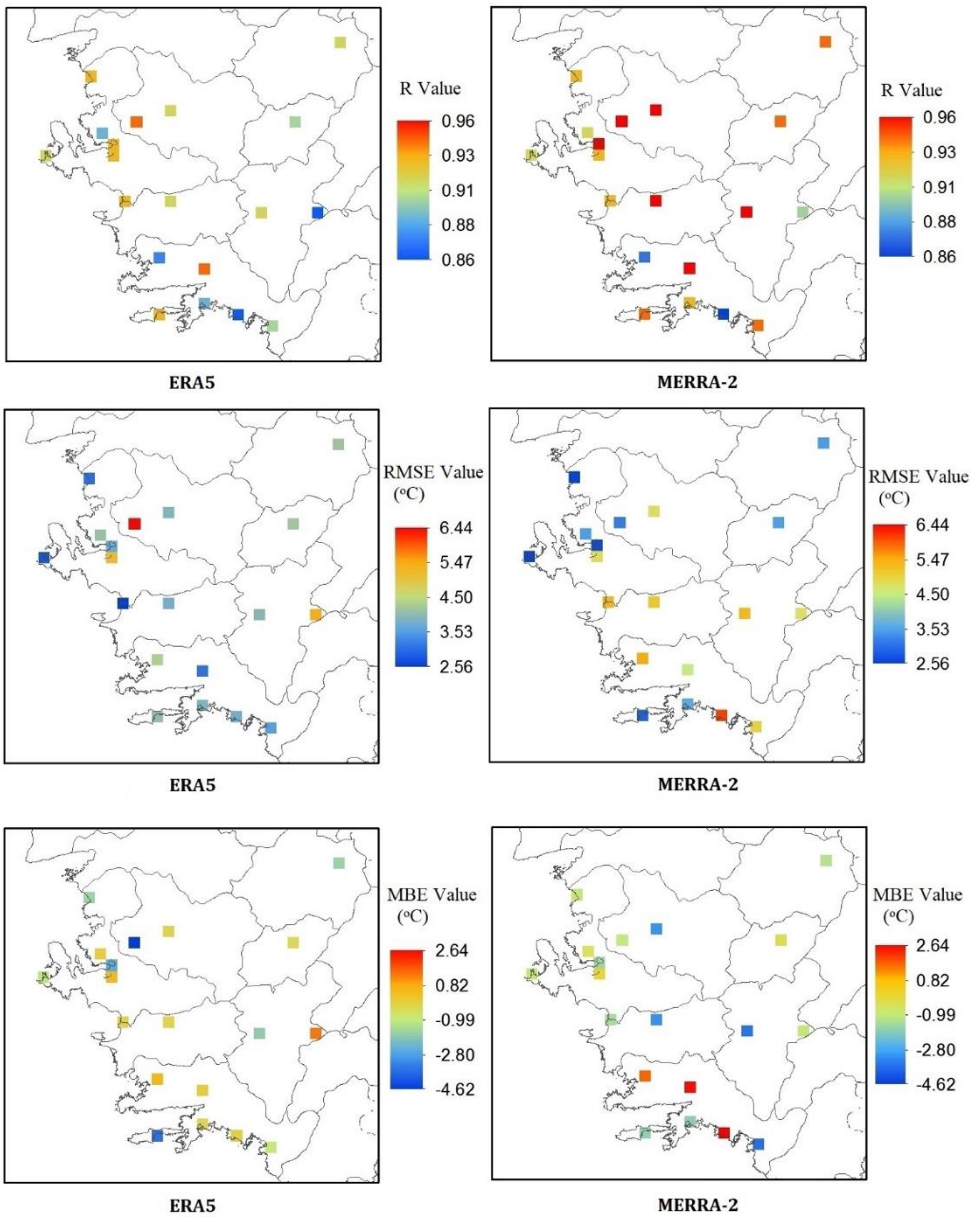

Figure 6. Estimation performance of the ERA5 dataset (on the left) and the MERRA-2 dataset (on the right) for T2M

3.2.3 Wind Speed

Lower R-values of 0.53 and 0.45 indicated a weak correlation for WS for MERRA2 and ERA5, respectively (Figure 7). MERRA-2 had a higher overall RMSE (2.512 m/s) than ERA5 (2.18 m/s). While MERRA-2 underestimated the observed WS values with a higher bias (1.1886 m/s), ERA5 overestimated the WS (0.2418 m/s). Santos et al. (2019) correlated ERA5 and MERRA-2 with wind speed data from a meteorological tower at 78 m height, and the R-values found were 0.64 and 0.59, respectively, which agrees with the results of this study [52]. Both datasets failed to estimate extreme wind speed, as mentioned by the same study [52].

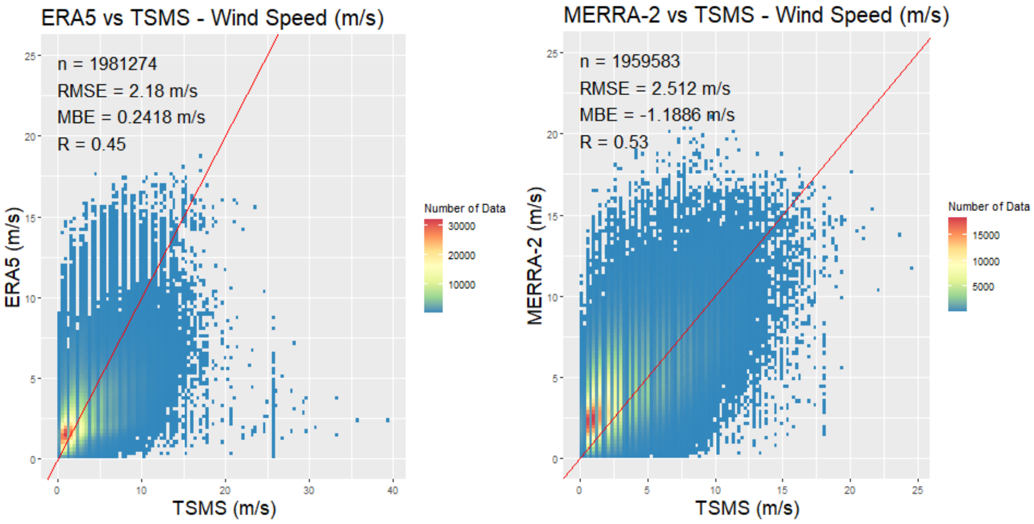

Figure 7. Density scattered plots showing comparative statistics for WS

ERA5 had a correlation coefficient between 0.14 and 0.70 (Figure 8). The lowest correlation was at the Dikili station, and the highest was at the Cesme station (at 5 m altitude) at the western of Izmir. The Dikili station is 12.6 km away, and the Cesme station is 7.1 km away from the grid points of ERA5. The R-value at the closest station, Cigli, was 0.68. The ERA5 dataset correlations were higher than 0.5 at 86.4% of the stations. There was almost no correlation at the Dikili station, while the R-values were less than 0.5 at the Aydin and Denizli stations, which indicated a weak correlation. ERA5 overestimated WS at 55% of the stations. ERA5 underestimated the stations that had higher mean wind speeds (>2.7 m/s) and overestimated lower mean wind speeds (<2.5 m/s). The RMSE values were in the range of 0.95 - 4.106 m/s.

MERRA-2 correlation coefficients varied between 0.08 - 0.7 (Figure 8). It is in agreement with Kim et al. (2018) [53]. The worst estimation was at the Dikili station, and the best was at the Cesme station (7.1 km from the grid point). The correlation coefficient at the Cardak station was 0.54. The MERRA-2 dataset showed a correlation greater than 0.5 at 68.2% of the stations. Although the Dikili station has the shortest distance of 7.5 km, there was also no correlation, likewise ERA5. The Aydin, Milas/Bodrum, and Dalaman stations in the coastal areas and the Denizli, Usak, and Mugla stations at higher altitudes in the interior regions had R-values lesser than 0.5, which indicated a weak correlation. MERRA-2 generally tended to overestimate wind speed. MERRA-2 estimations were greater than the observed values at 17 stations. The RMSE values were in the range of 1.84 - 4.01 m/s. MERRA-2 had a higher RMSE at 13 stations.

Reanalysis datasets showed a strong performance for wind speed compared to each other. The lowest performance was at the Denizli station, with an R-value of 0.66, while the highest was at the Cesme station, with 0.9. The results showed that 90% of stations had correlation coefficients equal to or greater than 0.7. MERRA-2 values were more significant than ERA5, and MERRA-2 overestimated at 16 stations.

3.3. Dataset suggestion

MERRA-2 showed slightly better performance than ERA5 for the mean sea level pressure, whereas there was a significant agreement between both datasets and the observed data. Both datasets had the highest estimation performance for mean sea level pressure in the coastal areas and the lowest at higher altitudes (425-1000 m). MERRA-2 showed a better performance in terrestrial regions with higher altitudes estimating temperature. ERA5 had a better performance than MERRA-2 for wind speed. ERA5 underestimated the stations that have higher mean wind speeds (>2.7 m/s) and overestimated lower mean wind speeds (<2.5 m/s). MERRA-2 performed better at the stations with mean wind speeds higher than 3.7 m/s. Suggested reanalysis datasets according to the RMSE values are given in Table 6 for all stations.

4. Conclusion

The ERA5 and MERRA-2 reanalysis datasets were compared with the on-site meteorological observations at 19 meteorological stations in the Aegean region of Türkiye. A comparison covering 25 years aimed to identify which reanalysis dataset best approximates three meteorological parameters: air temperature, mean sea level pressure, and wind speed.

Results indicate a strong correlation between both reanalysis datasets and the observed data for T2M and MSLP. The lowest R-values were obtained at the highest altitudes, and the stations located in the interior of Western Türkiye for estimating MSLP. Therefore, as the altitude increases, MSLP estimation accuracy gets lower for both datasets.

Differences between the predictions of the reanalysis datasets occur due to forecasting models, spatial resolutions, and quality of observations in the assimilation schemes [54].

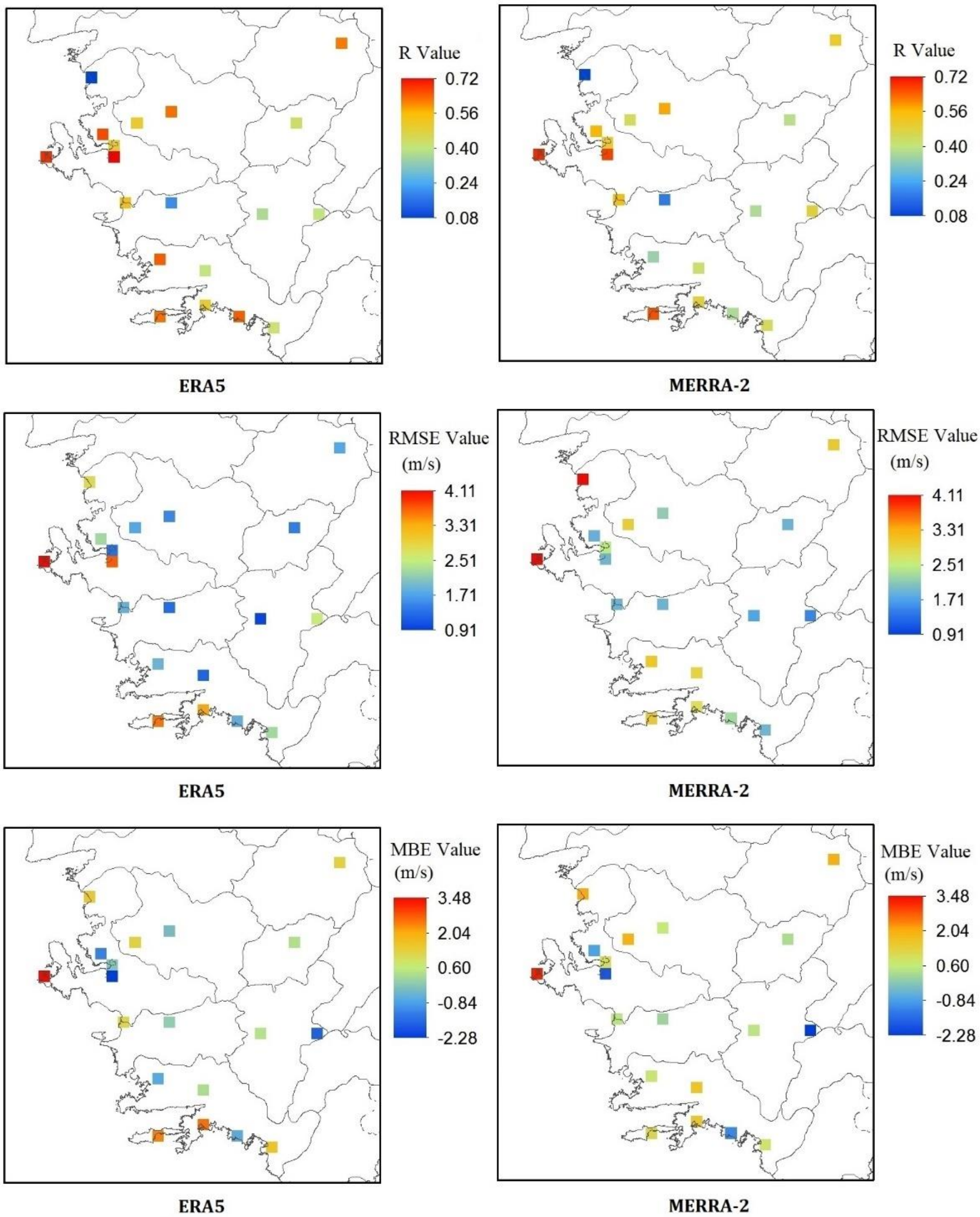

Figure 8. Estimation performance of the ERA5 dataset (on the left) and the MERRA-2 dataset (on the right) for WS

Table 6. Suggested datasets for each station

Stations	MSLP	T2M	WS
Adnan Menderes Airport	MERRA-2	MERRA-2	MERRA-2
Akhisar	ERA5	ERA5	ERA5
Aydin	ERA5	ERA5	ERA5
Cardak	ERA5	MERRA-2	MERRA-2
Cesme	MERRA-2	MERRA-2	MERRA-2
Cigli	MERRA-2	MERRA-2	MERRA-2
Dalaman	ERA5	ERA5	ERA5
Datca	MERRA-2	MERRA-2	MERRA-2
Denizli	ERA5	ERA5	ERA5
Dikili	MERRA-2	MERRA-2	ERA5
Fethiye	ERA5	ERA5	ERA5
Izmir/Guzelyali	MERRA-2	MERRA-2	ERA5
Kusadasi	MERRA-2	ERA5	ERA5
Kutahya	ERA5	MERRA-2	ERA5
Manisa	n.a.	MERRA-2	ERA5
Marmaris	MERRA-2	MERRA-2	MERRA-2
Milas Bodrum	MERRA-2	ERA5	ERA5
Mugla	MERRA-2	ERA5	ERA5
Usak	MERRA-2	MERRA-2	ERA5

n.a.: not available

The distances between grid points and stations are related to spatial resolution. MERRA-2 performed better than ERA5 for the T2M and MSLP. On the other hand, MERRA-2 had poorer scores for WS due to its coarse resolution. These results indicated that the finer resolution does not always yield better results for each parameter [55]. In other words, distance from the nearest grid point is not as effective as the altitude or the magnitude range of the parameter.

Both reanalysis datasets failed to estimate the extreme wind speeds. Therefore, the downscaling of meteorological parameters from a coarse spatial resolution of reanalysis datasets should be considered for future works.

Ethics committee approval and conflict of interest statement

This article does not require ethics committee approval. This article has no conflicts of interest with any individual or institution.

Acknowledgements

We are grateful to ECMWF and NASA for providing reanalysis datasets and to NOAA for observational data.

Author Contribution Statement

Gülşah Tulger Kara: Conceptualization, Literature Review, Methodology, Data Collection, Validation, Writing - Original Draft, Visualization. Tolga Elbir: Conceptualization, Methodology, Writing - Review & Editing, Supervision

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