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Assessment of the Accuracy of ERA5 and ERA5-Land Reanalysis Products over Croatia

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Contents

ABSTRACT

This thesis evaluates the accuracy of the ERA5 and ERA5-Land reanalysis products over a geographically diverse region of Croatia using ground-based meteorological observations from DHMZ and HOPS stations. The analysis applies data preprocessing, temporal harmonisation, spatial matching and interpolation, and statistical validation techniques to compare the two reanalysis products with each other and with observed air temperature, relative humidity, wind speed, precipitation and pressure. Particular attention is given to whether the higher spatial resolution of ERA5-Land results in improved agreement with local observations and to the influence of elevation differences between reanalysis grid cells and meteorological stations. The results show that both products reproduce the principal temporal variability of observed meteorological conditions, although their performance varies considerably between variables and locations. ERA5-Land does not systematically outperform ERA5 despite its finer spatial resolution, with the relative performance of the two products depending on the meteorological variable considered. Elevation and pressure reference level are shown to substantially influence validation results, particularly for temperature and pressure. Overall, the findings demonstrate that spatial resolution alone is not sufficient to determine reanalysis accuracy at the local scale and highlight the importance of validation against ground-based observations.

Keywords:
ERA5; ERA5-Land; meteorological reanalysis; reanalysis validation; spatial resolution; Croatia

RESUMEN

Esta tesis evalúa la precisión de los productos de reanálisis ERA5 y ERA5-Land en una región geográficamente diversa de Croacia mediante observaciones meteorológicas terrestres procedentes de estaciones de DHMZ y HOPS. El análisis aplica técnicas de preprocesamiento de datos, armonización temporal, correspondencia e interpolación espacial y validación estadística para comparar ambos productos de reanálisis entre sí y con observaciones de temperatura del aire, humedad relativa, velocidad del viento, precipitación y presión. Se presta especial atención a determinar si la mayor resolución espacial de ERA5-Land se traduce en una mejor concordancia con las observaciones locales, así como a la influencia de las diferencias de altitud entre las celdas de la cuadrícula de los reanálisis y las estaciones meteorológicas. Los resultados muestran que ambos productos reproducen la principal variabilidad temporal de las condiciones meteorológicas observadas, aunque su rendimiento varía considerablemente entre variables y ubicaciones. ERA5-Land no supera sistemáticamente a ERA5 a pesar de su mayor resolución espacial, y el rendimiento relativo de ambos productos depende de la variable meteorológica considerada. Se demuestra que la altitud y el nivel de referencia de la presión influyen considerablemente en los resultados de la validación, especialmente en el caso de la temperatura y la presión. En conjunto, los resultados demuestran que la resolución espacial por sí sola no es suficiente para determinar la precisión de los reanálisis a escala local y destacan la importancia de su validación mediante observaciones terrestres.

Palabras clave:
ERA5; ERA5-Land; reanálisis meteorológico; validación de reanálisis; resolución espacial; Croacia

1. INTRODUCTION

Meteorological data play an important role in a wide range of scientific, environmental, and engineering applications, including climate monitoring, weather analysis, renewable energy assessment, environmental modelling, and the study of atmospheric processes. While ground-based meteorological stations provide direct observations of atmospheric conditions, their spatial distribution is often limited and uneven. As a result, gridded meteorological datasets are commonly used to provide spatially and temporally continuous information over larger areas.

Reanalysis datasets combine numerical weather prediction models with observations from multiple sources in order to reconstruct past atmospheric conditions in a consistent framework. Among the most widely used contemporary reanalysis products are ERA5 and ERA5-Land, developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 provides global atmospheric data at relatively high temporal and spatial resolution, while ERA5-Land offers a substantially finer spatial resolution for land-surface variables. The increased resolution of ERA5-Land is intended to provide a more detailed representation of local land-surface conditions, which may be particularly relevant in regions with complex topography and strong spatial variability in meteorological conditions (Hersbach et al., 2020; Muñoz-Sabater et al., 2021).

Despite their widespread use, reanalysis products do not represent direct measurements and may contain systematic differences from locally observed conditions. Their performance can depend on the meteorological variable considered, geographic location, terrain, proximity to the coast, elevation, and the spatial resolution of the underlying model. Validation against ground-based observations is therefore important when assessing whether a particular reanalysis dataset is suitable for regional or local applications (Almeida & Coelho, 2023; Gomis-Cebolla et al., 2023).

Croatia represents an interesting area for such an assessment due to its relatively complex geography. The country includes coastal, island, lowland, and mountainous environments within a comparatively small area, resulting in substantial spatial variability in meteorological conditions. These characteristics may present a particular challenge for gridded datasets whose values represent conditions over grid cells rather than at individual observation points. Differences in spatial resolution between ERA5 and ERA5-Land may therefore influence their ability to reproduce meteorological conditions observed at specific locations.

The aim of this thesis is to evaluate and compare the performance of ERA5 and ERA5-Land reanalysis datasets within the investigated region of Croatia using available ground-based meteorological observations. The analysis covers the period from 2020 to 2024, depending on dataset availability. ERA5 and ERA5-Land data extend through 2024, while the DHMZ observations used for validation are available from 2020 to the end of 2023. Reanalysis and observational data are spatially and temporally harmonised before their agreement is evaluated using statistical indicators such as bias, root mean square error and correlation.

Particular attention is given to determining whether the higher spatial resolution of ERA5-Land results in improved agreement with local observations compared with ERA5. In addition to overall performance, differences between individual monitoring stations and meteorological variables are examined in order to identify possible spatial and temporal patterns in reanalysis accuracy. Through this comparison, the thesis aims to provide an assessment of the advantages and limitations of ERA5 and ERA5-Land for representing meteorological conditions in Croatia and to evaluate their suitability for subsequent regional environmental and atmospheric analyses.

2. BACKGROUND

2.1 Meteorological observations and gridded datasets

Reliable meteorological information is required for the analysis of atmospheric conditions, climate variability, hydrological processes, renewable energy resources, environmental conditions, and numerous other scientific and engineering applications. Meteorological conditions can be described using several types of data sources, including direct observations, numerical weather prediction models, remote sensing products, and atmospheric reanalysis datasets.

Ground-based meteorological stations provide direct measurements of variables such as air temperature, atmospheric pressure, precipitation, wind speed, and wind direction at specific locations. These observations are particularly valuable for describing local meteorological conditions and for evaluating other sources of meteorological information. However, station measurements are spatially discrete. Their geographical distribution may also be uneven, while differences in instrumentation, station characteristics, measurement frequency, and data availability can further limit their use in spatial analyses.

Gridded datasets provide an alternative representation in which meteorological variables are available at regularly distributed locations covering a geographical area. This facilitates spatial analyses and provides meteorological information in locations where direct observations may not be available. However, a gridded value represents conditions associated with an area or model grid cell rather than a direct measurement at an individual meteorological station. Consequently, differences can occur between gridded estimates and observations, particularly in areas where meteorological conditions vary considerably over short distances.

2.2 Meteorological reanalysis

Meteorological reanalysis provides a spatially and temporally consistent reconstruction of past atmospheric conditions. Reanalysis systems combine numerical weather prediction models with observations from a range of sources using data assimilation techniques. The resulting datasets provide a physically consistent representation of atmospheric conditions across a regular spatial and temporal framework (Hersbach et al., 2020).

Unlike an individual meteorological station, a global reanalysis can provide estimates for locations throughout the world and for extended historical periods. This combination of spatial coverage, temporal continuity, and availability of numerous atmospheric variables makes reanalysis data useful for applications in which observational measurements are incomplete or unavailable.

Nevertheless, reanalysis values should not be interpreted as equivalent to direct observations. They are estimates produced by a modelling and data-assimilation system and therefore contain uncertainties associated with model formulation, assimilated observations, spatial resolution, and the representation of physical processes. Evaluation against independent or ground-based observations is consequently important when reanalysis datasets are used for regional and local applications (Hersbach et al., 2020).

2.3 ERA5

ERA5 is the fifth-generation global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) for the Copernicus Climate Change Service. It provides a reconstruction of atmospheric conditions from 1940 onwards and includes a large number of atmospheric, land-surface, and ocean-wave variables. ERA5 analyses are available at hourly temporal resolution, allowing both short-term meteorological variability and longer-term patterns to be investigated (Hersbach et al., 2020; Copernicus Climate Change Service [C3S], 2018).

The native horizontal resolution of the high-resolution ERA5 atmospheric product is approximately 31 km (Hersbach et al., 2020). ERA5 data distributed through the Copernicus Climate Data Store can also be obtained on a regular latitude-longitude grid, commonly at a resolution of 0.25°. This relatively high temporal resolution and global coverage have contributed to the widespread application of ERA5 in meteorological and climatological research.

Despite these advantages, the spatial resolution of ERA5 can limit its representation of local meteorological conditions. A single grid cell may contain considerable variations in elevation, land cover, or proximity to the coastline. These differences are particularly relevant when gridded values are compared with observations made at individual meteorological stations.

2.4 ERA5-Land

ERA5-Land is a higher-resolution land-surface reanalysis produced by replaying the land component of ERA5. Its purpose is to provide a more detailed representation of land-surface processes while maintaining consistency with the atmospheric forcing supplied by ERA5 (Muñoz-Sabater et al., 2021).

ERA5-Land has a native spatial resolution of approximately 9 km and is distributed through the Climate Data Store on a regular 0.1° × 0.1° latitude-longitude grid. Like ERA5, it provides hourly information and currently extends from 1950 onwards (Muñoz-Sabater et al., 2021; C3S, 2019). Its substantially finer spatial resolution is one of the principal differences between ERA5-Land and ERA5.

The finer grid can potentially provide a better representation of spatial variations in land-surface conditions. However, ERA5-Land should not simply be considered a spatially finer and automatically more accurate version of ERA5. ERA5-Land is derived by replaying the land component of ERA5 and is primarily designed for land-surface applications. Whether its increased spatial resolution results in improved agreement with observations therefore depends on the variable, location, and application considered (Muñoz-Sabater et al., 2021).

This distinction is particularly important when comparing the two products at meteorological station locations. A higher spatial resolution reduces the geographical scale represented by an individual grid cell, but it does not eliminate differences between modelled grid-cell conditions and point observations.

2.5 Validation of reanalysis datasets

The suitability of reanalysis data for regional applications is commonly assessed by comparison with ground-based observations. Such validation provides information about systematic errors, the magnitude of deviations from observations, and the ability of the reanalysis product to reproduce temporal variability.

Several statistical measures can be used for this purpose. Bias describes systematic overestimation or underestimation relative to observations, while error measures such as root mean square error (RMSE) quantify the magnitude of differences between datasets. Correlation coefficients can additionally be used to evaluate how closely temporal variations in reanalysis data correspond to those observed at meteorological stations.

Previous assessments of ERA5 and ERA5-Land demonstrate the importance of evaluating their performance at regional scales. Studies comparing the products with meteorological station observations have generally found substantial agreement for variables such as near-surface air temperature, while also identifying differences between products, geographical areas, seasons, and station characteristics. Similarly, precipitation evaluations have shown that neither the finer spatial resolution nor the more detailed land representation of ERA5-Land guarantees superior performance for every metric and location (Gomis-Cebolla et al., 2023).

Validation is therefore not limited to identifying which dataset is globally more accurate. It can instead determine the conditions under which a particular dataset performs well or poorly and whether its characteristics make it appropriate for a specific application.

2.6 Spatial resolution and complex geographical environments

The relationship between spatial resolution and local accuracy is especially important in geographically complex regions. Meteorological conditions can change substantially over short distances because of elevation, terrain orientation, land-sea contrasts, and other surface characteristics. Gridded datasets necessarily simplify this spatial variability because a grid value represents conditions at a scale considerably larger than that of an individual observation point.

This issue is particularly relevant for coastal and mountainous regions. A grid cell close to a coastline may represent a mixture of geographical influences that differs from the conditions experienced at a coastal station. Similarly, differences between the model elevation associated with a grid cell and the actual elevation of a meteorological station can contribute to discrepancies in temperature, pressure, wind, and other variables. Previous evaluations of reanalysis products have identified terrain and station elevation as important factors influencing their agreement with observations (Almeida & Coelho, 2023; Gomis-Cebolla et al., 2023).

These considerations are relevant for Croatia, where coastal areas, islands, mountainous terrain, and inland regions occur within relatively short geographical distances. Comparing ERA5 and ERA5-Land with ground-based observations therefore provides an opportunity not only to evaluate their overall performance but also to investigate whether the increased spatial resolution of ERA5-Land provides an advantage in representing meteorological conditions across geographically diverse locations.

3. DATA AND METHODOLOGY

3.1 Study Area

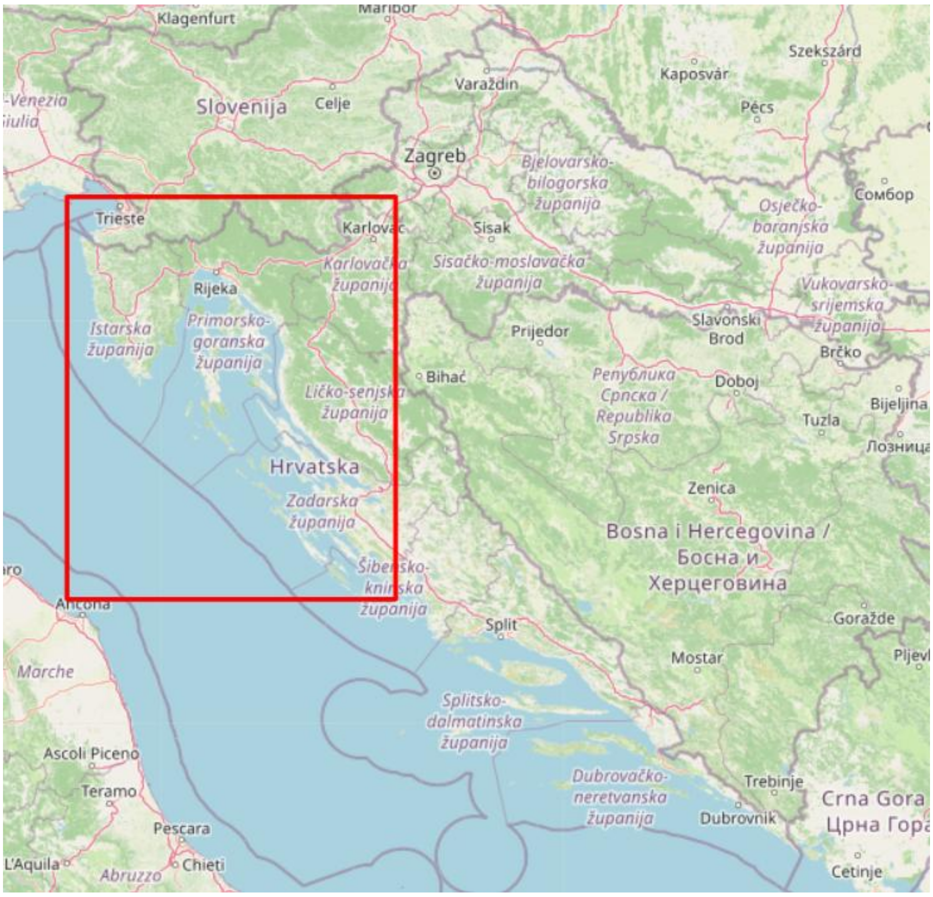

Figure 1. Study area and geographical extent of the analysis.

The study focuses on a region of Croatia characterised by considerable geographical and meteorological variability, as seen in Figure 1. The area of interest (AOI) extends from 13.4°E to 15.7°E and from 43.7°N to 45.7°N. The area includes parts of the northern Adriatic coast and islands as well as inland and mountainous regions. This geographical diversity makes the area particularly suitable for evaluating the ability of gridded meteorological products to reproduce conditions measured at individual observation locations.

The presence of coastlines, islands, valleys and mountainous terrain within a relatively limited geographical area can result in substantial spatial variation in meteorological conditions. The study area includes sea, islands, peninsulas, valleys, mountains, and urban and rural environments. Such characteristics are particularly relevant when comparing ground observations with gridded reanalysis products, as differences in spatial resolution may influence the representation of local meteorological conditions.

The analysis covers the period from January 2020 to December 2024, although the exact temporal coverage varies between datasets. ERA5 and ERA5-Land data are available throughout this period, whereas the DHMZ observations used for validation extend to December 2023. The HOPS observations generally become available from around the middle of 2020 and are used according to their individual periods of availability. Although ERA5 and ERA5-Land extend considerably further into the past, the availability of ground-based observations is more limited.

3.2 Meteorological Datasets

Four principal meteorological data sources are considered in this study: ERA5, ERA5-Land, observations from meteorological stations operated by the Croatian Meteorological and Hydrological Service (DHMZ), and meteorological measurements associated with the Croatian Transmission System Operator (HOPS).

ERA5 and ERA5-Land provide spatially continuous gridded reanalysis information, whereas the DHMZ and HOPS datasets provide measurements at specific geographical locations. This combination allows the two reanalysis products to be compared both with each other and with ground-based observations.

3.2.1 ERA5

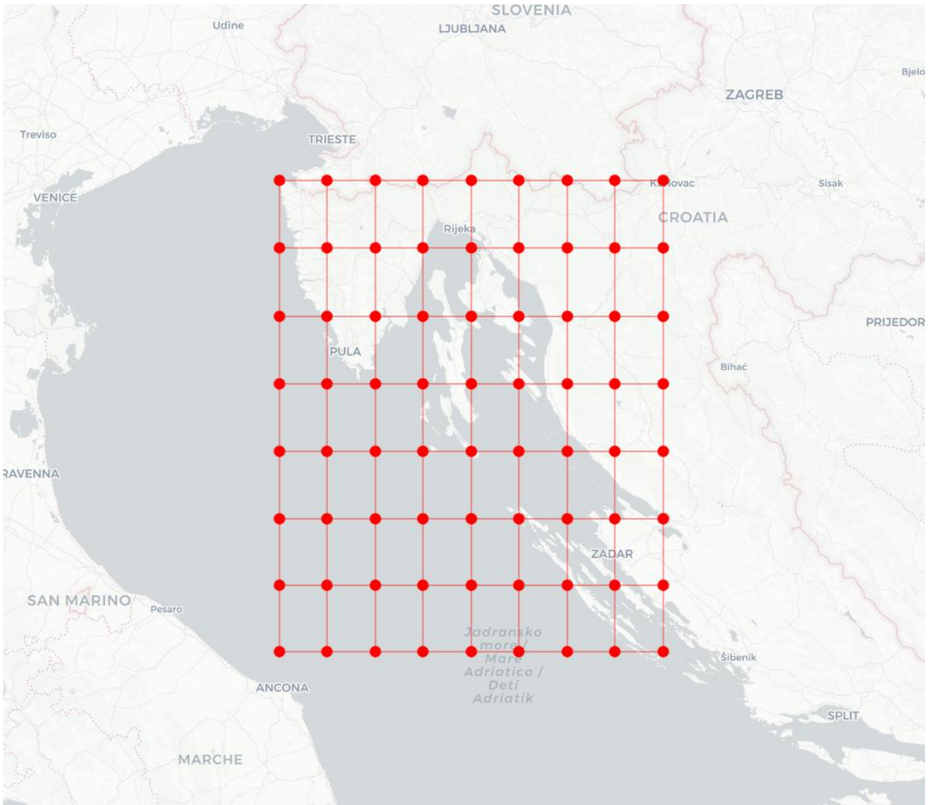

Figure 2. ERA5 grid in AOI

ERA5 reanalysis data were obtained from the Copernicus Climate Change Service (C3S) Climate Data Store (Hersbach et al., 2023). ERA5 combines numerical modelling with meteorological observations and provides hourly estimates of atmospheric and surface conditions.

For this study, ERA5 data were used at a spatial resolution of 0.25° × 0.25°. The temporal resolution of the dataset is one hour. The dataset provides spatially continuous meteorological information across the study area and serves as the lower-resolution reanalysis product evaluated in this study (Hersbach et al., 2023).

The relevant ERA5 variables were extracted for the study area and analysis period and subsequently processed to allow comparison with ERA5-Land and ground-based observations.

3.2.2 ERA5-Land

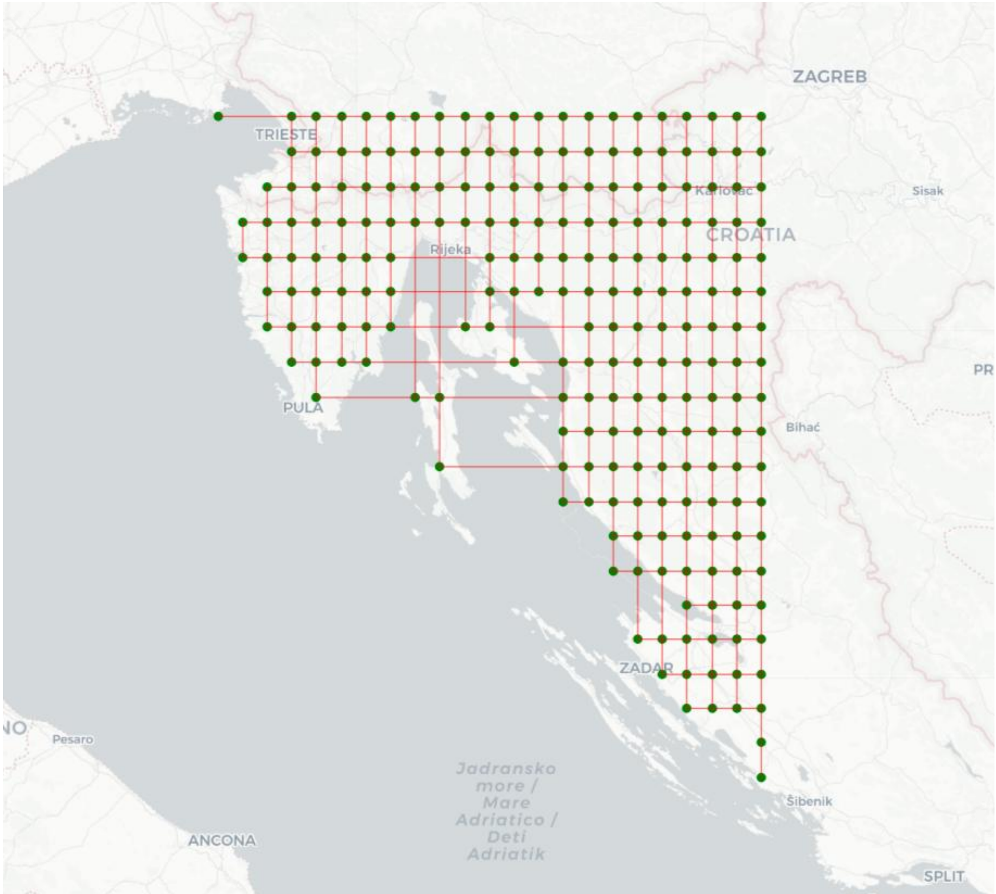

Figure 3. ERA5-Land grid in AOI

ERA5-Land data were also obtained through the Copernicus Climate Change Service. ERA5-Land provides hourly land-surface information at a finer spatial resolution than ERA5. In the dataset used for this study, ERA5-Land has a spatial resolution of 0.1° × 0.1°, compared with 0.25° × 0.25° for ERA5 (Muñoz Sabater, 2019).

The higher spatial resolution results in a considerably denser grid over the study area. This difference is central to the comparison performed in this thesis, as one of the main objectives is to determine whether the finer spatial representation of ERA5-Land results in improved agreement with ground-based meteorological observations.

Because ERA5 and ERA5-Land are defined on different spatial grids, direct grid-point comparison requires spatial harmonisation. Similarly, validation against meteorological stations requires the gridded reanalysis data to be spatially associated with the observation locations. The procedures used for this purpose are described in Section 3.4.

3.2.3 DHMZ Meteorological Observations

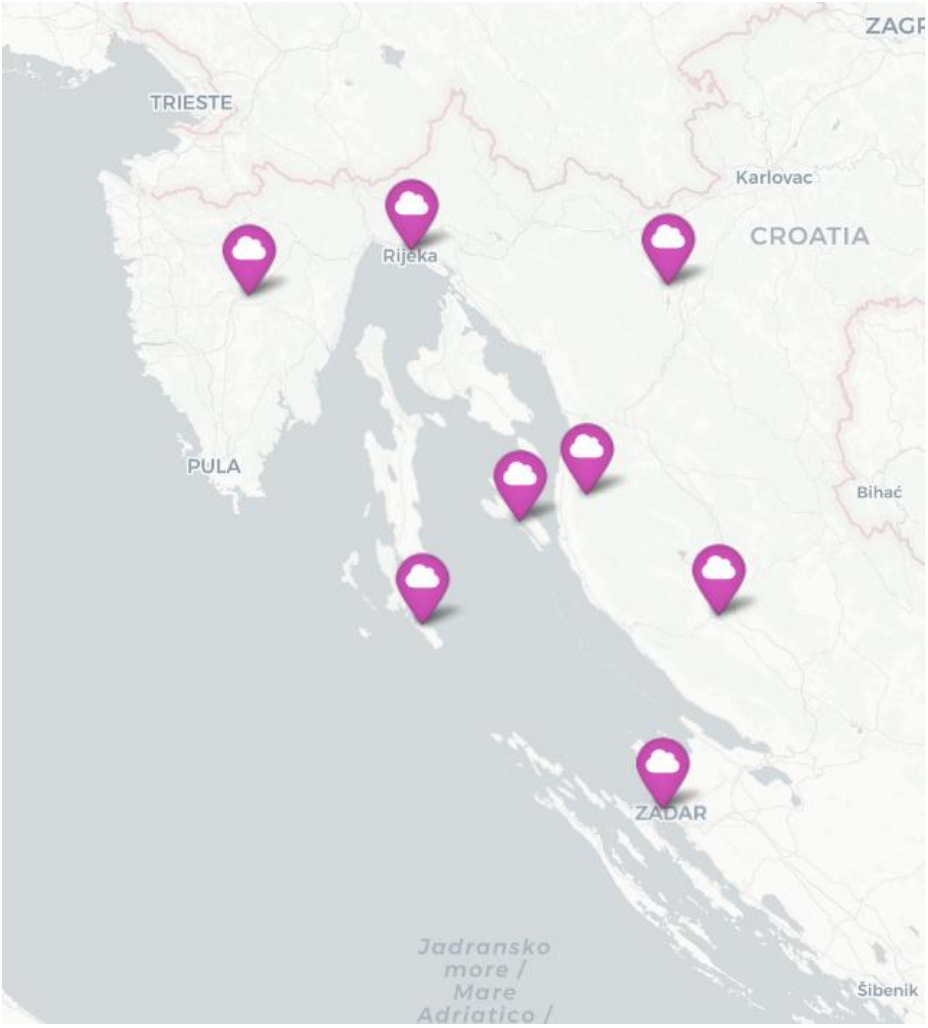

Figure 4. DHMZ station locations

Ground-based meteorological observations from the Croatian Meteorological and Hydrological Service (DHMZ) were used as the primary reference dataset. Unlike reanalysis data, which represent meteorological conditions on a spatial grid, DHMZ observations represent conditions measured at individual station locations.

The DHMZ dataset used in the analysis contains observations from multiple stations distributed across the study region, including coastal, island, inland and mountainous locations. This spatial distribution provides an opportunity to assess whether the performance of ERA5 and ERA5-Land varies according to geographical setting.

Station coordinates were used to associate the observational records with the corresponding reanalysis fields. Each DHMZ station was matched independently to the geographically nearest ERA5 and ERA5-Land grid point using the Haversine distance, as described in Section 3.4.

3.2.4 HOPS Meteorological Observations

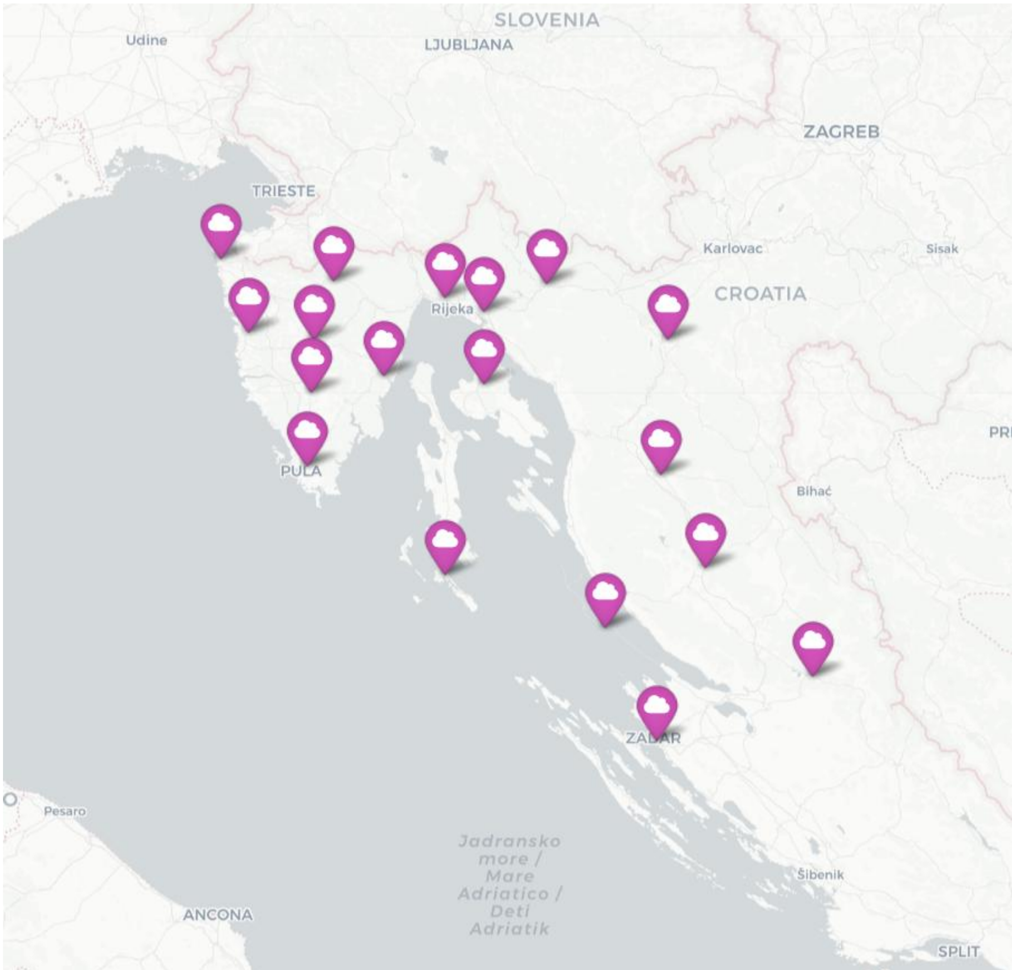

Figure 5. HOPS station locations.

The second observational dataset consists of measurements from automatic weather stations associated with HOPS transmission-network locations, primarily electrical substations. Measurement availability varied between HOPS locations, with observations generally becoming available around the middle of 2020.

The original meteorological measurements have a temporal resolution of one minute. For integration with the hourly reanalysis datasets, the observations were reduced to hourly resolution. For air temperature, relative humidity, wind speed, wind direction and air pressure, the hourly value was calculated using measurements recorded within a 20-minute interval centred on the full hour, from ten minutes before to ten minutes after it. Precipitation was represented by the accumulated precipitation during the preceding hour, while wind gusts were represented by the maximum gust during the preceding hour together with its corresponding direction.

An inconsistency was identified around the spring and autumn clock changes; these periods therefore required particular attention during temporal preprocessing and matching.

As with the DHMZ observations, the geographical coordinates of the HOPS stations were used to identify the nearest ERA5 and ERA5-Land grid points, as described in Section 3.4.

3.2.5 Meteorological Variables

The meteorological variables included in the analysis were selected according to their availability across the reanalysis and observational datasets. ERA5 provided air temperature, dew-point temperature, the zonal and meridional components of wind, total precipitation, mean sea-level pressure, and surface pressure. ERA5-Land provided the same variables except for mean sea-level pressure (Hersbach et al., 2023; Muñoz Sabater, 2019).

Relative humidity and wind speed were not used directly from the reanalysis datasets but were derived from the available variables (Alduchov & Eskridge, 1996). Relative humidity was calculated using air temperature and dew-point temperature, while wind speed was calculated from the zonal (u) and meridional (v) wind components.

$$\mathrm{RH} = 100\,\frac{\exp\left(\frac{17.625\,T_d}{243.04 + T_d}\right)}{\exp\left(\frac{17.625\,T}{243.04 + T}\right)}$$

$$\mathrm{WS} = \sqrt{u_{10}^2 + v_{10}^2}$$

The DHMZ observational dataset contained air temperature, relative humidity, wind speed, surface pressure, and total precipitation. The HOPS observations contained the same set of meteorological variables, with mean sea-level pressure provided instead of surface pressure. Consequently, validation was performed only between variables representing equivalent meteorological quantities in the corresponding observational and reanalysis datasets.

Table 1. Meteorological variables available from the ERA5, ERA5-Land, DHMZ, and HOPS datasets.

Meteorological variable	**ERA5**	**ERA5-Land**	**DHMZ**	**HOPS**
Air temperature	✓	✓	✓	✓
Dew-point temperature	✓	✓	—	—
Relative humidity	Derived	Derived	✓	✓
Zonal wind component (u)	✓	✓	—	—
Meridional wind component (v)	✓	✓	—	—
Wind speed	Derived	Derived	✓	✓
Total precipitation	✓	✓	✓	✓
Surface pressure	✓	✓	✓	—
Mean sea-level pressure	✓	—	—	✓

3.3 Data Preprocessing and Temporal Harmonisation

Before statistical comparisons could be performed, the datasets required preprocessing to ensure consistency in their spatial and temporal representations.

The first step consisted of selecting observations and reanalysis records belonging to the common study period. Date and time variables were converted to consistent datetime formats, after which records from the different datasets could be matched temporally. Particular attention was given to missing observations and to timestamps for which one dataset did not contain a corresponding value.

The temporal resolution also required harmonisation. ERA5 and ERA5-Land are available at hourly resolution, while the original HOPS meteorological observations were recorded at one-minute intervals and subsequently aggregated to hourly values according to the procedures described in Section 3.2.4.

For analyses involving daily observational data, hourly reanalysis values were aggregated to corresponding daily statistics before comparison. Only temporally overlapping observations were retained for the calculation of validation statistics.

Variables were additionally converted into common physical units where necessary. This ensured that differences identified during the subsequent analysis represented differences between the datasets rather than differences in their original conventions or units.

3.3.1 Precipitation-Specific Preprocessing

Total precipitation required additional dataset-specific preprocessing prior to temporal alignment and validation. ERA5 and ERA5-Land precipitation values were converted from metres to millimetres. DHMZ precipitation measurements were additionally divided by a factor of 10 to account for the scaling of precipitation values in the original observational dataset. The DHMZ precipitation records did not contain explicit rows for hours with no recorded precipitation. A complete hourly time series was therefore reconstructed for each station, with absent timestamps assigned a precipitation amount of 0 mm. Explicit zero values were also present in the original records because very small precipitation amounts could be rounded to zero. This reconstruction ensured that dry hours were represented consistently during subsequent temporal alignment with the reanalysis datasets.

ERA5-Land total precipitation required an additional deaccumulation procedure. The downloaded ERA5-Land precipitation values represented cumulative precipitation within accumulation periods rather than independent hourly totals (European Centre for Medium-Range Weather Forecasts [ECMWF], n.d.-b). Hourly precipitation was therefore obtained from differences between consecutive accumulated values at each grid point. To prevent erroneous precipitation estimates caused by gaps in the hourly time series, differences were calculated only when consecutive observations were separated by exactly one hour. During continuous accumulation, the hourly precipitation amount was calculated as the difference between the current and preceding accumulated values. When an accumulation reset occurred, identified by the current accumulated value being lower than the preceding value, the current value was retained as the precipitation amount following the reset. If the preceding hourly observation was missing, the resulting precipitation value was instead treated as unavailable, preventing differences across multi-hour gaps from being incorrectly interpreted as one-hour precipitation totals.

3.4 Spatial Matching and Interpolation

Spatial harmonisation represents an important component of the methodology because ERA5, ERA5-Land and the meteorological stations describe atmospheric conditions using different spatial representations. ERA5 and ERA5-Land provide values on regular grids, whereas DHMZ and HOPS observations correspond to specific geographical coordinates. Two spatial matching procedures were therefore applied depending on the type of comparison.

For the direct intercomparison between ERA5 and ERA5-Land, their different spatial resolutions had to be accounted for. ERA5-Land, with a resolution of 0.1° × 0.1°, contains substantially more grid points within the study region than ERA5 at 0.25° × 0.25°. In addition to comparison at naturally overlapping grid points, ERA5-Land values were spatially interpolated to the ERA5 grid, allowing the two products to be evaluated at a larger set of common geographical locations. Linear interpolation was used as the principal method, with nearest-neighbour interpolation applied where linear interpolation could not provide a valid value, particularly near the boundaries of the study area.

For validation against ground-based observations, spatial interpolation was not applied. Instead, each DHMZ and HOPS station was matched independently to the geographically nearest ERA5 and ERA5-Land grid point. The distance between each station and the surrounding reanalysis grid points was calculated using the Haversine formula, which accounts for the curvature of the Earth when determining the great-circle distance between two geographical coordinates. The grid point with the minimum distance to each station was selected, and its reanalysis time series was subsequently matched temporally with the corresponding station observations.

This approach preserves the original values of both reanalysis products during station validation while providing a consistent method for associating point-based observations with gridded meteorological data. Because the ERA5-Land grid is finer than the ERA5 grid, its selected grid points were generally located closer to the observational stations; however, the resulting station-to-grid distances were retained as part of the analysis rather than assumed to imply greater meteorological representativeness.

3.4.1 Elevation Adjustment

Differences between the elevation represented by reanalysis grid cells and the actual elevation of meteorological stations may contribute to discrepancies between reanalysis data and ground-based observations. Therefore, elevation-adjusted comparisons were additionally performed for air temperature, relative humidity, and pressure. Grid-cell elevations for ERA5 and ERA5-Land were derived from geopotential according to

$$h = \frac{z}{g},$$

where h is elevation in metres, z is geopotential in m^2 s^{-2}, and $g = 9.80665$ m s^{-2} is the standard acceleration due to gravity (ECMWF, n.d.-a). Elevations of the DHMZ stations were obtained from official DHMZ station information (Državni hidrometeorološki zavod [DHMZ], n.d.).

Air temperature

To reduce the influence of differences between station and reanalysis-grid elevations, air-temperature measurements from each dataset were independently adjusted to a common reference elevation at sea level. A standard environmental lapse rate of 6.5 °C km^{-1} was applied according to

$$T_{SL} = T + 0.0065h$$

where T_{SL} is the sea-level-adjusted temperature (°C), T is the original temperature (°C), and h is the elevation of the corresponding station or reanalysis grid cell in metres (Dutra et al., 2020). DHMZ observations were adjusted using the elevation of each meteorological station, while ERA5 and ERA5-Land temperatures were adjusted using the elevation of their respective grid cells. The resulting sea-level-equivalent temperatures were subsequently compared using the same validation procedure as the unadjusted data.

Relative humidity

Relative humidity was not adjusted directly. Instead, reanalysis air temperature and dew-point temperature were independently adjusted to station elevation. Air temperature was adjusted using a lapse rate of 0.0065 °C m^{-1}, while dew-point temperature was adjusted using a lapse rate of 0.0020 °C m^{-1}:

$$T_{d,\mathrm{adj}} = T_d + 0.0020\Delta h$$

$$T_{adj} = T + 0.0065\Delta h$$

Relative humidity was subsequently recalculated from the adjusted air and dew-point temperatures using

$$RH = 100\frac{\exp\left(\frac{17.625T_{d,\mathrm{adj}}}{243.04 + T_{d,\mathrm{adj}}}\right)}{\exp\left(\frac{17.625T_{\mathrm{adj}}}{243.04 + T_{\mathrm{adj}}}\right)}.$$

The same procedure was used for validation against both DHMZ and HOPS relative-humidity observations (Alduchov & Eskridge, 1996).

Pressure

An elevation adjustment was also investigated for the DHMZ pressure comparison. Since DHMZ provides surface pressure, surface-pressure values from DHMZ, ERA5, and

ERA5-Land were converted to approximate mean sea-level pressure using the standard-atmosphere barometric relationship:

$$p_0 = \frac{p}{(1 - 2.25577 \times 10^{-5} h)^{5.25588}},$$

where p is surface pressure, h is the corresponding station or grid-cell elevation, and p_0 is the estimated mean sea-level pressure (National Oceanic and Atmospheric Administration et al., 1976). This adjustment was not required for the HOPS pressure comparison because the HOPS dataset already provides mean sea-level pressure.

The elevation-adjusted analyses were compared with the corresponding unadjusted results to assess the extent to which elevation differences between observational stations and reanalysis grid cells influenced validation performance. The use of constant lapse rates and standard-atmosphere relationships represents a simplification of actual atmospheric conditions, which vary spatially and temporally (Dutra et al., 2020).

3.5 Statistical Evaluation

The agreement between the reanalysis products and observational datasets was evaluated using a combination of statistical indicators. Using several complementary metrics is important because no single statistic provides a complete description of model performance.

Bias was used to quantify systematic differences between reanalysis estimates and observations. A positive bias indicates systematic overestimation by the reanalysis product, while a negative bias indicates systematic underestimation.

Root Mean Square Error (RMSE) was used as an additional measure of error magnitude. Because errors are squared before averaging, RMSE gives greater weight to relatively large deviations and is consequently useful for identifying datasets in which occasional large errors occur.

Correlation coefficients were calculated to assess the degree to which temporal variations in the reanalysis datasets correspond to variations in the observational measurements. High correlation indicates that the reanalysis product reproduces the temporal behaviour of the observed variable, although it does not necessarily imply the absence of systematic bias.

The statistical significance of the Pearson correlation coefficients was additionally evaluated using associated p-values. All reported correlations were statistically significant ($p < 0.001$); individual p-values are therefore not reported separately.

The metrics were calculated separately for individual meteorological stations and reanalysis products. This allows performance differences that may be obscured by an overall average to be identified and enables the spatial variability of reanalysis accuracy to be examined.

3.6 Analysis Framework

The empirical analysis was conducted in two principal stages.

The first stage consisted of an intercomparison between ERA5 and ERA5-Land. This analysis was used to determine the degree of agreement between the two reanalysis products and to identify systematic spatial and temporal differences associated with their different spatial resolutions and land-surface representations.

The second stage consisted of validation against ground-based meteorological observations. DHMZ observations were used as the primary reference dataset, as they originate from the national meteorological monitoring network and provide measurements from dedicated meteorological stations. ERA5 and ERA5-Land data were compared with observations from eight DHMZ stations, with statistical performance evaluated separately by station and meteorological variable using bias, RMSE and correlation. Elevation-related adjustments were additionally examined for selected variables to assess the influence of differences between station and reanalysis-grid elevations on validation performance.

HOPS observations were used as a supplementary independent validation dataset. Although the HOPS network provides observations from a larger number of locations, its meteorological sensors are primarily associated with electricity-transmission infrastructure rather than a dedicated meteorological monitoring network. The HOPS analysis was therefore used to assess whether the principal patterns identified using the DHMZ observations were also evident across an independent and spatially broader station network.

This two-stage approach distinguishes differences between the two reanalysis products from their respective differences relative to observations. The use of a primary meteorological reference network together with supplementary independent observations further allows the consistency of the validation results to be assessed across different observational sources. The analysis therefore makes it possible to determine not only whether ERA5 and ERA5-Land produce similar meteorological estimates, but also whether the higher spatial resolution of ERA5-Land translates into systematically improved agreement with locally measured conditions.

4. RESULTS

4.1 ERA5 and ERA5-Land Intercomparison

An initial intercomparison was performed between ERA5 and ERA5-Land to assess the consistency of the two reanalysis products before their validation against ground-based meteorological observations. Since ERA5 and ERA5-Land are provided on different spatial grids, with resolutions of 0.25° × 0.25° and 0.1° × 0.1°, respectively, the original grids coincide at only a limited number of locations within the study area. Eight overlapping land grid points were identified and used for an initial direct comparison. Subsequently, ERA5-Land was linearly interpolated to the ERA5 grid, allowing the comparison to be extended over a substantially larger portion of the study area. The interpolation used the original ERA5-Land grid points as input locations and ERA5 grid points as target locations.

The comparison considered 2 m air temperature, 2 m dew-point temperature, relative humidity, 10 m wind components and derived wind speed, as well as total precipitation. Bias was consistently defined as the ERA5-Land value minus the corresponding ERA5 value, meaning that positive values indicate higher estimates by ERA5-Land and negative values indicate lower estimates.

4.1.1 Comparison at Overlapping Grid Points

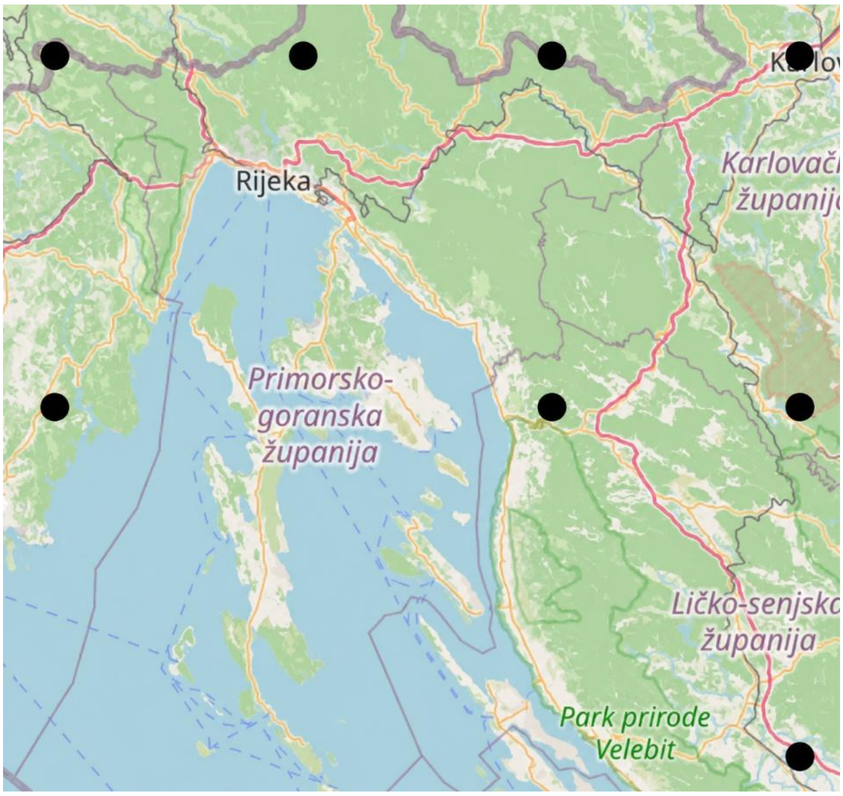

Figure 6. Overlapping grid points.

Overall, ERA5 and ERA5-Land showed a high degree of agreement at the eight overlapping grid points. Particularly strong correspondence was observed for temperature, atmospheric moisture and wind variables, with Pearson correlation coefficients generally exceeding 0.93.

For 2 m air temperature, ERA5-Land exhibited a mean bias of −0.56 °C, indicating slightly lower temperatures than ERA5. The relationship between the datasets remained very strong, with a Pearson correlation coefficient of 0.9874. For 2 m dew-point temperature, the systematic difference was smaller, with a mean bias of −0.30 °C, an RMSE of 1.20 °C, and a correlation coefficient of 0.9867.

Relative humidity, derived from air temperature and dew-point temperature, also showed strong agreement. ERA5-Land produced values approximately 1.07 percentage points higher than ERA5 on average. The RMSE was 5.54 percentage points, while the Pearson correlation coefficient reached 0.9518. Monthly differences showed greater variability than those observed for temperature and dew point and changed sign during the study period, although no persistent temporal trend was identified.

The individual 10 m wind components displayed similarly strong agreement. The U-component had a mean bias of only 0.070 m s^{-1}, an RMSE of 0.635 m s^{-1}, and a correlation coefficient of 0.9536. The V-component showed an even smaller systematic difference, with a mean bias of 0.027 m s^{-1}, an RMSE of 0.560 m s^{-1}, and a correlation coefficient of 0.9585.

When the two wind components were combined to obtain wind-speed magnitude, the difference between the datasets became more pronounced. ERA5-Land produced lower wind speeds on average, with a mean bias of −0.400 m s^{-1}. Nevertheless, agreement remained strong, with an RMSE of 0.683 m s^{-1} and a Pearson correlation coefficient of 0.9328.

Table 2. Statistical comparison of ERA5 and ERA5-Land at the overlapping grid points.

Variable	Mean bias	RMSE	Pearson r
2 m air temperature	−0.56 °C	1.44 °C	0.9874
2 m dew-point temperature	−0.30 °C	1.20 °C	0.9867
Relative humidity	+1.07 pp	5.54 pp	0.9518
U wind component	+0.070 m s^{-1}	0.635 m s^{-1}	0.9536
V wind component	+0.027 m s^{-1}	0.560 m s^{-1}	0.9585
Mean wind speed	−0.400 m s^{-1}	0.683 m s^{-1}	0.9328
Total precipitation	+0.00018 mm	0.0017 mm	0.4863

4.1.2 Comparison Following Spatial Interpolation

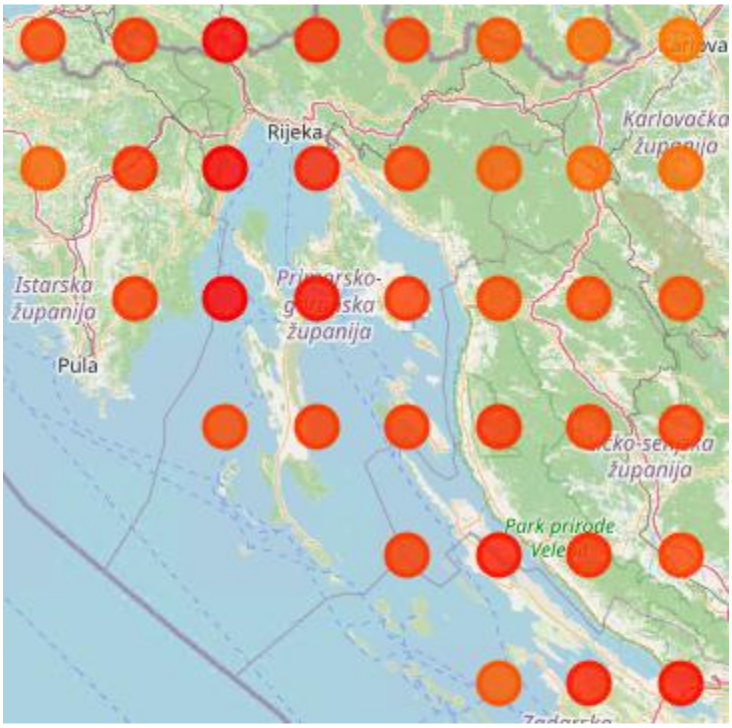

Figure 7. Locations of interpolated ERA5-Land points

To extend the comparison beyond the limited number of naturally overlapping grid points, ERA5-Land data were spatially interpolated onto the ERA5 grid. Linear interpolation was performed using the griddata() function from the SciPy library, with ERA5-Land grid points serving as the source locations and ERA5 grid points as the target locations (Virtanen et al., 2020). The interpolation was applied separately at each hourly time step, substantially increasing the number of locations at which the two datasets could be directly compared.

For 2 m air temperature, the interpolated ERA5-Land data showed a mean bias of −0.6303 °C, indicating that ERA5-Land remained slightly colder than ERA5 on average. The RMSE was 1.3898 °C, while the Pearson correlation coefficient was 0.9884, demonstrating very strong agreement between the two datasets. These values were highly consistent with those obtained at the overlapping grid points, where the mean bias, RMSE and correlation coefficient were −0.56 °C, 1.44 °C and 0.9874, respectively. The slightly lower RMSE and marginally higher correlation following interpolation indicate that extending the comparison spatially did not reduce the overall agreement between the datasets.

Relative humidity also showed strong agreement between ERA5 and interpolated ERA5-Land. The mean bias, calculated as interpolated ERA5-Land minus ERA5, was +0.86 percentage points, indicating a small overall tendency towards higher relative humidity values in ERA5-Land. The RMSE was 5.83 percentage points, while the Pearson correlation coefficient was 0.9394, indicating a strong correspondence between the two datasets. Compared with the analysis at the eight overlapping grid points, where the mean bias was +1.07 percentage points, the RMSE was 5.54 percentage points and the correlation coefficient was 0.9518, the results remained broadly similar after interpolation. The slightly lower correlation and higher RMSE indicate a modest reduction in agreement when the comparison was extended across the ERA5 grid, although the overall relationship between the datasets remained strong.

Mean wind speed exhibited a small negative bias following interpolation, with interpolated ERA5-Land values being on average 0.33 m s^{-1} lower than ERA5. The RMSE was 0.74 m s^{-1}, and the Pearson correlation coefficient was 0.9355, indicating strong agreement in wind-speed variability between the two datasets. These results were comparable to those obtained at the overlapping grid points, where the mean bias was −0.40 m s^{-1}, the RMSE was 0.68 m s^{-1} and the correlation coefficient was 0.9328. Thus, extending the analysis through spatial interpolation produced only minor changes in the statistical relationship between ERA5 and ERA5-Land wind speed.

Total precipitation showed an overall mean bias close to zero following interpolation (−0.0039 mm) and an RMSE of 0.2055 mm. The Pearson correlation coefficient was 0.9687, indicating a strong correspondence between ERA5 and interpolated ERA5-Land precipitation values. Unlike temperature, relative humidity and wind speed, the precipitation statistics differed substantially from those obtained using only the eight overlapping grid points, particularly in terms of correlation. This indicates that the precipitation comparison was more sensitive to the spatial comparison procedure. Given the highly localized and intermittent nature of precipitation, these differences should be interpreted with greater caution than those observed for the other meteorological variables.

Table 3. Comparison of statistical indicators obtained from the overlapping-grid and interpolated ERA5–ERA5-Land analyses.

Variable	**Bias: overlapping**	**Bias: interpolated**	**RMSE: overlapping**	**RMSE: interpolated**	***r*: overlapping**	***r*: interpolated**
2 m air temperature	−0.56 °C	−0.63 °C	1.44 °C	1.39 °C	0.9874	0.9884
Relative humidity	+1.07 pp	+0.86 pp	5.54 pp	5.83 pp	0.9518	0.9394
Mean wind speed	−0.40 m s^{-1}	−0.33 m s^{-1}	0.68 m s^{-1}	0.74 m s^{-1}	0.9328	0.9355
Total precipitation	+0.00018 mm	−0.0039 mm	0.0017 mm	0.2055 mm	0.4863	0.9687

4.2 Validation Against DHMZ Observations

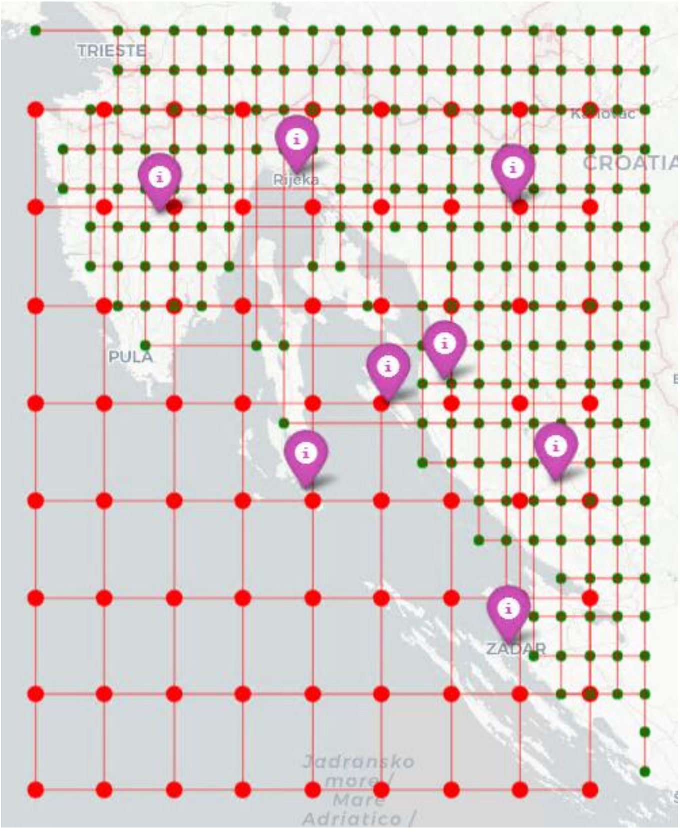

Figure 8. Position of DHMZ stations relative to ERA5 grids

Following the intercomparison between ERA5 and ERA5-Land, both reanalysis products were validated against ground-based observations from eight DHMZ meteorological stations. For each station, the geographically nearest ERA5 and ERA5-Land grid points were identified using the Haversine distance between their coordinates. The corresponding reanalysis and station observations were then temporally aligned, and only simultaneously available measurements were included in the statistical evaluation.

4.2.1 Air Temperature

Both ERA5 and ERA5-Land showed strong agreement with observed 2 m air temperature across the eight DHMZ stations. The average correlation coefficients were 0.959 for ERA5 and 0.958 for ERA5-Land, indicating that both reanalysis products closely reproduced the temporal variability of observed temperature. Their overall error magnitudes were also similar. ERA5 produced an average RMSE of 3.456 °C, compared with 3.591 °C for ERA5-Land. The average biases were +0.682 °C for ERA5 and −0.635 °C for ERA5-Land, indicating a slight overall tendency for ERA5 to overestimate and ERA5-Land to underestimate observed temperature.

Table 4. ERA5 (Land) vs DHMZ temperature metrics.

Station	ERA5 distance (km)	ERA5-Land distance (km)	ERA5 Bias (°C)	ERA5 RMSE (°C)	ERA5 Corr	ERA5-Land Bias (°C)	ERA5-Land RMSE (°C)	ERA5-Land Corr
Mali Lošinj	4.24	19.480	-0.220	2.260	0.952	-1.360	2.230	0.969
Gospić	11.26	5.910	2.690	3.840	0.951	0.740	3.120	0.940
Pazin	4.40	5.760	1.950	3.650	0.943	1.610	3.580	0.936
Ogulin	2.60	4.490	-0.070	2.350	0.964	-0.410	2.640	0.955
Zadar	13.79	7.790	-1.240	2.010	0.977	-1.280	2.160	0.975
Rijeka	10.66	7.760	-3.080	3.440	0.980	-4.360	4.710	0.975
Zavižan	7.45	2.540	7.070	7.590	0.938	4.620	5.240	0.950
Rab	1.60	11.480	-1.640	2.510	0.966	-4.640	5.050	0.965
Average	7.00	8.151	0.682	3.456	0.959	-0.635	3.591	0.958

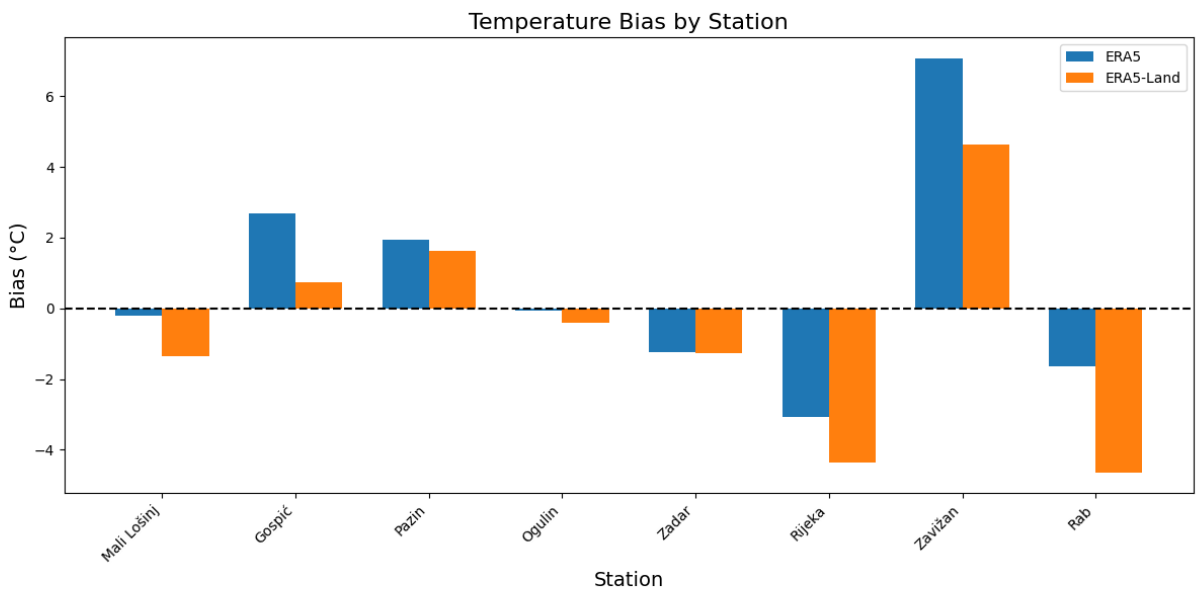

Figure 9. Temperature bias (ERA5-DHMZ).

Performance nevertheless varied substantially between individual stations. The most pronounced discrepancies occurred at Zavižan, where ERA5 exhibited a bias of +7.07 °C and an RMSE of 7.59 °C, while ERA5-Land produced a bias of +4.62 °C and an RMSE of 5.24 °C. Despite these comparatively large errors, correlations remained high at 0.938 and 0.950, respectively. At Rijeka, by contrast, both products underestimated temperature, with biases of −3.08 °C for ERA5 and −4.36 °C for ERA5-Land. ERA5 also achieved a lower RMSE at this station (3.44 °C compared with 4.71 °C), despite the ERA5-Land grid point being geographically closer to the station.

Overall, neither reanalysis product consistently outperformed the other for air temperature. ERA5 achieved a slightly lower average RMSE, whereas the two products produced virtually identical average correlations. ERA5-Land performed substantially better at Zavižan but exhibited larger negative biases at several coastal stations, including Rijeka and Rab. The considerable station-to-station variability indicates that the overall averages conceal important spatial differences in performance.

4.2.2 Relative Humidity

Relative humidity derived from ERA5 and ERA5-Land was compared with the relative humidity measurements provided directly by the DHMZ stations. Both reanalysis products showed moderate to strong agreement with the observations, although their performance was noticeably weaker than for air temperature. The average correlation coefficient was 0.705 for ERA5 and 0.690 for ERA5-Land. ERA5 also exhibited a lower average bias (+1.586 percentage points) than ERA5-Land (+3.445 percentage points) and a slightly lower average RMSE (15.236 percentage points compared with 16.305 percentage points). Overall, ERA5 therefore showed a modest advantage over ERA5-Land in reproducing observed relative humidity.

As with temperature, however, performance varied considerably between stations. The largest positive biases occurred at Rijeka, reaching +12.15 percentage points for ERA5 and +15.59 percentage points for ERA5-Land, while both products substantially underestimated relative humidity at Zavižan, with biases of −10.52 and −8.80 percentage points, respectively. Zavižan also exhibited the largest RMSE values, at 21.29 percentage points for ERA5 and 20.56 percentage points for ERA5-Land, as well as the weakest correlations, approximately 0.49 for both datasets.

Considerable differences between the two products were also apparent at individual stations. At Mali Lošinj, ERA5-Land achieved a substantially lower RMSE and higher correlation than ERA5, whereas at Gospić, Ogulin, Rijeka and Rab, ERA5 generally showed stronger statistical agreement with the observations. Consequently, the higher spatial resolution of ERA5-Land did not translate into consistently improved relative-humidity performance across the investigated stations.

Table 5. ERA5 (Land) vs DHMZ relative humidity metrics.

Station	ERA5 distance (km)	ERA5-Land distance (km)	ERA5 Bias (pp)	ERA5 RMSE (pp)	ERA5 Corr	ERA5-Land Bias (pp)	ERA5-Land RMSE (pp)	ERA5-Land Corr
Mali Lošinj	4.24	19.480	5.580	15.110	0.545	4.080	13.020	0.661
Gospić	11.26	5.910	-2.240	14.550	0.741	3.460	16.250	0.689
Ogulin	2.60	4.490	-0.480	12.290	0.821	1.340	14.430	0.748
Pazin	4.40	5.760	-2.080	14.620	0.803	-3.070	15.460	0.770
Zadar	13.79	7.790	1.930	12.190	0.730	3.290	12.440	0.737
Rijeka	10.66	7.760	12.150	16.950	0.789	15.590	20.050	0.769
Zavižan	7.45	2.540	-10.520	21.290	0.490	-8.800	20.560	0.499
Rab	1.60	11.480	8.350	14.890	0.723	11.670	18.230	0.651
Average	7.00	8.151	1.586	15.236	0.705	3.445	16.305	0.690

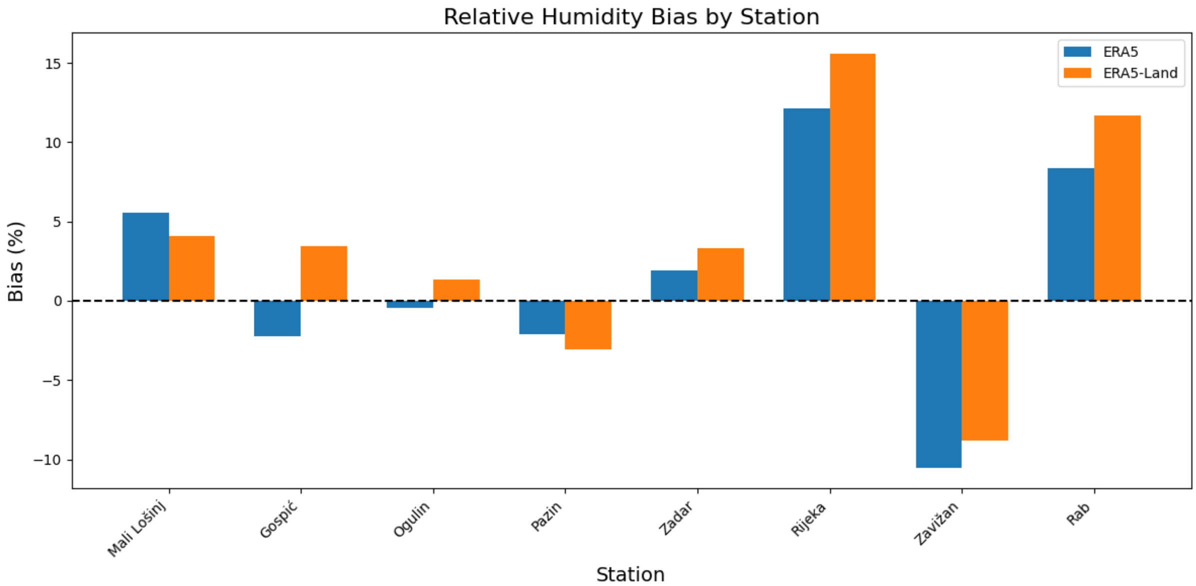

Figure 10. Relative Humidity Bias (ERA5-DHMZ).

4.2.3 Mean Wind Speed

Mean wind speed derived from ERA5 and ERA5-Land was compared with the corresponding wind-speed observations from the DHMZ stations. Both reanalysis products showed moderate agreement with the observations and produced very similar overall results. The average correlation coefficient was 0.590 for ERA5 and 0.597 for ERA5-Land, while the average RMSE was 2.018 m s^{-1} and 1.930 m s^{-1}, respectively. ERA5 exhibited a small positive average bias of +0.12 m s^{-1}, whereas ERA5-Land showed a small negative average bias of −0.226 m s^{-1}. Thus, ERA5-Land achieved a marginally lower overall RMSE and slightly higher correlation, although the differences between the two products were small.

Table 6. ERA5 (Land) vs DHMZ mean wind speed metrics.

Station	ERA5 distance (km)	ERA5-Land distance (km)	ERA5 Bias (m/s)	ERA5 RMSE (m/s)	ERA5 Corr	ERA5-Land Bias (m/s)	ERA5-Land RMSE (m/s)	ERA5-Land Corr
Gospić	11.26	5.910	0.40	1.170	0.575	-0.060	0.95	0.648
Mali Lošinj	4.24	19.480	1.43	2.420	0.642	1.500	2.63	0.621
Ogulin	2.60	4.490	0.20	1.210	0.539	-0.230	1.10	0.540
Rijeka	10.66	7.760	0.54	1.400	0.643	-0.330	1.12	0.610
Rab	1.60	11.480	0.57	2.050	0.596	-0.410	1.91	0.591
Zadar	13.79	7.790	-0.23	1.880	0.558	-0.060	1.83	0.588
Pazin	4.40	5.760	1.37	2.040	0.501	1.220	1.83	0.513
Zavižan	7.45	2.540	-3.32	3.970	0.664	-3.440	4.07	0.664
Average	7.00	8.151	0.12	2.018	0.590	-0.226	1.93	0.597

The relatively small average biases concealed considerably larger differences between individual stations. Both products substantially underestimated wind speed at Zavižan, with biases of −3.32 m s^{-1} for ERA5 and −3.44 m s^{-1} for ERA5-Land. This station also exhibited the largest RMSE values, reaching 3.97 m s^{-1} and 4.07 m s^{-1}, respectively. Nevertheless, both products achieved a correlation coefficient of 0.664 at Zavižan, the highest ERA5 correlation among the investigated stations. This combination of relatively high correlation and substantial negative bias indicates that the reanalysis products captured variations in wind speed more successfully than their absolute magnitude.

In contrast, both datasets overestimated wind speed at Mali Lošinj and Pazin. Biases at Mali Lošinj were +1.43 m s^{-1} for ERA5 and +1.50 m s^{-1} for ERA5-Land, while at Pazin they reached +1.37 and +1.22 m s^{-1}, respectively. ERA5-Land produced particularly small errors at Gospić, where its bias was only −0.06 m s^{-1} and its RMSE was 0.95 m s^{-1}, the lowest RMSE among the station-product combinations. It also reduced both bias and RMSE relative to ERA5 at Rijeka. Overall, ERA5-Land provided a small advantage in terms of average RMSE and correlation, but neither product consistently outperformed the other across all stations.

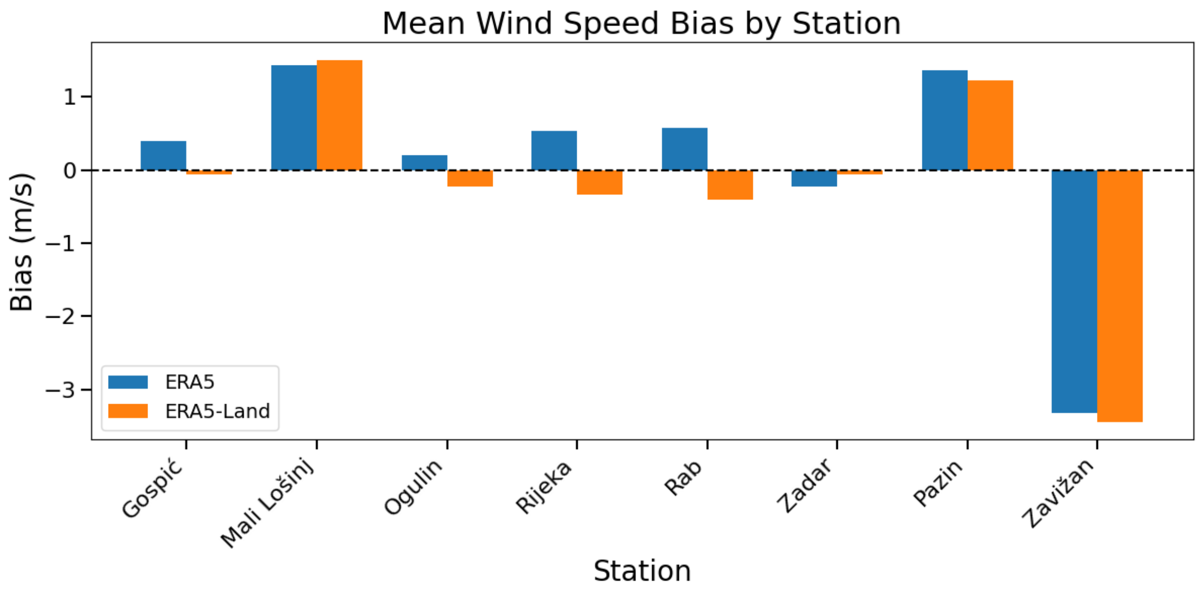

Figure 11. Mean Wind Speed Bias (ERA5-DHMZ).

4.2.4 Total Precipitation

Total precipitation showed weaker agreement with the DHMZ observations than air temperature, relative humidity and mean wind speed. In contrast to the other variables, however, ERA5 and ERA5-Land produced almost identical overall precipitation statistics. The average bias was +0.094 mm for ERA5 and +0.095 mm for ERA5-Land, indicating only a small overall tendency to overestimate observed precipitation. The average RMSE values were likewise nearly identical, at 1.408 mm for ERA5 and 1.409 mm for ERA5-Land. Average correlation coefficients were 0.325 and 0.320, respectively, indicating relatively weak correspondence between the temporal variability of reanalysis and observed precipitation.

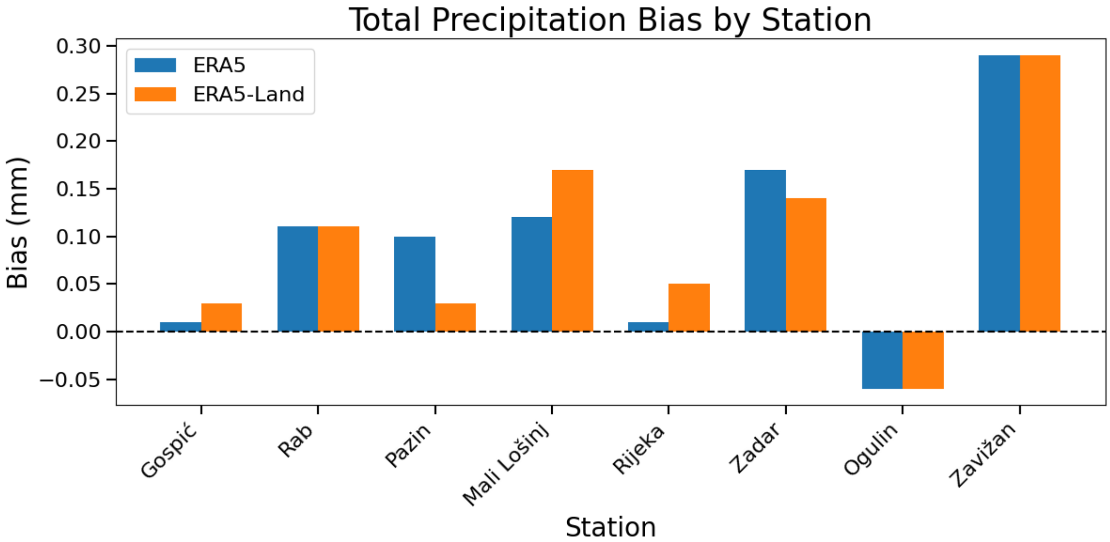

Figure 12. Total Precipitation Bias (ERA5-DHMZ)

Differences between the two reanalysis products remained small at the individual stations. The lowest biases were observed at Ogulin, where both ERA5 and ERA5-Land produced a bias of −0.06 mm, while the largest positive biases occurred at Zavižan, reaching +0.29 mm for both products. At most other stations, biases were positive but remained below +0.20 mm. The largest RMSE values occurred at Rijeka, reaching 1.87 mm for ERA5 and 1.90 mm for ERA5-Land, whereas the lowest values were approximately 1.16 mm at Ogulin and Zavižan.

Correlation showed greater variation between stations than bias. The highest correlations were observed at Ogulin, with coefficients of 0.445 for ERA5 and 0.438 for ERA5-Land, while the lowest occurred at Zavižan, at 0.182 and 0.173, respectively. Although ERA5 achieved a marginally higher average correlation, the difference between the two products was small, and neither dataset consistently outperformed the other across all stations. Overall, the results indicate that ERA5 and ERA5-Land exhibited very similar performance for total precipitation, with small mean biases and comparable RMSE values but considerably weaker temporal correlations than those obtained for the other meteorological variables.

Table 7. ERA5 (Land) vs DHMZ total precipitation metrics.

Station	ERA5 distance (km)	ERA5-Land distance (km)	ERA5 Bias (mm)	ERA5 RMSE (mm)	ERA5 Corr	ERA5-Land Bias (mm)	ERA5-Land RMSE (mm)	ERA5-Land Corr
Gospić	11.26	5.910	0.010	1.210	0.397	0.030	1.220	0.386
Rab	1.60	11.480	0.110	1.600	0.326	0.110	1.580	0.341

Station	ERA5 distance (km)	ERA5-Land distance (km)	ERA5 Bias (mm)	ERA5 RMSE (mm)	ERA5 Corr	ERA5-Land Bias (mm)	ERA5-Land RMSE (mm)	ERA5-Land Corr
Pazin	4.40	5.760	0.100	1.440	0.303	0.030	1.420	0.301
Mali Lošinj	4.24	19.480	0.120	1.320	0.330	0.170	1.350	0.311
Rijeka	10.66	7.760	0.010	1.870	0.370	0.050	1.900	0.348
Zadar	13.79	7.790	0.170	1.500	0.248	0.140	1.470	0.258
Ogulin	2.60	4.490	-0.060	1.160	0.445	-0.060	1.160	0.438
Zavižan	7.45	2.540	0.290	1.160	0.182	0.290	1.170	0.173
Average	7.00	8.151	0.094	1.408	0.325	0.095	1.409	0.320

4.2.5 Surface Pressure

Surface pressure exhibited very strong temporal agreement between the reanalysis products and the DHMZ observations. Average correlation coefficients exceeded 0.98 for both ERA5 and ERA5-Land, with correlations above 0.97 at seven of the eight investigated stations. Despite this strong temporal agreement, substantially larger differences were observed in the absolute pressure values. The average RMSE was 26.60 hPa for ERA5 and 26.34 hPa for ERA5-Land, while the corresponding average biases were +5.69 hPa and −5.72 hPa, respectively. The two products therefore showed very similar overall error magnitudes, but with opposite signs in their average systematic deviations.

Table 8. ERA5 (Land) vs DHMZ surface pressure metrics.

Station	ERA5 distance (km)	ERA5-Land distance (km)	ERA5 Bias (hPa)	ERA5 RMSE (hPa)	ERA5 Corr	ERA5-Land Bias (hPa)	ERA5-Land RMSE (hPa)	ERA5-Land Corr
Gospić	11.26	5.910	6.510	6.610	0.987	-1.860	2.100	0.990
Mali Lošinj	4.24	19.480	5.250	5.290	0.997	-9.390	9.420	0.995

Station	ERA5 distance (km)	ERA5-Land distance (km)	ERA5 Bias (hPa)	ERA5 RMSE (hPa)	ERA5 Corr	ERA5-Land Bias (hPa)	ERA5-Land RMSE (hPa)	ERA5-Land Corr
Ogulin	2.60	4.490	-13.790	13.820	0.993	-8.380	8.450	0.991
Rijeka	10.66	7.760	-34.300	34.310	0.991	-41.850	41.870	0.979
Rab	1.60	11.480	-17.240	17.250	0.996	-58.500	58.520	0.978
Zadar	13.79	7.790	-18.180	18.190	0.996	-7.980	8.010	0.996
Pazin	4.40	5.760	9.220	9.260	0.994	6.890	6.970	0.990
Zavižan	7.45	2.540	108.010	108.050	0.894	75.330	75.360	0.941
Average	7.00	8.151	5.685	26.598	0.981	-5.718	26.338	0.982

The magnitude and direction of the bias varied considerably between stations. The most pronounced discrepancy occurred at Zavižan, where ERA5 exhibited a bias of +108.01 hPa and an RMSE of 108.05 hPa, while ERA5-Land produced a bias of +75.33 hPa and an RMSE of 75.36 hPa. Nevertheless, correlations remained relatively high at this station, reaching 0.894 for ERA5 and 0.941 for ERA5-Land. ERA5-Land therefore substantially reduced the absolute error at Zavižan while also providing stronger temporal agreement.

Large negative biases were also observed at Rijeka, where the bias reached −34.30 hPa for ERA5 and −41.85 hPa for ERA5-Land. At Rab, the difference between the products was particularly pronounced: ERA5 produced a bias of −17.24 hPa, whereas the ERA5-Land bias reached −58.50 hPa, accompanied by an increase in RMSE from 17.25 to 58.52 hPa. In contrast, relatively small errors were observed at several other stations. At Gospić, for example, RMSE was 6.61 hPa for ERA5 and only 2.10 hPa for ERA5-Land, while both products also produced comparatively low RMSE values at Mali Lošinj and Pazin.

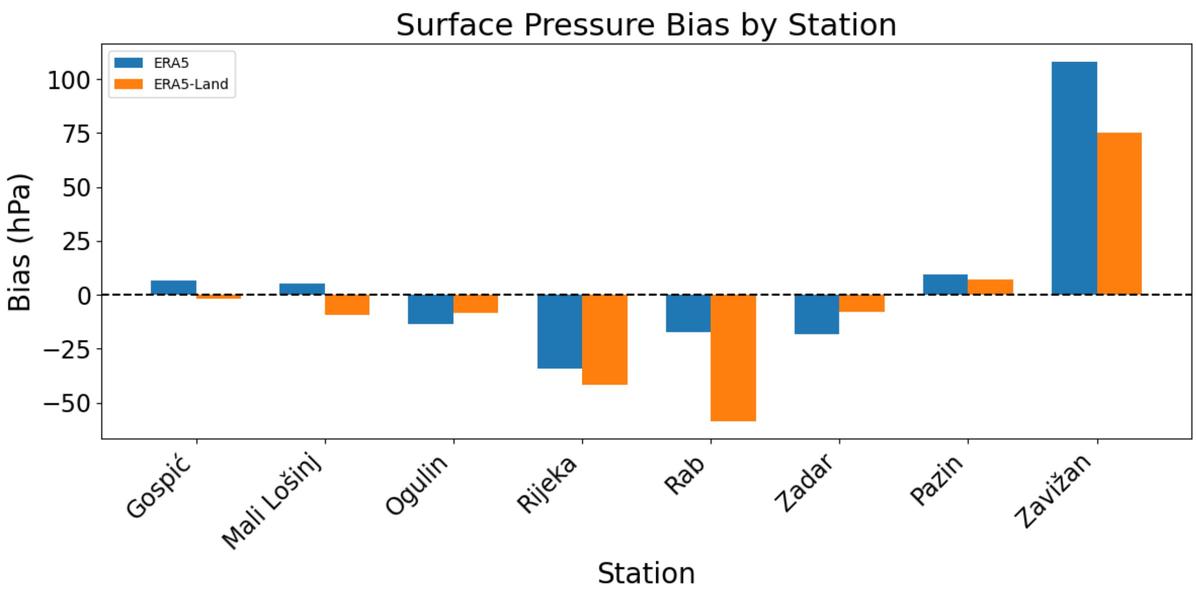

Figure 13. Surface Pressure Bias (ERA5-DHMZ)

Overall, ERA5 and ERA5-Land captured the temporal variability of surface pressure very closely, but their ability to reproduce its absolute magnitude differed considerably between stations. Neither product consistently outperformed the other: ERA5-Land substantially reduced the errors at stations such as Gospić, Ogulin, Zadar and Zavižan, whereas ERA5 performed better at Mali Lošinj, Rijeka and particularly Rab. The combination of very high correlations and large station-specific biases indicates that systematic differences in pressure level, rather than an inability to reproduce temporal variability, constituted the principal source of disagreement.

4.2.6 Effect of Elevation Adjustment

The baseline validation revealed substantial station-to-station differences in the magnitude of the errors, particularly for air temperature and surface pressure. Since the elevation represented by a reanalysis grid cell may differ considerably from the actual elevation of a meteorological station, an additional analysis was performed to examine the influence of this elevation mismatch on the validation results. The elevation-adjustment procedures described in Section 3.4.1 were applied to air temperature, relative humidity and surface pressure, after which the statistical evaluation was repeated using the same metrics as in the baseline analysis. The adjusted results were subsequently compared with the corresponding unadjusted results to assess the extent to which differences in elevation contributed to the observed discrepancies.

4.2.6.1 Air Temperature

The adjustment to a common sea-level reference substantially reduced the temperature errors for both reanalysis products. For ERA5, the average bias decreased from +0.682 °C in the original comparison to +0.296 °C after adjustment, while the average RMSE decreased from 3.456 °C to 2.504 °C. A similar improvement was observed for ERA5-Land, for which the average bias changed from −0.635 °C to −0.315 °C and the average RMSE decreased from 3.591 °C to 2.669 °C. The average correlation coefficients remained unchanged at 0.959 for ERA5 and 0.958 for ERA5-Land, indicating that the adjustment primarily reduced differences in absolute temperature magnitude without affecting the temporal correspondence with the observations.

Table 9. ERA5 (Land) vs DHMZ altitude-corrected temperature metrics.

Station	ERA5 distance (km)	ERA5-Land distance (km)	ERA5 Bias (°C)	ERA5 RMSE (°C)	ERA5 Corr	ERA5-Land Bias (°C)	ERA5-Land RMSE (°C)	ERA5-Land Corr
Mali Lošinj	4.24	19.480	-0.520	2.300	0.952	-1.330	2.210	0.969
Gospić	11.26	5.910	2.280	3.560	0.951	1.170	3.250	0.940
Pazin	4.40	5.760	1.430	3.400	0.943	1.490	3.520	0.936
Ogulin	2.60	4.490	0.650	2.440	0.964	0.300	2.620	0.955
Zadar	13.79	7.790	-0.220	1.600	0.977	-1.550	2.330	0.975
Rijeka	10.66	7.760	-1.110	1.900	0.980	-1.860	2.590	0.975
Zavižan	7.45	2.540	0.530	2.810	0.938	0.440	2.510	0.950
Rab	1.60	11.480	-0.670	2.020	0.966	-1.180	2.320	0.965
Average	7.00	8.151	0.296	2.504	0.959	-0.315	2.669	0.958

The most substantial improvement occurred at Zavižan, which had exhibited the largest temperature errors in the original comparison. ERA5 bias decreased from +7.07 °C to +0.53 °C, accompanied by a reduction in RMSE from 7.59 °C to 2.81 °C. ERA5-Land showed a similar improvement, with bias decreasing from +4.62 °C to +0.44 °C and RMSE from 5.24 °C to 2.51 °C. Considerable reductions were also observed at several coastal stations. At Rijeka, ERA5 RMSE decreased from 3.44 °C to 1.90 °C, while ERA5-Land RMSE decreased from 4.71 °C to 2.59 °C. At Rab, the corresponding reductions were from 2.51 °C to 2.02 °C for ERA5 and from 5.05 °C to 2.32 °C for ERA5-Land.

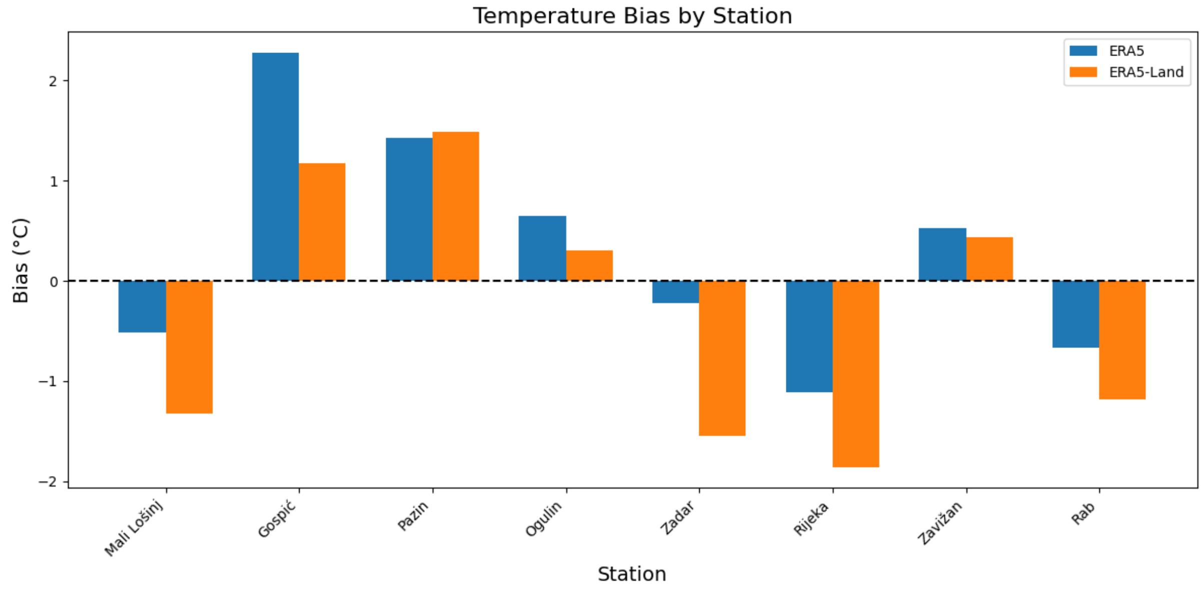

Figure 14. Altitude-Corrected Temperature Bias (ERA5-DHMZ)

The effect of the adjustment was not uniformly beneficial at every station. At Ogulin, ERA5 RMSE increased slightly from 2.35 °C to 2.44 °C, while ERA5-Land RMSE remained nearly unchanged, decreasing marginally from 2.64 °C to 2.62 °C. At Pazin, improvements were comparatively small, with ERA5 RMSE decreasing from 3.65 °C to 3.40 °C and ERA5-Land RMSE from 3.58 °C to 3.52 °C. Nevertheless, the overall reduction in both average bias and RMSE demonstrates that differences in the elevations represented by the station and reanalysis data contributed substantially to the temperature discrepancies observed in the original comparison.

Overall, adjustment to a common sea-level reference improved the agreement of both reanalysis products with the DHMZ observations, particularly at stations with large initial temperature biases. ERA5 retained a slightly lower average RMSE than ERA5-Land after adjustment, while both products exhibited considerably smaller average biases. The essentially unchanged correlation coefficients further indicate that the principal effect of the elevation adjustment was the reduction of systematic temperature offsets rather than a change in the representation of temporal variability.

4.2.6.2 Relative Humidity

Following the elevation-based adjustment of reanalysis temperature and dew-point temperature, relative humidity was recalculated and compared with the original DHMZ observations. The adjustment resulted in a moderate reduction in overall error magnitude for both reanalysis products. The average ERA5 RMSE decreased from 15.236 to 14.395 percentage points, while the ERA5-Land RMSE decreased from 16.305 to 14.784 percentage points. The effect on average bias differed between the two datasets. For ERA5, the average bias increased from +1.586 to +2.299 percentage points, whereas for ERA5-Land it decreased from +3.445 to +2.184 percentage points.

Average correlations remained essentially unchanged, decreasing slightly from 0.705 to 0.702 for ERA5 and from 0.690 to 0.688 for ERA5-Land. Thus, the elevation adjustment reduced the overall magnitude of relative-humidity errors but did not improve the temporal correspondence with the observations.

Table 10. ERA5 (Land) vs DHMZ altitude-corrected relative humidity metrics.

Station	ERA5 distance (km)	ERA5-Land distance (km)	ERA5 Bias (pp)	ERA5 RMSE (pp)	ERA5 Corr	ERA5-Land Bias (pp)	ERA5-Land RMSE (pp)	ERA5-Land Corr
Mali Lošinj	4.24	19.480	6.520	15.480	0.546	3.980	12.990	0.661
Gospić	11.26	5.910	-0.880	14.460	0.741	1.950	15.900	0.689
Ogulin	2.60	4.490	-2.940	12.600	0.820	-1.150	14.350	0.747
Pazin	4.40	5.760	-0.420	14.370	0.804	-2.680	15.370	0.771
Zadar	13.79	7.790	-1.150	11.970	0.732	4.170	12.760	0.736
Rijeka	10.66	7.760	5.860	13.240	0.790	7.250	14.270	0.770
Zavižan	7.45	2.540	5.970	19.510	0.457	2.860	19.080	0.478
Rab	1.60	11.480	5.430	13.530	0.723	1.090	13.550	0.655
Average	7.00	8.151	2.299	14.395	0.702	2.184	14.784	0.688

The effect of the adjustment varied considerably between stations. At Zavižan, which exhibited the largest RMSE values in the original comparison, ERA5 RMSE decreased from 21.29 to 19.51 percentage points, while ERA5-Land RMSE decreased from 20.56 to 19.08 percentage points. The corresponding biases changed from −10.52 to +5.97 percentage points for ERA5 and from −8.80 to +2.86 percentage points for ERA5-Land. Although the magnitude of the bias was therefore reduced substantially, particularly for ERA5-Land, the adjustment also reversed its direction. Correlations remained low at this station, changing only slightly from 0.490 to 0.457 for ERA5 and from 0.499 to 0.478 for ERA5-Land.

Improvements were also evident at several other stations. At Rijeka, ERA5 RMSE decreased from 16.95 to 13.24 percentage points, while ERA5-Land RMSE decreased from 20.05 to 14.27 percentage points. The ERA5-Land bias at Rijeka was also reduced substantially, from +15.59 to +7.25 percentage points. At Rab, ERA5-Land showed another pronounced improvement, with its bias decreasing from +11.67 to +1.09 percentage points and its RMSE from 18.23 to 13.55 percentage points. By contrast, changes at some stations were smaller, and the adjustment did not consistently improve every individual metric.

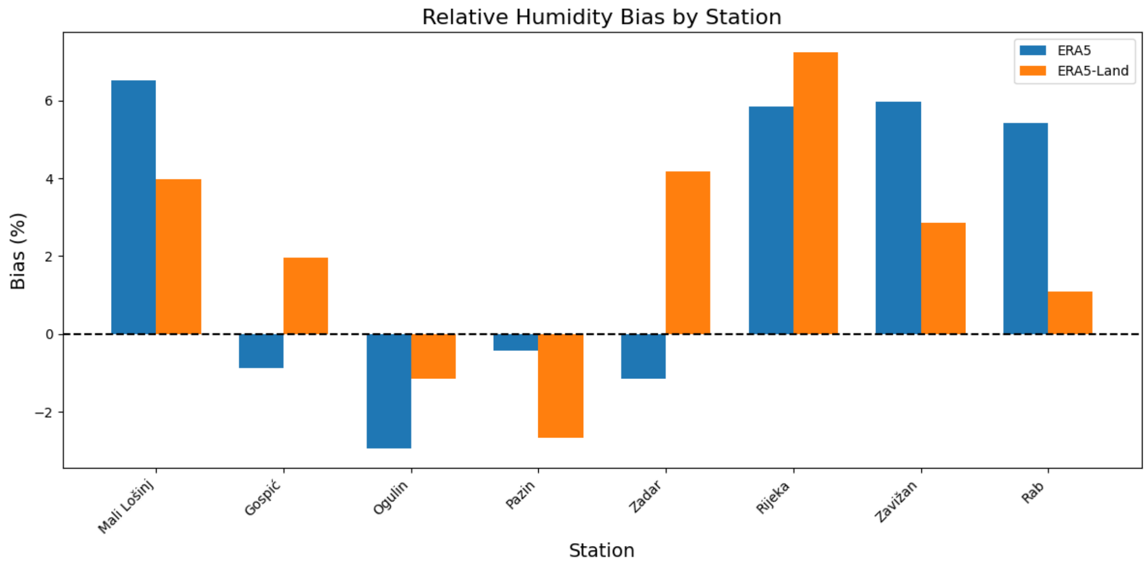

Figure 15. Altitude-Corrected Relative Humidity Bias (ERA5-DHMZ)

Overall, accounting for the elevation difference between the reanalysis grid cells and DHMZ stations improved relative-humidity RMSE for both ERA5 and ERA5-Land, although the effect was considerably less pronounced than for air temperature. ERA5 retained a slightly lower average RMSE and a marginally higher average correlation after adjustment, while ERA5-Land exhibited the smaller average bias. The limited changes in correlation indicate that elevation adjustment primarily affected the magnitude of the relative-humidity discrepancies rather than the ability of either reanalysis product to reproduce their temporal variability.

4.2.6.3 Surface Pressure

Adjustment of surface pressure to a common sea-level reference produced a substantial reduction in the absolute errors observed in the original comparison. The average ERA5 RMSE decreased from 26.60 hPa to 1.446 hPa, while the average ERA5-Land RMSE decreased from 26.34 hPa to 6.725 hPa. The average biases also changed considerably, from +5.69 hPa to −0.156 hPa for ERA5 and from −5.72 hPa to +1.069 hPa for ERA5-Land. Correlations remained very high following the adjustment, averaging 0.981 for ERA5 and 0.982 for ERA5-Land. As with air temperature, the largely unchanged correlations alongside the pronounced reductions in RMSE indicate that the elevation adjustment primarily reduced systematic differences in the absolute magnitude of pressure rather than altering the representation of its temporal variability.

Table 11. ERA5 (Land) vs DHMZ altitude-corrected surface pressure metrics.

Station	ERA5 distance (km)	ERA5-Land distance (km)	ERA5 Bias (hPa)	ERA5 RMSE (hPa)	ERA5 Corr	ERA5-Land Bias (hPa)	ERA5-Land RMSE (hPa)	ERA5-Land Corr
Gospić	11.26	5.910	-0.910	1.540	0.987	6.190	6.280	0.990
Mali Lošinj	4.24	19.480	-0.230	0.650	0.997	-8.850	8.880	0.995
Ogulin	2.60	4.490	-0.970	1.360	0.993	4.510	4.640	0.991
Rijeka	10.66	7.760	1.260	1.620	0.991	3.220	3.590	0.979
Rab	1.60	11.480	0.460	0.820	0.996	4.130	4.430	0.978
Zadar	13.79	7.790	0.530	0.850	0.996	-13.000	13.020	0.996
Pazin	4.40	5.760	-0.160	0.870	0.994	4.840	4.960	0.990
Zavižan	7.45	2.540	-1.230	3.860	0.894	7.510	8.000	0.941
Average	7.00	8.151	-0.156	1.446	0.981	1.069	6.725	0.982

The most pronounced improvement occurred at Zavižan, where the original comparison exhibited exceptionally large positive biases of +108.01 hPa for ERA5 and +75.33 hPa for ERA5-Land, with corresponding RMSE values of 108.05 hPa and 75.36 hPa. Following sea-level adjustment, the ERA5 bias decreased to −1.23 hPa and its RMSE to 3.86 hPa, while the ERA5-Land bias decreased to +7.51 hPa and its RMSE to 8.00 hPa. The substantial reduction in error at this high-elevation station indicates that the difference in reference elevation accounted for a large proportion of the pressure discrepancy observed in the original comparison.

Large improvements were also observed at several other stations. At Rijeka, ERA5 RMSE decreased from 34.31 hPa to 1.62 hPa, while ERA5-Land RMSE decreased from 41.87 hPa to 3.59 hPa. At Rab, the corresponding RMSE values decreased from 17.25 hPa to 0.82 hPa for ERA5 and from 58.52 hPa to 4.43 hPa for ERA5-Land. Following adjustment, ERA5 RMSE remained below 2 hPa at seven of the eight stations, with Zavižan representing the only exception.

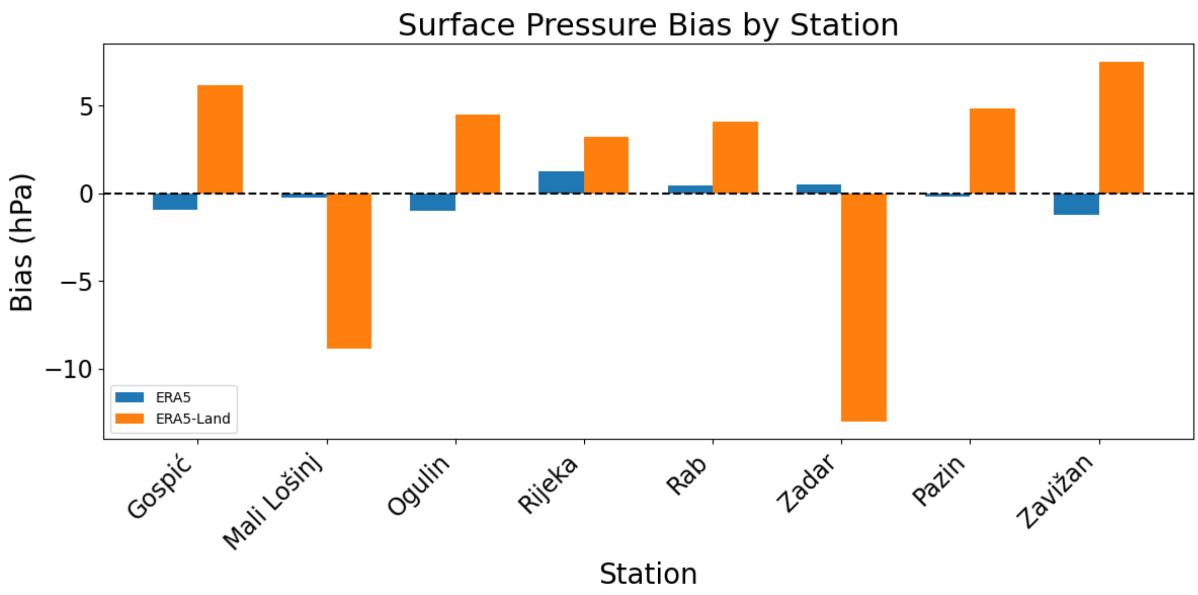

Figure 16. Altitude-Corrected Surface Pressure Bias (ERA5-DHMZ).

Despite the substantial overall improvement, ERA5-Land retained larger station-specific errors than ERA5 following adjustment. The largest remaining ERA5-Land discrepancy occurred at Zadar, where the bias was −13.00 hPa and the RMSE 13.02 hPa. Comparatively large ERA5-Land errors also remained at Mali Lošinj, with a bias of −8.85 hPa and an RMSE of 8.88 hPa, and at Zavižan, where the corresponding values were +7.51 hPa and 8.00 hPa. In contrast, ERA5 biases after adjustment remained between approximately −1.23 and +1.26 hPa across all stations. Consequently, although adjustment to a common sea-level reference substantially improved both products, the improvement was considerably more consistent for ERA5, which exhibited substantially lower station-level errors than ERA5-Land after adjustment.

4.3 Validation Against HOPS Observations

To provide an additional independent assessment of the validation results, ERA5 and ERA5-Land were also evaluated against observations from 18 HOPS automatic weather stations. As described in Section 3.6, the HOPS observations were used as a supplementary validation dataset rather than the primary meteorological reference. The analysis therefore focused primarily on network-level performance and on whether the principal patterns identified using the DHMZ observations were reproduced across the larger HOPS station network.

Table 12. Network-average validation statistics for ERA5 and ERA5-Land against HOPS observations.

Meteorological variable	ERA5 Bias	ERA5 RMSE	ERA5 Corr.	ERA5-Land Bias	ERA5-Land RMSE	ERA5-Land Corr.
Air temperature	+0.19 °C	2.41 °C	0.964	−0.50 °C	2.56 °C	0.960
Relative humidity	+2.12 pp	12.17 pp	0.771	+3.20 pp	12.98 pp	0.756
Mean wind speed	+0.64 m s^{-1}	1.98 m s^{-1}	0.640	+0.32 m s^{-1}	1.88 m s^{-1}	0.640
Total precipitation	+0.058 mm	0.729 mm	0.358	+0.058 mm	0.729 mm	0.358

The HOPS validation broadly supported the principal patterns identified using the DHMZ observations. Air temperature showed the strongest agreement with the observations, with average correlations of 0.964 for ERA5 and 0.960 for ERA5-Land and RMSE values of 2.41 °C and 2.56 °C, respectively. Relative humidity exhibited lower correlations and larger relative errors, with ERA5 showing a modest overall advantage. Mean wind speed produced moderate correlations of 0.640 for both products, although ERA5-Land reduced the average bias from +0.64 to +0.32 m s^{-1} and the average RMSE from 1.98 to 1.88 m s^{-1}. Total precipitation again exhibited the weakest temporal agreement, with an average correlation of 0.358 for both datasets and virtually identical bias and RMSE values.

The similarity between ERA5 and ERA5-Land performance is particularly notable given their different spatial resolutions. Across the HOPS network, the average distance between a station and the nearest ERA5-Land grid point was approximately 5.17 km, compared with 11.98 km for ERA5. Despite this considerably closer spatial representation, ERA5-Land did not consistently achieve better validation statistics. ERA5 performed slightly better overall for air temperature and relative humidity, ERA5-Land showed a modest advantage for mean wind speed, and the two products produced essentially identical results for total precipitation.

These results are consistent with the DHMZ validation in showing that the finer spatial resolution of ERA5-Land does not by itself result in systematically improved agreement with point-based meteorological observations. The relative performance of the two products instead remained dependent on the meteorological variable considered, while differences between their network-average validation statistics were generally small.

4.3.1 Mean Sea-Level Pressure

Mean sea-level pressure represents an additional component of the HOPS validation, as HOPS provides pressure observations directly at mean sea level rather than as surface pressure. Since mean sea-level pressure is not available as a variable in ERA5-Land, this comparison was performed only for ERA5. ERA5 showed very strong agreement with the HOPS observations across the 18 stations. The average bias was −0.592 hPa, indicating a small overall underestimation, while the average RMSE was 1.736 hPa. Temporal agreement was particularly strong, with an average correlation coefficient of 0.972 and station-level correlations exceeding 0.87 at all investigated locations.

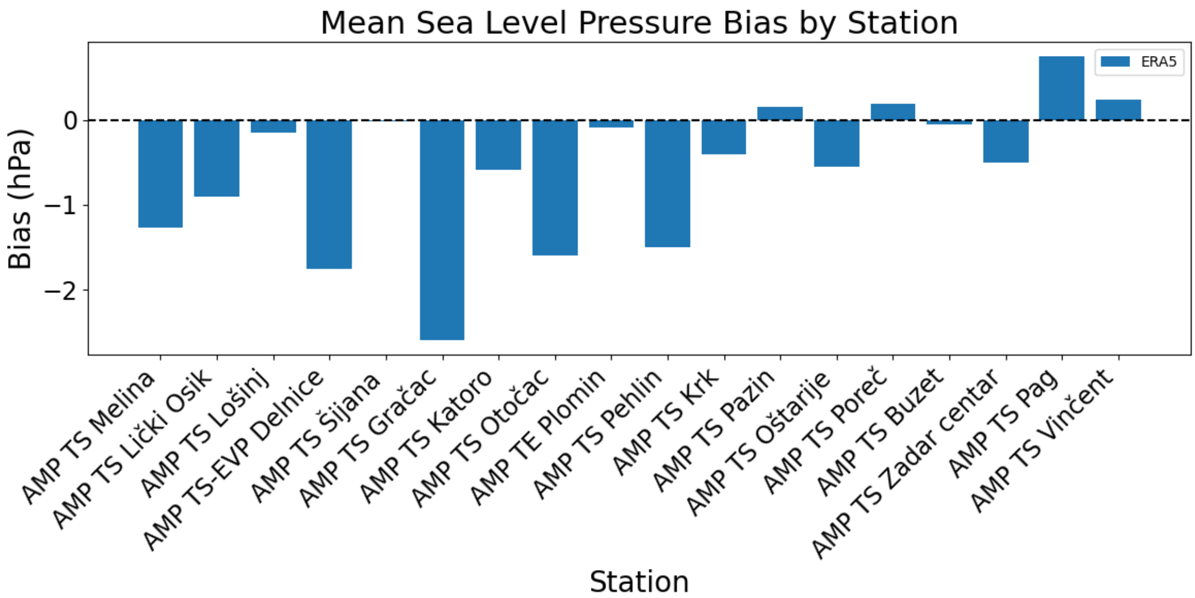

Figure 17. Mean Sea Level Pressure Bias (ERA5-HOPS)

The station-level biases shown in Figure 17 indicate that the small overall negative bias was not distributed uniformly across the network, although the magnitude of the discrepancies remained comparatively limited. The strong agreement obtained for HOPS mean sea-level pressure is also consistent with the substantial improvement observed when the DHMZ surface-pressure comparison was converted to a common sea-level reference. In the original DHMZ comparison, large station-specific systematic offsets were present despite very high correlations, whereas conversion to sea-level-equivalent pressure substantially reduced these errors. The comparatively small errors obtained directly against HOPS mean sea-level pressure therefore further demonstrate the importance of using a consistent pressure reference level when evaluating reanalysis pressure against ground-based observations.

4.3.2 Effect of Elevation Adjustment

To examine whether the influence of elevation identified in the DHMZ validation was also evident in the supplementary HOPS dataset, the elevation-related adjustments were repeated for air temperature and relative humidity. As in the DHMZ analysis, air temperature was normalised to a common sea-level reference, while relative humidity was recalculated after adjusting the reanalysis temperature and dew-point temperature to the elevation of the corresponding HOPS station. The resulting network-average statistics were compared with those obtained in the original HOPS validation.

Table 13. Network-average validation statistics before and after elevation-related adjustment for HOPS air temperature and relative humidity.

Variable	Dataset	Bias before	Bias after	RMSE before	RMSE after	Corr. before	Corr. after
Air temperature (°C)	ERA5	+0.193	+0.572	2.406	2.327	0.964	0.964
	ERA5-Land	−0.497	−0.078	2.558	2.548	0.960	0.960
Relative humidity (pp)	ERA5	+2.118	+0.898	12.166	12.239	0.771	0.771
	ERA5-Land	+3.195	+1.800	12.978	12.847	0.756	0.756

The elevation-related adjustments produced comparatively modest changes in the HOPS validation results. For air temperature, ERA5 RMSE decreased from 2.406 °C to 2.327 °C, while ERA5-Land RMSE decreased slightly from 2.558 °C to 2.548 °C. The ERA5-Land average bias moved substantially closer to zero, from −0.497 °C to −0.078 °C, whereas the ERA5 average bias increased from +0.193 °C to +0.572 °C. Correlations remained unchanged at 0.964 for ERA5 and 0.960 for ERA5-Land, indicating that the adjustment primarily affected the magnitude of the temperature differences rather than their temporal correspondence.

The effect on relative humidity was similarly limited. Average bias decreased from +2.118 to +0.898 percentage points for ERA5 and from +3.195 to +1.800 percentage points for ERA5-Land. Changes in RMSE were considerably smaller: ERA5 RMSE increased slightly from 12.166 to 12.239 percentage points, whereas ERA5-Land RMSE decreased from 12.978 to 12.847 percentage points. Overall, the HOPS results indicate that accounting for elevation differences can reduce systematic offsets, particularly in mean bias, but the effect was substantially smaller than that observed in the DHMZ validation. This suggests that the importance of elevation-related adjustment depends on the characteristics and locations of the observational stations rather than producing a uniform improvement across all validation networks.

5. DISCUSSION

The results of this study demonstrate that both ERA5 and ERA5-Land are capable of representing the principal temporal variability of meteorological conditions within the investigated Croatian region, but their accuracy is strongly dependent on the meteorological variable and the characteristics of the observation location. The higher spatial resolution of ERA5-Land did not result in systematic improvement relative to ERA5. Instead, differences between the products were generally small at the network level, while substantially larger variations occurred between individual stations and between meteorological variables. This pattern was evident in the detailed DHMZ validation and was independently reproduced by the supplementary HOPS analysis. The findings therefore suggest that spatial resolution alone is not an adequate criterion for selecting between ERA5 and ERA5-Land for local applications.

5.1 Overall Performance of ERA5 and ERA5-Land

The initial intercomparison showed that ERA5 and ERA5-Land are highly consistent for most of the investigated variables. Air temperature, dew-point temperature, relative humidity and wind all exhibited strong correlations between the two products, and the statistical relationships obtained at the eight directly overlapping grid points remained broadly similar when ERA5-Land was interpolated over the larger ERA5 grid. In particular, the temperature correlation remained close to 0.99, while the correlations for relative humidity and wind speed remained above approximately 0.93. The stability of these relationships following spatial interpolation indicates that the similarity between the products was not restricted to the small set of naturally overlapping grid locations.

Such strong agreement is not unexpected given the relationship between the two reanalysis products. ERA5 is a global atmospheric reanalysis based on the ECMWF Integrated Forecasting System and assimilates a large range of atmospheric observations, whereas ERA5-Land is generated by replaying the land component of ERA5 at a finer horizontal resolution using downscaled ERA5 atmospheric forcing. ERA5-Land therefore does not represent an independent atmospheric analysis with entirely new information at 9 km resolution. Instead, the two products share much of the same large-scale atmospheric information and land-surface parameterisation. Muñoz-Sabater et al. (2021) similarly emphasise that differences between ERA5 and ERA5-Land are less straightforward than the difference in grid spacing might imply and report comparable performance for several components of the surface energy cycle. The high inter-product correlations observed in the present study should consequently be interpreted partly as a consequence of this common modelling framework rather than as independent evidence of accuracy.

This distinction becomes important when the products are compared with observations. Although ERA5 and ERA5-Land agreed closely with each other, neither product was consistently superior relative to the DHMZ stations. ERA5 produced slightly better network-average results for air temperature and relative humidity, while ERA5-Land showed a small advantage for mean wind speed. For precipitation, their network-average performance was almost indistinguishable. The HOPS validation reproduced the same general pattern: ERA5 achieved marginally better temperature and relative-humidity statistics, ERA5-Land performed somewhat better for wind speed, and precipitation statistics were effectively identical. The agreement between the DHMZ and HOPS assessments is particularly important because the two observational datasets differ in station number, siting and operational purpose. Their broadly consistent conclusions make it less likely that the absence of a universal ERA5-Land advantage is simply an artefact of the relatively small DHMZ network.

The main conclusion is therefore not that one reanalysis product is categorically more accurate than the other. Rather, ERA5 and ERA5-Land represent closely related estimates whose relative performance depends on the variable and location considered. This agrees with the original description of ERA5-Land, which demonstrates clear added value for some land-surface quantities but does not report universally superior performance over ERA5 for all variables and environments (Muñoz-Sabater et al., 2021). Similar behaviour has been reported in regional validation studies. Almeida and Coelho (2023), for example, found ERA5-Land to perform better than ERA5 for daily air temperature over Portugal, while also observing poorer reanalysis performance in high-altitude and complex terrain. For precipitation over Spain, Gomis-Cebolla et al. (2023) found ERA5 and ERA5-Land to perform very similarly despite their different spatial resolutions, with differences in accuracy depending more strongly on climate, topography and precipitation characteristics.

5.2 Spatial Resolution, Topography and Station Representativeness

One of the principal questions addressed in this study was whether the finer horizontal resolution of ERA5-Land translates into improved agreement with local meteorological observations. The results indicate that this relationship is substantially more complicated than a simple reduction in grid spacing. The HOPS network provides the clearest demonstration. The average distance from a HOPS station to the corresponding ERA5-Land grid point was approximately 5.17 km, compared with 11.98 km for ERA5. Despite this reduction of more than half in horizontal station-to-grid distance, ERA5-Land did not consistently produce lower errors. ERA5 remained slightly better for temperature and relative humidity, ERA5-Land showed only a modest advantage for wind speed, and precipitation performance was identical at the reported network-average precision.

Horizontal proximity to a station is therefore not equivalent to meteorological representativeness. A station is a point measurement influenced by its immediate elevation, exposure, land cover, surface roughness and surrounding terrain, whereas a reanalysis value represents the conditions of an entire model grid cell. A grid point located geographically closer to a station can consequently still represent a substantially different effective elevation or surface environment. Conversely, a more distant grid point may happen to reproduce the large-scale atmospheric conditions at a station comparatively well. This helps explain why the validation produced examples in both directions. At Rijeka, for instance, the ERA5-Land grid point was geographically closer than the ERA5 point, yet ERA5 produced a substantially smaller temperature RMSE. At Zavižan, ERA5-Land was both closer and more accurate for the unadjusted temperature comparison. The relationship between distance and performance was therefore clearly station-dependent rather than monotonic.

Croatia presents an especially difficult environment for this type of point-to-grid comparison. Within the study area, the Adriatic coast, islands, mountainous terrain and inland valleys occur over relatively short distances. A 9 km grid can represent these features more explicitly than a grid of approximately 31 km, but it still cannot reproduce all of the local-scale heterogeneity experienced by individual stations. This is consistent with studies from other geographically complex regions. Almeida and Coelho (2023) found both reanalyses to perform less favourably for temperature in high-altitude and complex terrain than in flatter regions, while Gomis-Cebolla et al. (2023) identified orography and Mediterranean coastal conditions as important controls on precipitation performance in Spain.

The structure of ERA5-Land also helps explain why the benefit of its finer grid is variable-dependent. ERA5-Land uses higher-resolution land-surface characteristics and performs its land-model calculations on a substantially denser grid, but its atmospheric forcing is ultimately derived from ERA5. It can therefore provide a more detailed representation of land-surface and topographic effects without generating an entirely new high-resolution description of atmospheric circulation. Muñoz-Sabater et al. (2021) show that the finer orography of ERA5-Land can produce important improvements, particularly where elevation and coastal representation matter, but that the added value varies according to the variable examined.

The present results support this interpretation. Increased spatial resolution appears to be beneficial in particular circumstances rather than universally. ERA5-Land substantially reduced some individual station errors, but these gains were offset by equal or better ERA5 performance elsewhere. Consequently, choosing ERA5-Land solely because its nominal grid spacing is smaller would not be justified by the validation performed here. For applications focused on a particular region or variable, local validation remains necessary.

5.3 Differences Between Meteorological Variables

The clearest distinction in the validation was not between ERA5 and ERA5-Land, but between the meteorological variables themselves. Air temperature was reproduced most consistently, whereas relative humidity and mean wind speed showed intermediate performance and hourly precipitation exhibited the weakest temporal agreement. This ordering was present in both observational networks, suggesting that it reflects differences in how the meteorological processes are represented rather than characteristics of a single station dataset. DHMZ temperature correlations averaged approximately 0.96 for both reanalyses, and almost identical values were obtained against HOPS. In contrast, relative-humidity correlations were approximately 0.69–0.71 for DHMZ and 0.76–0.77 for HOPS, while wind-speed correlations were around 0.59–0.60 and 0.64, respectively. Precipitation correlations were only approximately 0.32 against DHMZ and 0.36 against HOPS.

The strong temperature performance is consistent with previous evaluations of ERA5 and ERA5-Land. Near-surface temperature varies relatively continuously in space and time, and its large-scale synoptic and diurnal variability is represented effectively by modern reanalysis systems. Hersbach et al. (2020) reported improved agreement of ERA5 atmospheric temperature with observations compared with its predecessor, while European and regional station studies have similarly found strong agreement between reanalysis and observed near-surface temperature, while also identifying terrain elevation as an important source of local error, particularly in mountainous environments (Almeida & Coelho, 2023). The present study follows this pattern closely: temporal correlations were already very high before elevation adjustment, while some absolute station biases were large.

Relative humidity was less accurately represented and showed stronger station-to-station variability. One reason is that the relative humidity used here is not an independently modelled output but is calculated from air temperature and dew-point temperature. Errors in either quantity can therefore propagate into the derived humidity estimate, while the nonlinear dependence of saturation vapour pressure on temperature can amplify relatively small thermodynamic differences (Alduchov & Eskridge, 1996). In addition, near-surface humidity is strongly influenced by boundary-layer mixing, local vegetation and soil moisture, proximity to the sea and small-scale moisture transport. These processes can vary considerably within a single model grid cell. The moderate improvement produced by the elevation adjustment further suggests that elevation explains only part of the relative-humidity discrepancy.

Mean wind speed presented a different difficulty. Both products reproduced a meaningful fraction of temporal variability, but the agreement was clearly weaker than for temperature. Wind near the surface is particularly sensitive to local terrain, surface roughness and exposure, all of which may differ substantially between a model grid cell and a meteorological station. Molina et al. (2021), in a comparison of ERA5 with 245 stations across Europe, similarly found that ERA5 captured broad wind-speed characteristics while retaining station-level limitations.

This issue is especially relevant along the Croatian Adriatic, where wind circulation is strongly affected by mountain gaps, coastal geometry and Bora-type downslope flows. High-resolution modelling studies of the northern Adriatic have demonstrated a strong sensitivity of Bora representation to atmospheric model resolution. Denamiel et al. (2021) found substantial differences between ERA5 and kilometre-scale simulations during severe Bora events, with wind-speed deviations reaching up to 43%. Earlier dynamical-downscaling work over Croatia similarly found that wind-speed simulation generally improved as horizontal model resolution was increased (Horvath et al., 2011). The substantial negative wind-speed bias observed at Zavižan and the generally moderate station correlations found in the present study are therefore consistent with the known difficulty of representing terrain-controlled wind regimes using relatively coarse reanalysis grids.

Precipitation was the most difficult variable at the hourly station scale. An important feature of the results is the combination of very small mean bias with relatively weak correlation. Against DHMZ, both products had average biases close to +0.1 mm and almost identical RMSE values, yet correlations remained around 0.32. HOPS produced the same qualitative result, with identical average biases of +0.058 mm and correlations of 0.358. This indicates that the reanalyses can reproduce the average amount of precipitation reasonably closely while still differing substantially from observations in the exact timing and magnitude of individual hourly events.

This behaviour is meteorologically plausible because precipitation is intermittent and can vary sharply over short distances. A convective or orographically enhanced precipitation event displaced by only several kilometres or one or two hours can generate a large pointwise error even when the same broader weather system and regional accumulation are represented correctly. This is particularly important when comparing a grid-cell estimate with a single rain gauge. Gomis-Cebolla et al. (2023) similarly found that ERA5 and ERA5-Land precipitation performance in Spain depended strongly on precipitation intensity, climate and topography and that the two products performed very similarly despite their different resolution. A recent ERA5-Land evaluation using DHMZ observations in Pannonian Croatia also identified scale-dependent behaviour: long-term and monthly precipitation patterns were reproduced considerably better than individual rainfall events, while light precipitation occurred too frequently and high-intensity rainfall was underestimated (Bostjančić et al., 2026).

The difference between the overlapping-grid and interpolated ERA5–ERA5-Land precipitation comparisons reinforces this caution. Unlike temperature, humidity and wind speed, for which the statistics were comparatively stable after interpolation, precipitation correlation changed substantially when the spatial comparison procedure was altered. This should not be interpreted as evidence that interpolation intrinsically improves precipitation accuracy. Rather, it demonstrates that statistical agreement for an intermittent field is particularly sensitive to spatial sampling, event alignment and preprocessing. For applications concerned with individual rainfall events or extremes, station-level validation and event-based metrics are therefore more informative than mean bias alone.

5.4 Influence of Elevation and Pressure Reference Level

The elevation analysis provides some of the strongest evidence in the thesis that a substantial part of the apparent reanalysis error can arise from differences in spatial representation rather than from an inability to reproduce atmospheric variability. This distinction is especially clear for temperature and pressure. Before adjustment, both variables frequently showed high correlations together with large station-specific biases. After normalisation to a common elevation reference, correlations changed very little while the magnitude of the errors decreased substantially. This indicates that the reanalyses were already reproducing the temporal evolution of the atmosphere but were describing it at a different effective elevation from the observation.

For DHMZ temperature, sea-level normalisation reduced average RMSE from 3.456 to 2.504 °C for ERA5 and from 3.591 to 2.669 °C for ERA5-Land, corresponding to reductions of approximately 28% and 26%, respectively. The importance of elevation was particularly evident at Zavižan. Before adjustment, its temperature biases reached +7.07 °C for ERA5 and +4.62 °C for ERA5-Land; afterwards, they were reduced to +0.53 and +0.44 °C. The correlations barely changed. This is a strong indication that the extreme baseline error at this station was dominated by the difference between the elevation represented by the grid and the high-elevation station rather than by a failure to reproduce its temperature fluctuations.

The importance of altitude corrections for reanalysis temperature has also been identified elsewhere. ERA5-Land itself applies a spatially and temporally varying environmental lapse-rate correction when ERA5 atmospheric forcing is downscaled to the higher-resolution ERA5-Land grid. Muñoz-Sabater et al. (2021) report that this procedure improves temperature performance in many circumstances and emphasise the importance of representing orographic differences. More recent validation over mountainous terrain has likewise found substantial reductions in temperature and pressure bias following elevation adjustment (Silva et al., 2026).

The present correction nevertheless used a constant environmental lapse rate, and its results should therefore be interpreted as a diagnostic estimate of the role of elevation rather than as a complete physical bias correction. Actual near-surface lapse rates vary according to season, time of day, atmospheric stability, humidity and topographic setting, and temperature inversions can even reverse the expected vertical gradient. Studies using spatially and temporally varying lapse rates have shown that they can outperform a single constant value (Dutra et al., 2020). The fact that some stations in the present study improved only slightly, while a small number of individual metrics deteriorated, is therefore not unexpected.

Relative humidity behaved differently. Adjusting temperature and dew-point temperature to station elevation reduced the average DHMZ RMSE by approximately 6% for ERA5 and 9% for ERA5-Land, but the correlations remained essentially unchanged and the bias response was not uniform. This smaller response indicates that relative-humidity errors cannot be reduced to elevation mismatch alone. Elevation affects both air temperature and the moisture variables from which relative humidity is calculated, but local moisture availability, boundary-layer processes and land–sea interactions remain important. The reversal of the Zavižan bias after adjustment also illustrates the limitations of applying fixed lapse-rate assumptions to a nonlinear humidity variable.

The HOPS elevation experiment strengthens this interpretation because it did not reproduce the large DHMZ temperature improvement. For HOPS temperature, the change in network-average RMSE was relatively small, and the relative-humidity RMSE changed only marginally, although the mean humidity biases moved closer to zero. This suggests that the importance of elevation correction depends on the characteristics of the station network and on the magnitude of the station-to-grid elevation mismatch. The much stronger response within DHMZ appears to have been driven partly by particular locations with substantial elevation-related discrepancies, most notably Zavižan. The HOPS result is consequently useful precisely because it prevents the conclusion from being overstated: elevation can be a dominant source of error, but it is not necessarily the dominant source at every station or within every observational network.

The pressure analysis provides an even clearer example of the importance of reference level. In the original DHMZ surface-pressure comparison, correlations were extremely high, averaging approximately 0.98, but RMSE values exceeded 26 hPa because the station and grid-cell pressures referred to surfaces at different elevations. Following conversion to a common sea-level reference, average RMSE decreased to only 1.446 hPa for ERA5 and 6.725 hPa for ERA5-Land. At Zavižan, an ERA5 pressure bias exceeding +108 hPa was reduced to −1.23 hPa. Such a change demonstrates that the original large pressure discrepancies should not be interpreted primarily as errors in the simulated atmospheric pressure field; they were largely a consequence of comparing pressure at different physical elevations.

The independent HOPS comparison provides useful support for this interpretation. HOPS reports pressure directly as mean sea-level pressure, and the native ERA5 MSLP field achieved an average bias of only −0.592 hPa, an RMSE of 1.736 hPa and a correlation of 0.972. Thus, when observational and reanalysis pressures are already expressed relative to a common reference level, the agreement is strong without the very large systematic offsets found in the original DHMZ surface-pressure comparison.

ERA5-Land could not be included in this direct comparison because it does not provide a native MSLP variable. Within the scope of this study, ERA5 therefore appears to be the more straightforward product for applications requiring mean sea-level pressure, whereas deriving sea-level-equivalent pressure from ERA5-Land surface pressure introduces additional uncertainty.

5.5 Limitations and Implications

Several limitations should be considered when interpreting these findings. First, the detailed primary validation is based on eight DHMZ stations. Although these stations represent coastal, island, inland and mountainous environments, they cannot capture the complete geographical variability of Croatia. The HOPS network increases the number of validation locations to 18 and provides valuable independent support for the principal conclusions, but these stations are primarily associated with electricity-transmission infrastructure rather than a dedicated meteorological monitoring network. The HOPS results were therefore appropriately treated as supplementary evidence rather than as a replacement for the DHMZ validation. Agreement between the two networks strengthens confidence in the main conclusions, but differences in station exposure, instrumentation and measurement procedures should be considered when comparing their absolute error statistics.

Second, point-to-grid comparison inevitably contains representativeness error. Even where a reanalysis grid point lies geographically close to a station, the grid value describes meteorological conditions over a much larger area and at a model-defined elevation and surface environment. This limitation is particularly relevant within the present study area because coastlines, islands and steep topographic gradients occur over distances comparable to or smaller than the ERA5-Land grid spacing. The validation statistics therefore contain both genuine reanalysis errors and differences arising because the station and model do not represent exactly the same physical environment.

Third, the hourly temporal scale used for much of the validation represents a demanding test, especially for precipitation and wind. Small temporal or spatial displacement of an individual precipitation cell can strongly reduce hourly correlation even where daily or monthly accumulations remain realistic. Similarly, local wind maxima associated with terrain-induced flows may occur over scales too small for either reanalysis grid. Consequently, the results should not automatically be interpreted as evidence that the datasets are equally inaccurate at longer climatological time scales. Previous work has shown improved agreement when precipitation or wind is evaluated at longer aggregation periods (Molina et al., 2021; Bostjančić et al., 2026).

Precipitation additionally required more extensive preprocessing than the other variables, including unit conversion, reconstruction of dry hours and deaccumulation of ERA5-Land totals. The considerable sensitivity of the ERA5–ERA5-Land precipitation intercomparison to spatial sampling further indicates that precipitation statistics should be interpreted with particular caution. Future work could complement the continuous metrics used here with event-based measures, wet-day detection statistics and separate evaluation of light, moderate and extreme precipitation. This would help distinguish errors in precipitation occurrence from errors in accumulated amount.

The elevation-adjustment procedure also represents a simplification. A constant temperature lapse rate and standard-atmosphere pressure relationship are useful for isolating the first-order effect of elevation differences, but they cannot reproduce the full spatial and temporal variability of the lower atmosphere. Future analyses could use time-varying lapse rates derived from vertical ERA5 temperature profiles or directly adjust reanalysis values to station elevation rather than to a common sea-level reference. Such approaches would be particularly relevant for mountainous locations where inversions and local circulation can cause substantial departures from a standard lapse rate.

Despite these limitations, the results have clear practical implications. Neither ERA5 nor ERA5-Land should be regarded as universally preferable for meteorological applications within the investigated region. Air temperature is represented strongly by both products, particularly after accounting for elevation differences. ERA5-Land's finer grid can improve individual locations but does not systematically outperform ERA5. Relative humidity and wind speed require greater caution because local surface and terrain effects become increasingly important. For hourly precipitation, the very similar ERA5 and ERA5-Land statistics and comparatively weak correlations indicate that higher spatial resolution alone does not resolve the fundamental difficulties associated with point-scale precipitation timing and intensity. For pressure, ensuring a consistent vertical reference level is more important than the nominal horizontal resolution of the dataset.

Taken together, the study therefore suggests that the principal benefit of ERA5-Land is greater spatial detail rather than universally greater point-scale accuracy. ERA5 remains highly competitive and in several comparisons performs marginally better despite its coarser grid. ERA5-Land can provide important advantages where land-surface heterogeneity and improved orographic representation are relevant, but those advantages depend on the variable and location. For regional environmental applications in Croatia, the choice between the products should consequently be based on the meteorological quantity being analysed, the required spatial and temporal scale, and—where possible—validation against local observations rather than spatial resolution alone. This directly answers the central question of the thesis: within the investigated region, the higher spatial resolution of ERA5-Land does not translate into a systematic improvement in agreement with ground-based meteorological measuremen

6. CONCLUSION

This thesis evaluated the performance of ERA5 and ERA5-Land reanalysis products over a geographically diverse region of Croatia through direct intercomparison and validation against ground-based meteorological observations. Particular attention was given to whether the finer spatial resolution of ERA5-Land resulted in systematically improved agreement with local measurements. Validation was performed primarily against eight DHMZ meteorological stations and was supplemented by observations from 18 HOPS automatic weather stations.

The results demonstrate that ERA5 and ERA5-Land are highly consistent with each other, particularly for air temperature, relative humidity and wind-related variables. However, the finer spatial resolution of ERA5-Land did not translate into systematically better agreement with station observations. Across the DHMZ network, ERA5 performed slightly better overall for air temperature and relative humidity, while ERA5-Land showed a modest advantage for mean wind speed. Total precipitation performance was almost identical between the two products. The supplementary HOPS validation reproduced the same general pattern: ERA5 again showed a small advantage for temperature and relative humidity, ERA5-Land performed somewhat better for wind speed, and precipitation statistics were effectively indistinguishable. This consistency is particularly notable because ERA5-Land grid points were substantially closer to the HOPS stations than ERA5 grid points, yet the reduction in horizontal distance did not produce a corresponding systematic improvement in validation performance.

Differences between meteorological variables were considerably larger than the overall differences between ERA5 and ERA5-Land. Air temperature was the most accurately reproduced variable, with average correlations close to 0.96 against both observational networks. Relative humidity and mean wind speed showed moderate agreement and greater station-to-station variability. Hourly total precipitation exhibited the weakest temporal correspondence with observations, despite very small average biases for both reanalysis products. This combination indicates that the reanalyses represented overall precipitation amounts more successfully than the exact timing and magnitude of individual hourly events. The results therefore emphasise that the suitability of a reanalysis product depends not only on its nominal spatial resolution but also on the meteorological process being investigated and the temporal scale at which it is evaluated.

Elevation and vertical reference level were identified as particularly important sources of apparent disagreement between gridded reanalysis data and station observations. Normalising air temperature to a common sea-level reference substantially reduced DHMZ temperature errors while leaving correlations essentially unchanged. The effect was especially pronounced at Zavižan, where very large original temperature biases were reduced to values close to zero. The pressure comparison provided an even clearer example. Large biases in the original DHMZ surface-pressure validation were dramatically reduced after conversion to sea-level-equivalent pressure, with average ERA5 RMSE decreasing from 26.60 hPa to 1.446 hPa. The strong agreement between ERA5 mean sea-level pressure and HOPS observations, for which an average RMSE of 1.736 hPa and correlation of 0.972 were obtained directly, independently supports the importance of comparing pressure quantities expressed at equivalent reference levels.

The elevation adjustments were not equally influential for all variables or observational networks. Relative-humidity improvements were comparatively modest, while the HOPS temperature and humidity results changed substantially less than their DHMZ counterparts. Elevation mismatch should therefore not be regarded as a universal explanation for reanalysis error. Instead, its importance depends on the individual station, surrounding terrain and difference between station and grid-cell elevations. More generally, the considerable station-to-station variability observed throughout the analysis demonstrates the limitations of interpreting network-average statistics without considering local geographical characteristics.

Overall, neither ERA5 nor ERA5-Land can be considered universally superior for representing local meteorological conditions in the investigated Croatian region. ERA5-Land provides considerably finer spatial detail and can improve performance at individual locations, but this advantage is variable- and location-dependent. ERA5 remains highly competitive despite its coarser resolution and, for several variables, achieved slightly better overall validation statistics. Consequently, the choice between the two products should be based on the specific meteorological variable, geographical setting and intended application rather than spatial resolution alone. For applications requiring local accuracy, particularly in coastal or mountainous environments, validation against ground observations and appropriate treatment of elevation and reference-level differences remain essential.

The principal research question can therefore be answered clearly: ERA5-Land's higher spatial resolution does not, by itself, produce systematically improved agreement with ground-based meteorological observations within the investigated Croatian region. Instead, the accuracy of both reanalysis products is primarily controlled by the meteorological variable considered, local geographical conditions, the spatial representativeness of the grid cell relative to the station, and—in the case of temperature and pressure—the consistency of elevation and vertical reference level.

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