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ClimUAd: Observation-Based Gridded Daily Climate Data for Ukraine, 1946–2020

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ABSTRACT

In this work, we present results of the development of an observation-based gridded climate dataset (ClimUAd), which covers the territory of Ukraine for the period of 1946–2020. The spatial resolution of the developed data is 0.1°×0.1° (approximately 10 km in both longitude and latitude directions), with a 1-day time step. Four essential climate variables are included in the dataset, namely daily sums of atmospheric precipitation and daily minimum, mean, and maximum air temperature. The created gridded product is based on the complete collection of station measurements performed at 178 weather stations in Ukraine. Quality control, homogenisation, and gridding of the station time series were performed by means of the widely used software, INQC, Climatol, and MISH, respectively. The created gridded time series were statistically compared with several existing datasets that have the same spatial resolution (i.e., previously developed gridded monthly data of Ukraine, ERA5-Land and E-OBS) on monthly and daily scales. The comparison showed good accordance with the Ukrainian monthly data (partly obtained from other paper sources than the daily data and homogenised with HOMER software) and acceptable agreement with ERA5-Land and E-OBS data. The developed data are of great importance as they were built with the involvement of as many real weather measurements as possible, representing a denser network than those included in continental/global gridded products. They can be used for regional climate monitoring and as the reference for a wide variety of climatological applications for the territory of Ukraine. The dataset is freely available for research purposes and can be downloaded from the data repository of the Ukrainian Hydrometeorological Institute.

1 | Introduction

Meteorological observations, covering a fairly long period of time, are extremely important in modern climate studies. They can be used directly to study past/current climate change and variability in a specific domain or region (e.g., Camuffo et al. 2017). On the other hand, they can be utilised to create different gridded climate products (such as reconstructions, analysis and reanalysis) or to evaluate/correct climate model simulations (e.g., Luterbacher et al. 2004; Brönnimann et al. 2018). It is worth noting that there have been initiated numerous international, regional, and national projects aiming to make observational climate data of different time resolutions freely available for scientific research (e.g., Brunet and Jones 2011; Allan et al. 2011; Ashcroft et al. 2018).

According to the recommendations of the World Meteorological Organization (WMO) (Aguilar et al. 2003), climate observation data should be processed through several obligatory steps before involving them in any kind of climate analysis. Two main steps are thorough quality control (QC) checks and homogenisation. Further, if there is a need to have evenly distributed climate information over a domain under study, some reliable interpolation/gridding methods should be applied to quality-controlled and homogenised station time series. It is worth noting that observation-based gridded climate data have been extensively used recently in climate applications (Haylock et al. 2008). There are several vivid examples of such data, which were developed for Europe or its certain regions/countries with different time and spatial resolutions: HISTALP (Hiebl et al. 2009), CARPATCLIM (Szalai et al. 2013), E-OBS (Cornes et al. 2018), HadUK-Grid (Hollis et al. 2019), G2DC-PL+ (Piniewski et al. 2021) and ROCIO_IBEB (Peral et al. 2017). Two of the listed datasets, CARPATCLIM and E-OBS, cover the territory of Ukraine or a certain part of the country. Both have 0.1°×0.1° (longitude × latitude) spatial and daily temporal resolutions.

The output of the CARPATCLIM project has been widely used in many publications dealing with the climate of the greater Carpathian region, including its essential part—the Ukrainian Carpathians (e.g., Skrynyk 2014; Spinoni et al. 2015a, 2015b; Lakatos et al. 2016). Unfortunately, the rest of the country was left uncovered by the project. In addition, the time coverage of the CARPATCLIM data is limited to a 50-year period, from 1961 until 2010. Obviously, there is a need to extend the well-approved CARPATCLIM methodology to the latest decade and the entire Ukrainian territory. The E-OBS database, which is updated regularly, covers the whole territory of Ukraine and it is also frequently used to study the regional climate (e.g., Krakovska et al. 2017). However, not all meteorological measurements performed at Ukrainian weather stations were involved in creating the E-OBS gridded data.

A monthly gridded dataset for Ukraine (ClimUAm) was developed in the previous works of the authors (Skrynyk et al. 2020; Osadchyi et al. 2022) based on a complete collection of quality-controlled and homogenised monthly station time series (Osadchyi et al. 2018; Skrynyk et al. 2019; Palamarchuk et al. 2023). The dataset has a spatial resolution of 0.1°×0.1° (approximately 10 km in both longitude and latitude directions) and contains gridded time series of four essential climate variables (ECV): atmospheric precipitation (RR), minimum (TN), mean (TG) and maximum (TX) air temperature for the period 1946–2020. Though the monthly data are still in use (e.g., Semenova and Vicente-Serrano 2024), many modern climate applications, however, demand data of finer temporal discreteness (e.g., daily, subdaily). Therefore, the purpose of this study is to present a daily version of the observation-based gridded climate dataset for Ukraine (ClimUAd). The list of included climate parameters, time coverage, and the spatial resolution of ClimUAd are the same as for the monthly version. Since the development of ClimUAd was also based on an almost complete collection of station measurements performed in Ukraine and the well-approved methodology, it has a great potential to be used in regional climate monitoring and as a reference for many climate applications for the territory of the country.

The rest of the work includes the following sections. The *Data processing* section contains a full description of the empirical meteorological information and how it was processed to create the gridded daily time series of Ukraine. The next section, *Results, discussion and data description*, presents the main results, including a statistical comparison of the developed product with other gridded data, which cover the territory of Ukraine with the same spatial resolution. Finally, the *Conclusions* section sums up the main outputs of the work.

2 | Data Processing

In our study, we used daily data (daily summaries) of atmospheric precipitation, minimum, mean, and maximum air temperature, which were obtained at 178 weather stations in Ukraine during the period of 1946–2020. These 178 stations (performing 8 times per day measurements since 1966 and typically just 4 measurements per day in 1946–1965) constitute the basis of the modern national meteorological monitoring network. The daily summaries of the meteorological measurements are published in special tables, which are stored in the Central Geophysical Observatory (CGO, Kyiv, Ukraine), the main governmental institution in the country that is in charge of meteorological/climatological/environmental data collection and storage. The spatial distribution of the stations on the territory of Ukraine is shown in Figure 1, while their complete list with some additional meta information (such as geographical coordinates, altitudes and climate classification types) is attached to this work as Data S1. Besides the climate data, dates of station relocations and other potentially influencing events were also made available for the analysis (see e.g., Osadchyi et al. 2018; Skrynyk et al. 2019; O'Neill et al. 2022). It is worth noting that in Ukraine daily mean air temperature, TG, is calculated as an arithmetic average of corresponding subdaily measurements. Therefore, it was decided to include this air temperature parameter in the dataset along with TN and TX.

2.1 | Data Rescue and QC

Almost all daily meteorological/climatological records used in the study were provided by CGO. A substantial part of the time series was provided in a digital form (as Excel worksheets), the data for an earlier period (up to 1960s) are still stored in the CGO's archive in paper reports/tables. This part of the data was digitised by the authors through a data rescue procedure conducted in accordance with the WMO rules and guideline documents (e.g., WMO 2016). In addition, some part of the data were obtained from free internet resources (e.g., Meteorological data 2005). Those are data from the Crimea peninsula and the Eastern part of Ukraine for 2015–2020, which are not directly accessible for Ukrainian scientists due to the ongoing Russian aggression and occupation of the mentioned territories.

The thorough QC of the daily values was mainly performed by means of the INQC software (https://CRAN.R-project.org/package=INQC) (Aguilar 2019), which was specifically developed to check climate data with daily time resolution. INQC

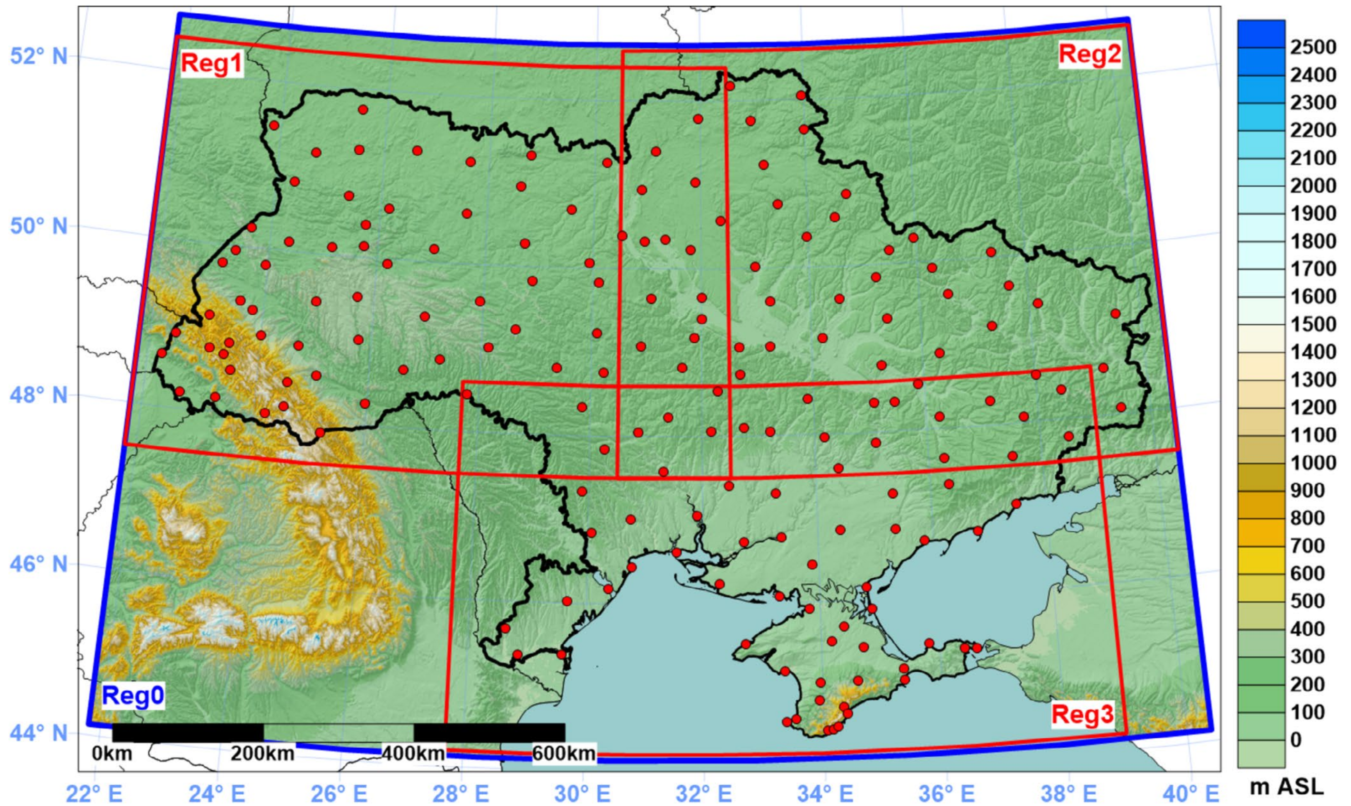

FIGURE 1 | Topography of the domain (Reg0) and spatial distribution of 178 Ukrainian weather stations (shown as red dots) used in the study. The red frames (Reg1, Reg2 and Reg3) denote overlapping regions where MISH gridding was performed individually.

consists of more than 20 fully tunable QC tests, which are applied to each station time series under study individually (with only exception when physical agreement between TN and TX time series at the same station, TN<TX, is considered through one of the software's tests). In our study, the tunable parameters were set according to the reference climatological information of Ukraine (Lipinsky et al. 2003). More detailed information regarding the INQC software and its QC tests can be found in (Aguilar 2019; Skrynyk et al. 2023).

In addition to INQC, the quality check of the data was also performed by means of the Climatol software (Guijarro 2023). Climatol is a modern homogenisation R package (https://CRAN.Rproject.org/package=climatol), it also provides valuable information about possible outliers, which are detected by comparison of a candidate time series with a corresponding reference composite one. The latter is created from a number of neighbour time series.

In our study, we performed several iterations of the QC procedure (with both INQC and Climatol packages). After each iteration, detected errors and suspicious values were compared with paper sources where it was possible (i.e., where we had corresponding photocopies obtained through the data rescue procedure) and respective corrections were made.

2.2 | Homogenisation

Homogenisation of the station time series was performed by means of the Climatol package. The detection algorithm of the package is based on the standard normal homogeneity test (SNHT) (Alexandersson and Moberg 1997), which is applied to an anomaly time series created by subtracting a composite reference series from the candidate series. Since SNHT was designed to detect a single break, it is applied iteratively, splitting the observed time series (or its segment) into two parts in every cycle until no break is found. This iterative procedure is applied twice: first, to stepped overlapping temporal windows, and then to a complete series/segment with tunable threshold parameters, *snht1* and *snht2*, respectively. Such a two-stage procedure allows minimising detection errors that occur when two or more shifts in the mean of similar size could mask its results. After all breaks are found, all missing data are estimated based on an orthogonal (type II) linear regression model. A more comprehensive description of the Climatol method can be found in the user manual (Guijarro 2023).

Climatol has been widely used recently to remove artificial artefacts from station raw data of many climate parameters on the monthly, daily, and even hourly time scales (e.g., Azorin-Molina et al. 2019; Coll et al. 2020; Dumitrescu et al. 2020; Kessabi et al. 2022). The first attempt to homogenise the Ukrainian daily precipitation (RR) and air temperature (TN, TG and TX) time series was performed in (Skrynyk et al. 2023). However, after publishing this paper, significant efforts have been made to complete missing periods/values as much as possible. Therefore, a new homogenisation run was necessary. Compared to (Skrynyk et al. 2023), we also slightly modified the homogenisation algorithm in order to have datasets adjusted to each other. For instance, the homogenised daily data should be consistent to some extent with the previously obtained quality controlled and homogenised monthly series (Osadchyi et al. 2018; Skrynyk et al. 2019; Palamarchuk et al. 2023). It should be mentioned for clarification that a substantial part of the monthly station data were digitised from other paper sources than the daily ones (namely, monthly reports, handbooks, etc), though essentially both datasets rely on the same station measurements. In addition, daily temperature time series, TN, TG and TX, should be adjusted to each other to show physically consistent patterns of temperature changes during a daily cycle (the inequality TN<TG<TX should be satisfied for each day of the period). One of the ways to do so is to use the same (or almost the same) sets of break points to homogenise TN, TG and TX station data, with the break confirmation (as much as possible) from available metadata.

In order to develop the set of break points common for all three air temperature variables (TN, TG and TX) we firstly performed homogenisation runs with Climatol parameters (*snht1* and *snht2*) which provide relatively large numbers of detected break points (as in test #3 of (Skrynyk et al. 2023)). Then, the common break points were selected by means of the following criteria (applied to each station): a break is included in the common list if (1) a break is observed in all three or any two climate parameters (time shift of 6 months is allowed); (2) a break is observed in any three parameters, but it is supported by the reported metadata (time shift of 1 year is allowed); and (3) a break is observed in any of the three parameters, but it is supported by at least two breaks detected by HOMER obtained when homogenising the corresponding monthly data (Osadchyi et al. 2018, 2022; Skrynyk et al. 2019) (time shift of 1 year is allowed). In such a way, we created a collection of 263 breaks, which were used to homogenise TN, TG and TX station time series. However, after the Climatol test run, 9 breakpoints for TN were removed from the common list due to their distorting influence on the homogenised time series (revealed after comparison with the corresponding homogenised monthly series). We would like to emphasise one more time that the applied criteria aimed to avoid the physical inconsistency between homogenised TN, TG and TX daily time series and also to adjust them (as much as possible) to the previously obtained dataset of monthly temperature time series, which were homogenised by means of the HOMER software. It is worth noting that the commonly available version of HOMER can be applied only on the monthly time scale. Homogenisation of atmospheric precipitation data was performed similarly to test #4 of (Skrynyk et al. 2023), with optimal values of parameters *snht1* and *snht2* obtained in a series of Climatol runs. Linear trends of climate parameters used in the homogenisation verification procedure were calculated by the ordinary least squares approach before and after homogenisation.

2.3 | Gridding

In order to perform gridding of quality-controlled and homogenised station time series (RR, TN, TG and TX), the software MISH (Meteorological Interpolation based on Surface Homogenised data basis) (Szentimrey and Bihari 2014) was applied. The MISH downscaling/interpolation software was created in the Hungarian Meteorological Service specifically for meteorological and climatological purposes. It is often used to perform interpolation of station time series with monthly (Mamara et al. 2017; Gofa et al. 2019; Skrynyk et al. 2020; Osadchyi et al. 2022), daily (Spinoni et al. 2015a; Izsák et al. 2022) and even hourly time resolution (Izsák 2023). MISH is a hybrid gridding approach (Szentimrey and Bihari 2014) which, along with deterministic interpolation algorithms, also uses geospatial stochastic modelling. MISH also takes advantage of utilising valuable climatological information contained inside long station time series in order to define statistical parameters (weighting factors) in the interpolation formulae. Depending on the statistical distribution of a climate parameter to be interpolated, two kinds of interpolation formulas can be used in MISH: additive (normal distribution, e.g. air temperature) and multiplicative (quasi lognormal distribution, e.g. atmospheric precipitation).

As it was mentioned in the Introduction, the gridding was performed using a standard longitude-latitude grid with a spatial resolution of $0.1° \times 0.1°$, approximately 10 km in both longitude and latitude directions. Similarly to the development of ClimUAm (Osadchyi et al. 2022), the grid was introduced for the whole territory of Ukraine (Reg0, Figure 1). However, due to some technical limitations of the MISH software, it was necessary to split the extended domain of Ukraine into three overlapping subdomains (Reg1, Reg2 and Reg3) where gridding was performed individually (Figure 1). Grids for Reg1, Reg2 and Reg3 were defined as parts of the common grid for Reg0. Using the overlapping areas, possible discontinuities in climate parameter fields over the whole Ukraine can be reduced by means of a harmonisation procedure (by averaging values from Reg1, Reg2 and Reg3 in common grid points). Compared to the development of ClimUAm (Osadchyi et al. 2022), we slightly extended overlapping regions, as daily fields of the climate parameters are much more spatially heterogeneous compared to monthly fields. In addition, in the harmonisation procedure, the averaging of values from Reg1, Reg2, and Reg3 was performed with weighting coefficients, which are proportional to inverse distances from a grid point to edges of the corresponding subdomain. It is worth noting that a similar harmonisation or blending procedure was applied by Brinckmann et al. (2016) to create a common European grid from several interpolation subdomains. Verification of the harmonisation procedure was performed mainly qualitatively, by building maps of the climate variables on different time scales (daily, monthly, yearly, multiyearly) with a detailed colour scale/legend.

In order to take into account geophysical and geographical peculiarities of a domain under study, the MISH software utilises additional deterministic predictors, such as altitude above sea level, distance to a coastal line of large water bodies, and the AURELHY principal components (Analyse Utilisant le RELief pour les besoins del' HYdrométéorologie) (Bénichou and Le Breton 1987), describing local topography in detail. Application of the former two is rather well approved: the dependence of climate variables such as air temperature on altitude or distance to a warm sea is well known. However, there are many cases when climatologically relevant processes, such as, for instance, orographic lifting of air masses (closely related to atmospheric precipitation occurrence), are influenced by morphological aspects and relative elevation differences of the local topography rather than by absolute altitude alone (Thomas and Herzfeld 2004). The AURELHY components, actually, provide such detailed morphological information to be used in climatological interpolation/geospatial modelling. Note that the AURELHY method, which is based on the AURELHY components, has been frequently used in many climatological works (e.g., Wotling et al. 2000; Thomas and Herzfeld 2004).

In our application of the software, we followed recommendations of MISH manual. Therefore, elevation above sea level, first 15 AURELHY components and distance to the Black and Azov seas were used as auxiliary deterministic predictors. First five AURELHY components calculated for the territory of Ukraine based on Digital Elevation Model data GTOPO30 (USGS 2018), as well as distances to the coastal line are shown in Figure 2. These first five components have clear physical meaning: AURELHY 1 (top left panel in Figure 2) indicates local peaks and valleys; AURELHY 2 (top middle panel) indicates north–south slopes; AURELHY 3 (top right panel) indicates east–west slopes; AURELHY 4 (bottom left panel) indicates north–south saddle and AURELHY 5 (bottom middle panel) indicated northeast-southwest saddle. Further components account for more subtle structures of the local topography.

Utilising the first 15 AURELHY components along with altitude is the default setting/configuration of the MISH software. However, MISH, through its modelling part, defines which of the provided covariates (auxiliary predictors) are important for a climate variable of interest at the domain under study and consequently are used in the interpolation. Usually, just several covariates are important and are retained in the interpolation procedure (Szentimrey and Bihari 2014).

Due to a lack of station data from neighbour countries, the interpolation results beyond the Ukrainian border are obviously not reliable. Therefore, after completing the MISH calculations and the harmonisation procedure, we cropped the grid and retained in the dataset only grid points belonging to the territory of Ukraine.

2.4 | Comparison of the Created Gridded Product With ClimUAm, ERA5-Land and E-OBS Data Sets

Finally, three statistical metrics, BIAS (or mean error), root mean square error (RMSE) and Pearson correlation (R), were applied to compare statistically the created dataset (ClimUAd) with existing gridded products, which have the same spatial resolution. Computation formulas for the metrics are well known (e.g., Wilks 2006). The only note should be made regarding R for air temperature data. A powerful seasonal cycle in TN, TG and TX time series observed in Ukraine significantly influences the calculated correlation, making R close to unity. In order to overcome this obstacle, instead of TN, TG and TX time series, their first differences series were used.

In addition to the observation-based gridded datasets, ClimUAm and E-OBS, in our comparison we also utilised ERA5-Land data, the land surface enhancement/refinement of ERA5, the latest global reanalysis product of the European Centre for Medium-Range Weather Forecast (ECMWF; Hersbach et al. 2020; Muñoz-Sabater et al. 2021). ERA5-Land as well as ERA5 have been used extensively in many climate studies and applications. Hourly ERA5-Land 2 m air temperature data were downloaded from the Copernicus Climate Data Store (CDS, https://cds.climate.copernicus.eu) and were converted to daily values by means of the Climate Data Operators (CDO) software (Schulzweida 2021). Calculation of TG daily values is rather straightforward, while TN and TX were calculated as daily minimum and maximum of corresponding hourly data of a particular day. Daily RR data were obtained from the CDS by extracting the values at 00UTC each day—these are totals for the previous 24 h, in accordance with the

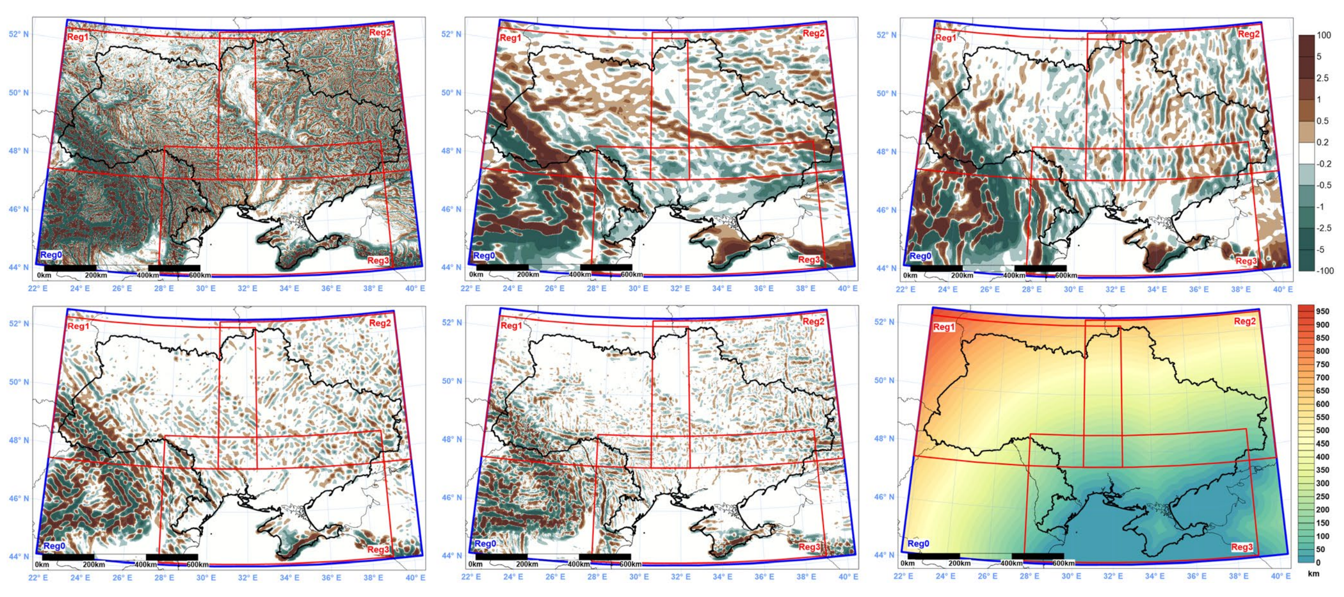

FIGURE 2 | Spatial patterns of first five AURELHY components (dimensionless AURELHY values are normalised by 1000) and distances to the coastal line of the Black and Azov seas.

description of accumulated variables in ERA5-Land (https://confluence.ecmwf.int/pages/viewpage.action?pageId=197702790). It is also worth noting that some part of the inconsistency between ClimUAd and ERA5-Land might come from different definitions of a day (00-00UTC in ERA5 and 21-21UTC since 1966 and 03-03UTC during 1946–1965 in ClimUAd). However, we believe that the different definitions of a day did not alter significantly the comparison statistics.

The E-OBS gridded daily observational data (Cornes et al. 2018) are provided as an ensemble dataset (20-member ensemble for each climate element) and are available with 0.1° and 0.25° spatial resolutions (https://www.ecad.eu/download/ensembles/download.php). However, in our study, we used only an ensemble mean realisation defined on the 0.1° regular grid. The data (v28.0) were downloaded from the Copernicus CDS. In addition, by means of the CDO software, we performed remapping of the E-OBS data since their grid is slightly shifted in space (by ~0.05° in both longitude and latitude directions) compared to the grid used to create ClimUAd. Such remapping (performed based on the bilinear interpolation) does not introduce large errors to the original E-OBS data since the spatial resolution was kept the same. Since E-OBS is created based on national daily datasets, the definitions of a day are the same in E-OBS and ClimUAd.

3 | Results, Discussion and Data Description

3.1 | Data Rescue and Quality Control

As it was already mentioned above, the significant amount of missing values/periods in the station time series was completed after publishing the first results on Ukrainian daily climate data (Skrynyk et al. 2023). The data rescue procedure resulted in the digitisation of meteorological records for almost all stations for each of the ECVs, mainly for the period of 1946–1960, less for the period of 1961–1991. The final time series completeness for all parameters is presented in Figure 3. Due to the data rescue procedure, the number of gaps in the datasets was reduced from approximately 10% (see Skrynyk et al. 2023) to about 5% for each climate variable. It is worth also noting that since the beginning of our work on the development of ClimUAd, we have rescued 3,571,778 daily values of RR, TN, TG and TX. This is a great amount of valuable climatological information, which should significantly increase the reliability of regional climate monitoring and analysis performed based on the developed dataset.

The summary of the QC procedure performed by means of INQC is presented in Table 1. Compared to the previous results of QC (Skrynyk et al. 2023), the number of errors for the maximum and minimum temperature has increased from 166

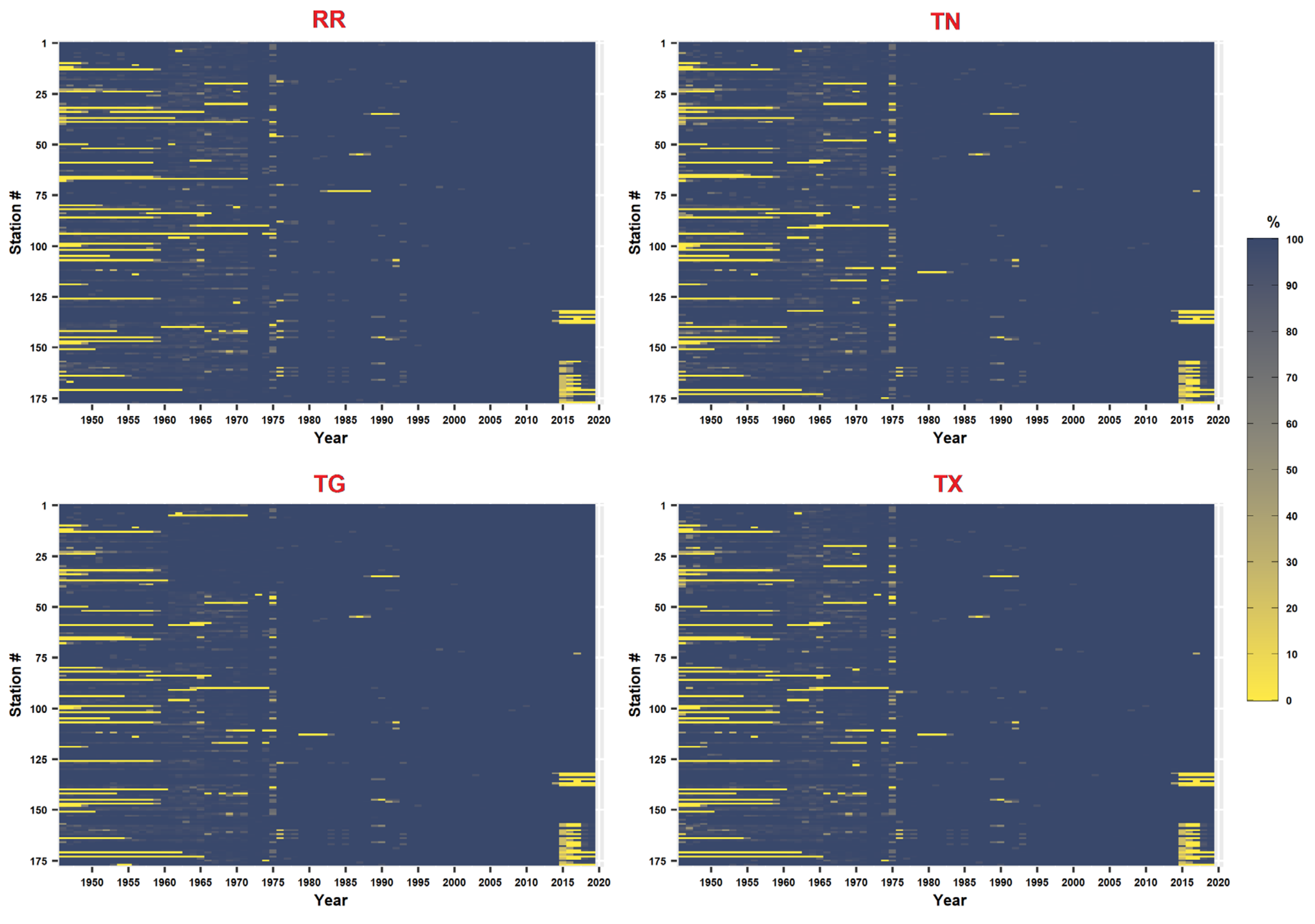

FIGURE 3 | Completeness of the station time series used in the development of the gridded dataset. The completeness is defined on a yearly basis as the percentage of available daily values relative to the number of days in a year.

TABLE 1 | Results of INQC applied to the daily time series of atmospheric precipitation and minimum, mean, and maximum air temperatures.

	Variable							
	RR		TN		TG		TX	
QC	Count	%	Count	%	Count	%	Count	%
Passed QC	4,623,015	94.81	4,628,924	94.93	4,642,717	95.21	4,627,063	94.89
Error	9	< 0.01	2015	0.04	139	< 0.01	1770	0.04
Almost certain, error	1939	0.04	932	0.02	2337	0.05	1489	0.03
Outlier, suspect	3725	0.08	3453	0.07	3437	0.07	3293	0.07
Collectively suspect[a]	1094	0.02	406	0.01	226	< 0.01	254	0.01
Missing	246,350	5.05	240,402	4.93	227,276	4.66	242,263	4.97
Total	4,876,132	100	4,876,132	100	4,876,132	100	4,876,132	100

[a]Values that, as individual observations are statistically and meteorologically valid, but when considered in view of the rest of the observations are not likely to be correct (e.g., repeated too many times in a short periods of time).

TABLE 2 | Number of checked, corrected, confirmed, and removed values after the QC iterative procedure (INCQ and Climatol).

	Variables				
QC	RR	TN	TG	TX	Total
Checked	6084	6085	6084	6086	24,339
Corrected	247	2231	1386	2156	6020
Confirmed	4202	2159	3054	2282	11,697
Removed	1635	1695	1644	1648	6622

to 1770 and from 502 to 2015 errors, respectively. The larger amount of errors is due to new data that were digitised since the previous study was published, and they originated mainly from a category when TN>TX. Totally, 1543 such cases were detected. Given that INQC revealed a fairly large number of TN>TX errors, it was decided to check the presence of other possible cases (TN>TG and TG>TX), which are not detected by the software. Our analysis revealed that there were 1331 cases when TN>TG and 1422 cases when TG>TX. All such errors were compared with paper sources (photocopies) if available.

In addition, the outliers from the Climatol exploratory runs were checked by comparison with available original paper records/photocopies. The outliers detected on both monthly and daily time scales were analysed. When checking the monthly outliers, all daily data belonging to a corresponding/suspected month were screened.

All errors detected at each of the QC stages, namely gross errors found by INQC iterations and Climatol exploratory runs, were combined and manually checked against the data in the photocopies (if available). If errors were proven, the corresponding values were corrected in the raw time series. If it was not possible to verify certain errors, they were removed and marked as missing. The summary of the examination procedure are presented in Table 2.

3.2 | Homogenisation

The primary output of the Climatol homogenisation procedure is a collection of daily time series, corrected and adjusted to different homogeneity segments, which were revealed for each station during the break points detection step. In our study, we used time series adjusted to the most recent segments. In addition, Climatol also provides corresponding homogenised monthly series. The latter were used in the comparison analysis where the Climatol results were verified against similar HOMER outputs (Osadchyi et al. 2018; Skrynyk et al. 2019; Palamarchuk et al. 2023), which can be considered as well approved. Figure 4 shows scatter diagrams of the Raw-HOMER and Climatol-HOMER corresponding pairs of the monthly data (for all stations together). As can be seen from the figure, the Climatol homogenisation reduces artefacts in raw data, approaching the Climatol homogenised monthly series to the similar HOMER results. For TN, TG and TX data, comparison metrics, BIAS and RMSE, show the reduction of their values after the homogenisation. For RR, the metrics slightly increased after Climatol application; however, simple visual inspection of the scatter diagram supports the conclusion about the removing of inhomogeneity artefacts. One of the possible reasons for larger discrepancies between the Climatol and HOMER homogenised precipitation data compared to TN, TG and TX is that in the HOMER application for RR, a substantially larger number of stations was used (224 against 178). As well as climatological stations, monthly atmospheric precipitation data from hydrological posts were also included in the analysis. Unfortunately, such data are not available at the daily scale. Therefore, we believe that Figure 4 demonstrates the acceptable agreement between the developed collections of daily and monthly homogenised station time series of Ukraine, obtained with Climatol and HOMER, respectively.

In order to additionally verify the performed homogenisation procedure, we converted time series to seasonal and yearly ones and calculated corresponding linear trend slopes. Such calculations were performed for each station before and after the homogenisation. Generally, a homogenisation procedure by removing artificial station signals should result in more self-consistent or more spatially homogeneous patterns of the slope distributions; consequently, statistical distributions of the slopes should be more compact. Figure 5 shows box plots of the trend slopes calculated for the yearly series. As can be seen from the figure, Climatol homogenisation reduces trend slope variability in the territory of Ukraine, making the time series more consistent with each other. With the exception of several outliers/stations, Climatol results are fairly close to HOMER ones. A similar reduction of the slope distributions is also observed on the seasonal scale (corresponding figures are not included into the text). It is worth noting that the ability of the Climatol software to preserve real linear trends in homogenised time series was shown in (Skrynyk et al. 2021). However, as shown in Figure 5 (leftmost panel), the median trend in the yearly precipitation series homogenised using Climatol is slightly higher compared to the median trends in the HOMER-homogenised and raw time series. The most likely reason for this difference could be the varying number of stations used in the homogenisation procedures performed with Climatol and HOMER for atmospheric precipitation, as well as differences in respective homogenisation algorithms.

3.3 | Gridding

After application of the MISH software, three files were obtained for each ECV (RR, TN, TG and TX). Two of them are data files, containing interpolated daily data for each grid point on the territory of Ukraine for each day of the period 1946–2020. The third file contains IDs of the grid points and their geographical coordinates. Data files are plain text files, storing precipitation/temperature values in the *csv* and *ser* formats (the latter is the MISH output format, which is formatted records suitable for FORTRAN reading/writing). The developed gridded daily data have been made freely available for research purposes through the web data repository of the Ukrainian Hydrometeorological Institute (https://uhmi.org.ua/eng/data_repo/). As an example of the gridding results, Figure 6 shows spatial patterns of multiyear mean values of yearly precipitation sums and minimum, mean, and maximum air temperature.

In order to evaluate the accuracy of the gridding, the MISH software provides as an output the results of a cross-validation procedure (Szentimrey and Bihari 2014). For each station, *RMSE* is calculated based on the formula.

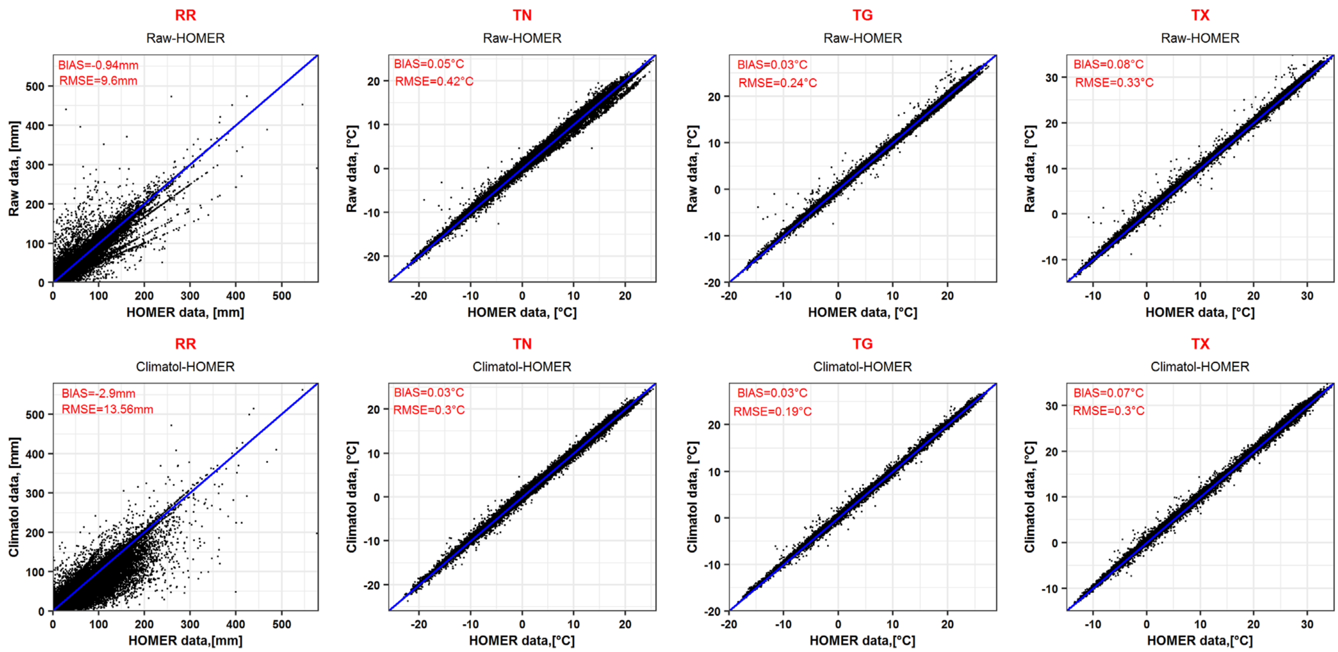

FIGURE 4 | Statistical comparison of the Climatol and HOMER results on the monthly scale.

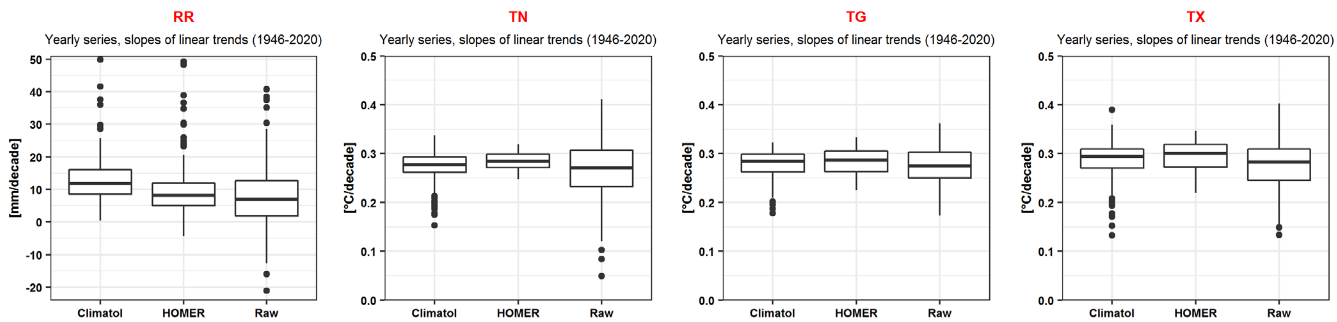

FIGURE 5 | Box-plots of trend slopes calculated for the yearly time series before and after the Climatol homogenisation. Similar results obtained based on the HOMER homogenised time series are shown for comparison.

$$RMSE(s) = \left(\overline{\left(Y(s,t) - \widehat{Y}(s,t) \right)^2} \right)^{1/2} \quad (1)$$

where $Y(s,t)$ is a measured value of a climate parameter at a station/spatial location s and time t, $\widehat{Y}(s,t)$ is a corresponding modelled/interpolated value, overline/overscore means averaging in time. Based on *RMSE* (1), the representativity (*REP*) of the interpolation is defined as follows.

$$REP(s) = 1 - \frac{RMSE(s)}{\sigma(s)} \quad (2)$$

where $\sigma(s)$ is a standard deviation of $Y(s,t)$ (i.e., $\sigma^2(s) = \overline{\left(Y(s,t) - \overline{Y(s,t)} \right)^2}$). *REP* is calculated for each station on the monthly basis. It is clear from (2), that the closer interpolated values $\widehat{Y}(s,t)$ are to corresponding measured ones $Y(s,t)$, the closer *REP* is to unity. Figure 7 demonstrates the representativity values averaged over all stations in the domains (Reg1-3). As can be seen from the figure, the accuracy of the interpolation of atmospheric precipitation is lower compared to air temperature variables. The yearly mean value of *REP* for RR is around 0.61. Amongst the temperature variables, the highest accuracy is observed for TG (around 0.91), while for TN and TX *REP* is slightly lower (0.84 and 0.88, respectively). Seasonal variations of the representativity are clearly seen for all ECVs, with maximum variations for precipitation data and minimum ones for TG. The minimal values of the accuracy are observed in summer months. Differences in the interpolation accuracy for the different regions are not clearly seen, though Reg3 (the one closest to the Black and Azov seas) shows slightly worse results. This can be related to the lack of reliable station data in this region for the last 5 years of the period under study. Generally, the accuracy of the gridding is fairly high for air temperature variables, while for atmospheric precipitation it can be considered as acceptable. The lower accuracy for RR is obvious, since spatial variations of atmospheric precipitation daily data are much more significant compared to air temperature.

3.4 | Comparison With Available Gridded Product

Firstly, we compare ClimUAd with the monthly version of Ukrainian climate data (ClimUAm) just to demonstrate their compatibility. Figure 8 shows the spatial distribution of the comparison statistics, BIAS, RMSE, and Pearson R, while Table 3 contains their averaged over all grid points values. Note that the statistics were calculated on the monthly scale (for monthly sums of atmospheric precipitation and monthly mean values of daily min, mean and max air temperature). As can be seen from the figure and table, all air temperature variables show exceptional accordance between ClimUAd and ClimUAm (with the highest agreement for TG). Atmospheric precipitations are less agreed, but the comparison metrics are still rather high.

Due to extensive use of ERA5-Land and E-OBS data in many modern climate applications (e.g., Gomis-Cebolla et al. 2023), it is interesting to know how large the differences are between these datasets and ClimUAd. As an example, Figure 9 shows spatial patterns of RR, TN, TG and TX for the selected day, July 7, 1990, which were built based on three datasets: ClimUAd, ERA5-Land, and E-OBS. This day was selected due to sharp spatial gradients observed in the four climate variables under study. As can be seen from the figure, even in such a complicated synoptic situation, all datasets show very similar spatial patterns. Figures 10 and 11 demonstrate spatial distributions of the comparison metrics, BIAS, RMSE, and Pearson R, calculated for ERA5-Land and

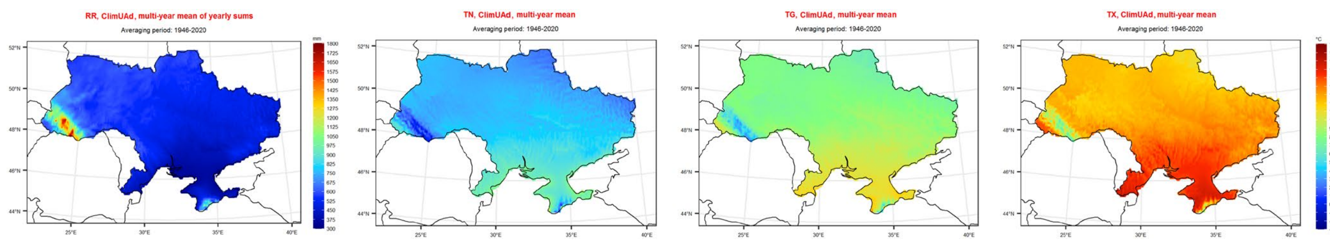

FIGURE 6 | Multi-year means (1946–2020) of yearly precipitation sums and air temperatures (TN, TG and TX) in Ukraine plotted based on the developed gridded data.

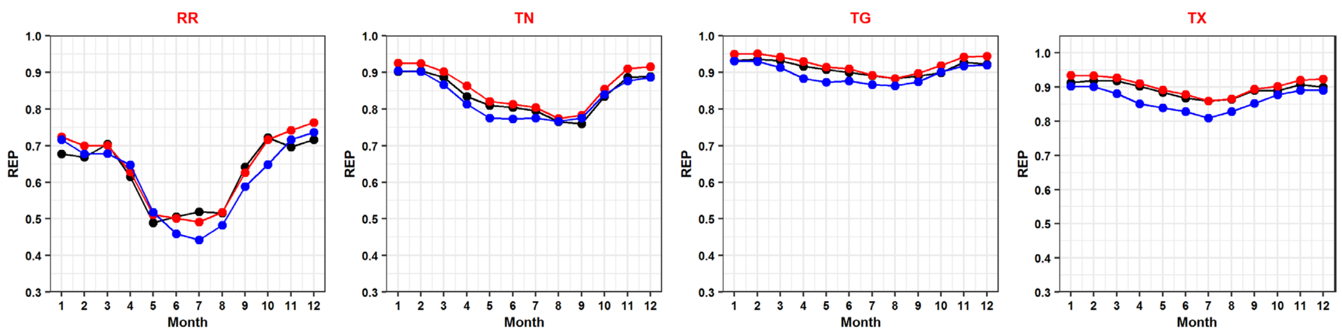

FIGURE 7 | Seasonal variations of the averaged over all stations representativity of the MISH gridding for Reg1 (black), Reg2 (red) and Reg3 (blue).

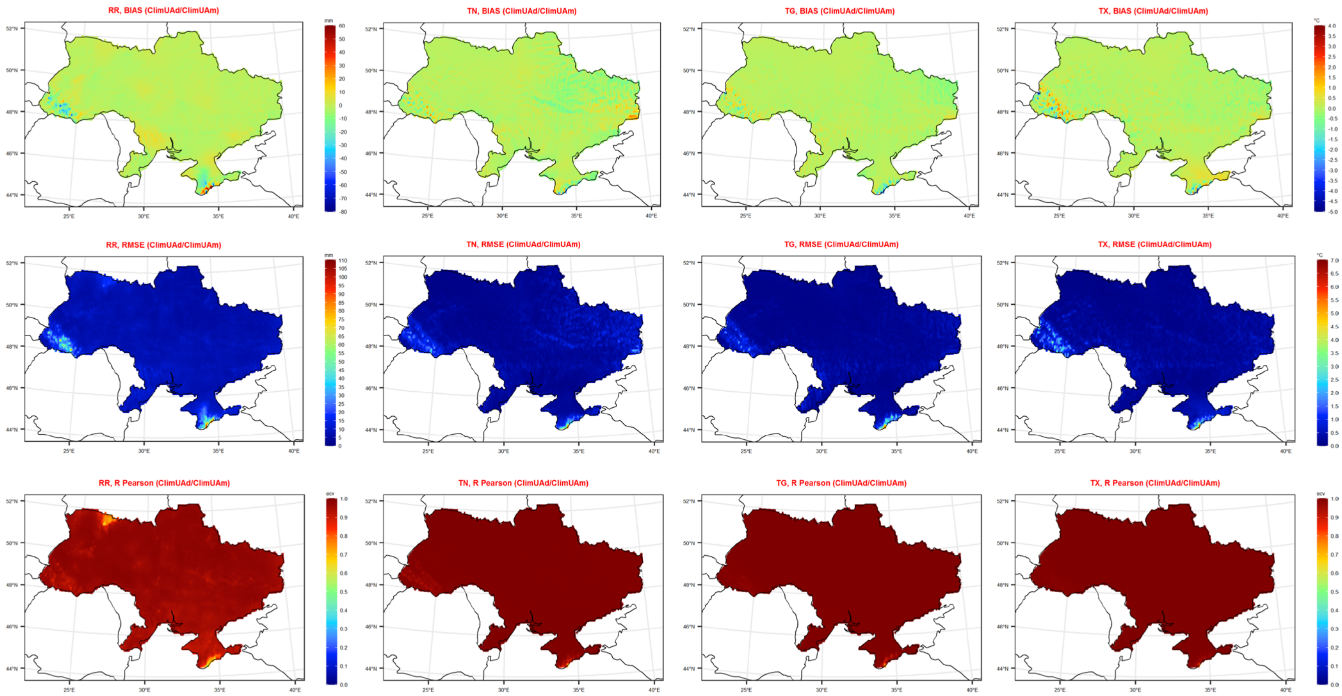

FIGURE 8 | Spatial distribution of comparison metrics, BIAS (top panel), RMSE (middle panel) and R. (bottom panel), calculated for ClimUAd and ClimUAm data on the monthly timescale.

TABLE 3 | Averaged over the whole territory of Ukraine comparison metrics, BIAS and RMSE (in [mm] for RR, [°C] for TN, TG and TX), and R, calculated between ClimUAd and three gridded products, ClimUAm, ERA5-Land and E-OBS.

		Climate variable			
Dataset	**Metric**	**RR**	**TN**	**TG**	**TX**
ClimUAm	BIAS	−1.29	−0.003	−0.001	0.008
	RMSE	8.22	0.30	0.22	0.25
	R	0.964	0.998	0.999	0.999
ERA5-Land	BIAS	−0.28	−0.59	−0.24	0.82
	RMSE	2.57	1.94	1.08	1.68
	R	0.61	0.77	0.90	0.86
E-OBS	BIAS	0.08	−0.33	−0.12	0.11
	RMSE	1.89	1.33	0.89	1.16
	R	0.78	0.87	0.92	0.90

Note: The evaluation metrics for ClimUAd were calculated at the monthly scale using ClimUAm, and at the daily scale using ERA5-Land and E-OBS.

E-OBS, respectively. Table 3 contains mean values of the metrics (averaged over the whole territory of Ukraine). As can be seen from the figures and table, data from ClimUAd are rather well agreed with both ERA5-Land and E-OBS, though the comparison metrics for E-OBS are slightly better. For both datasets, the highest agreement is observed for the TG variable, while atmospheric precipitation data show the largest discrepancies. All climate parameters for ERA5-Land and E-OBS have the largest discrepancies with ClimUAd in the regions with complicated topography, the Carpathian and Crimea Mountains.

It is also worth noting in the end that Ukraine will face a significant problem with observing climate data in the last several years due to the ongoing Russian aggression. Starting in 2014, the data from the Crimea peninsula and parts of the Donetsk and Lugansk regions are not accessible for Ukraine. The situation became even worse since the full-scale Russian aggressive war. Many stations have not had any possibility to perform measurements. Thus, we can expect significant missing periods in Ukrainian time series from the Eastern part of the country. The possible solution to recover the completeness of those time series could be the application of reanalysis data, such as ERA5-Land. This is the other reason why the performed statistical comparison is so important for further climate research in Ukraine. Definitely, we should keep in mind that the reanalysis data also rely to some extent on the station observations through a data assimilation process. Consequently, the absence of the station data at some part of Ukraine during the last years can worsen the reanalysis data for such regions and periods. But, in our case, any data would be better than nothing.

4 | Conclusions

In this work, we presented the observation-based daily gridded dataset, ClimUAd, developed for Ukraine for the period of 1946–2020 (75 years). The data have a rather high spatial resolution of 0.1° (~10 km) in both longitude and latitude directions. Four essential climate variables, namely atmospheric precipitation, minimum, mean, and maximum air temperature, were included in the created gridded product. The elaborated data are based on the almost complete collection of station measurements performed at 178 Ukrainian weather stations. The station time series were thoroughly quality

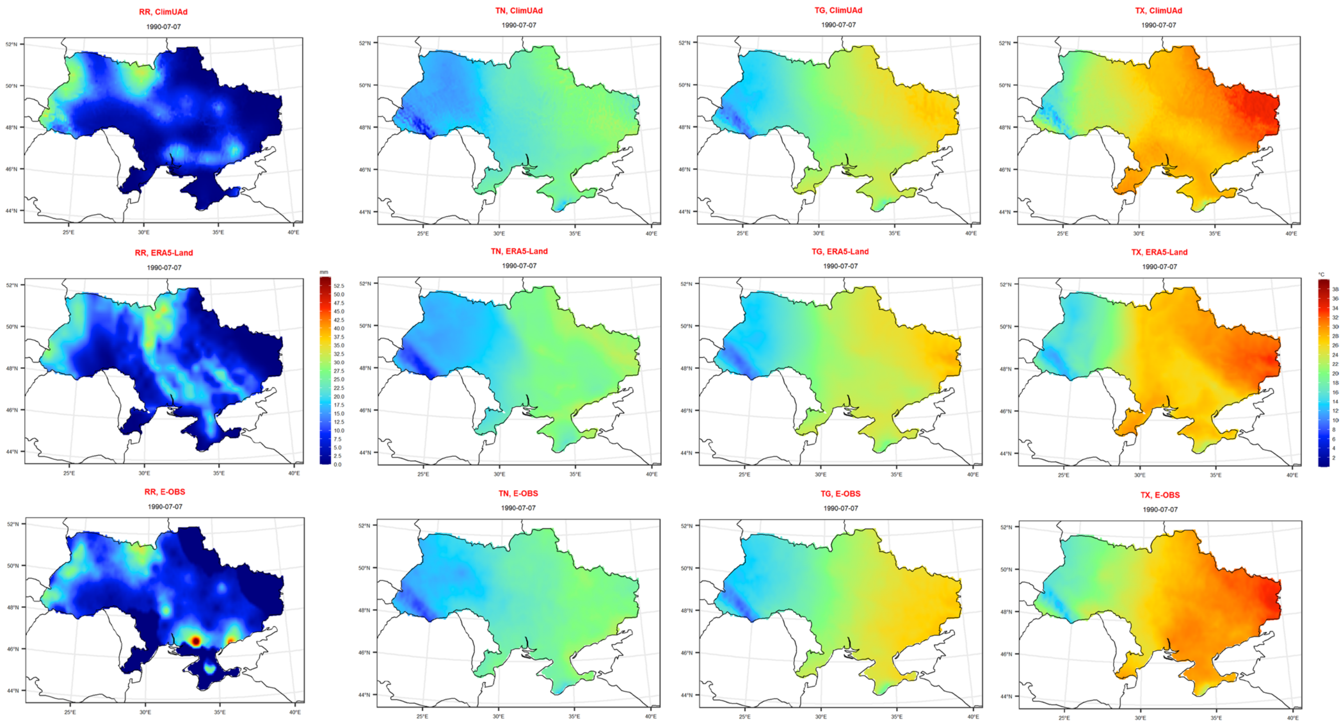

FIGURE 9 | Spatial patterns of daily RR, TN, TG and TX for a selected day (July 7, 1990), built based on three data sets: ClimUAd (top panel), ERA5-Land (middle panel) and E-OBS (bottom panel).

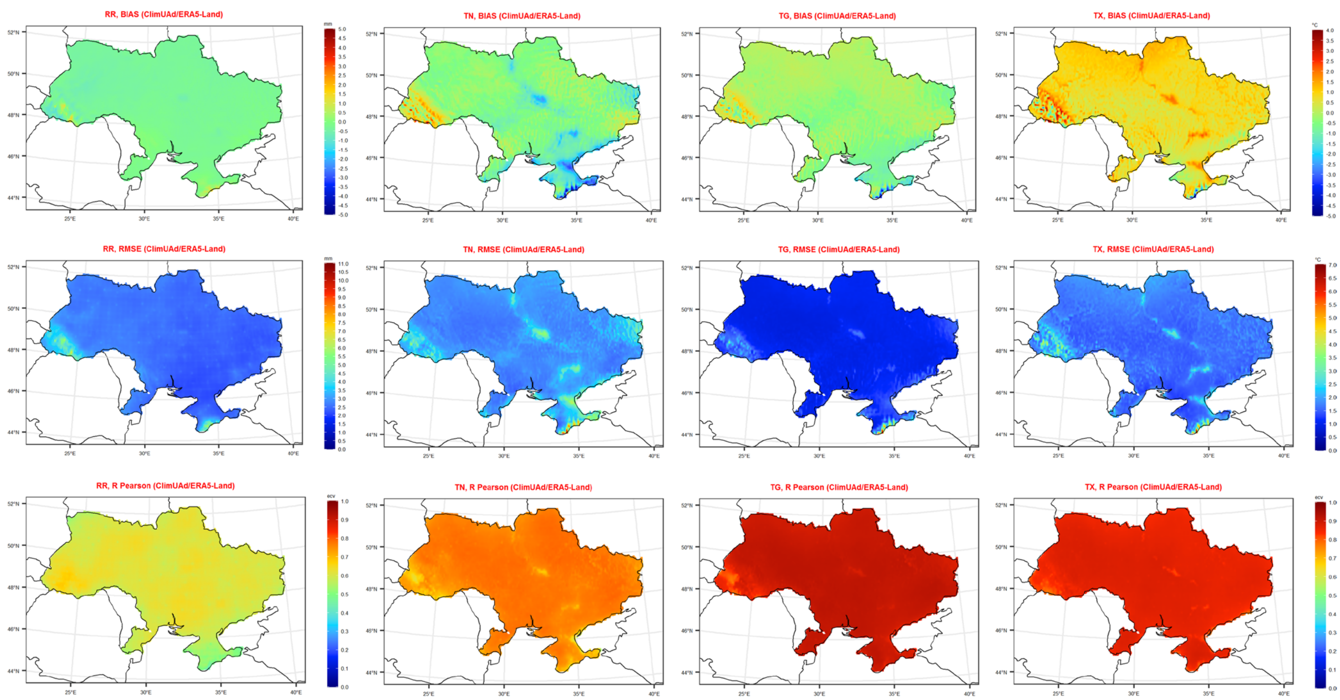

FIGURE 10 | Spatial distribution of comparison metrics, BIAS (top panel), RMSE (middle panel) and R (bottom panel), calculated for ClimUAd and ERA5-Land data on the daily timescale.

controlled and homogenised by means of the modern and well-established software, INQC and Climatol. The gridding (geospatial modelling) was performed with the sophisticated MISH software, recently used in many climate applications. The statistical comparison showed good accordance between the developed product and ClimUAm on the monthly scale and acceptable agreement with the E-OBS and ERA5-Land data on the daily scale.

The gridded time series of Ukraine have the great potential to be used in regional climate monitoring studies and as a reference for many climate applications for the territory of the

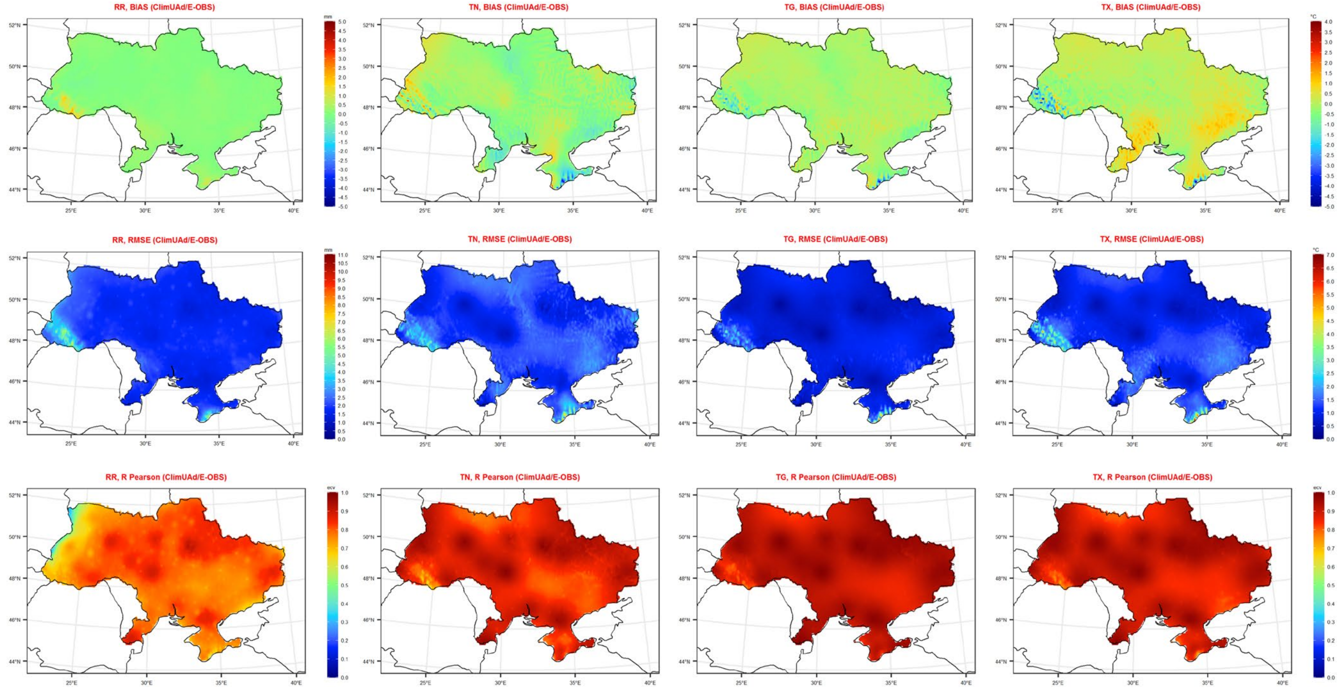

FIGURE 11 | Same as in Figure 10, but calculated for ClimUAd and E-OBS data on the daily timescale.

country. The developed dataset was made freely available for research purposes via the data repository of the Ukrainian Hydrometeorological Institute (https://uhmi.org.ua/eng/data_repo/).

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Data Availability Statement

The data that support the findings of this study are openly available in UHMI data repository at https://uhmi.org.ua/eng/data_repo, reference number https://doi.org/10.15407/uhmi.report.03.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.