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Zbigniew Ustrnul[1], Julia Sałaja[2], Agnieszka Wypych[3]

GRIDDED DATA IN THE CONTEMPORARY CLIMATOLOGY (REVIEW AND ASSESSMENT BASED ON THE EXAMPLE OF POLAND)

Abstract: The main goal of the work is to present contemporary possibilities of using climatological data sources, which are increasingly stored in the form of grids. The essence of these data was discussed against the background of traditional data based on classic station measurements (in-situ). The most famous available databases and their advantages are presented, which allow for their convenient use using GIS. In the last part, gridded data from the ERA5 database was validated based on in-situ data for Poland. Daily air temperature and precipitation values from the period 1991–2020 were taken into account for the analysis. The results indicate a good quality of the gridded data used in the case of average temperature values, however poorer in the case of daily minimum temperature values as well as daily precipitation sums. The research results confirm that gridded data offers many possibilities for regional analyses, but for some micro-scale application purposes it may be not sufficient enough.

Keywords: meteorological and climatological data, gridded values, reanalysis, validation methods, Poland

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[1] Jagiellonian University, Faculty of Geography and Geology, Institute of Geography and Spatial Management, Institute of Meteorology and Water Management, Department of Climatology, Kraków, Poland, ORCID ID: https://orcid.org/0000-0003-0957-4396, email: zbigniew.ustrnul@uj.edu.pl

[2] Institute of Meteorology and Water Management, Kraków, Poland, ORCID ID: https://orcid.org/0009-0001-0108-327X, email: Julia.Salaja@imgw.pl

[3] Jagiellonian University, Faculty of Geography and Geology, Institute of Geography and Spatial Management, Institute of Meteorology and Water Management, Department of Climatology, Kraków, Poland, ORCID ID: https://orcid.org/0000-0002-5379-5834, email: agnieszka.wypych@uj.edu.pl

Introduction

In the second half of the last century, the so-called gridded data have been introduced into operational meteorology. Briefly speaking, these data are calculated for the nodal points of the geographical grids. This net is formed by regular points, most often in the form of squares or rectangles, less often other geometric figures. Regular data structure allows for relatively simple data processing and their further analyses. Gridded data were the basis for current weather analyzes and were used to record prediction prognostic meteorological fields. Their main advantage was a simpler assessment of spatial diversity, often without the need to use various interpolation methods.

Over the last 2–3 decades, these data have become a significant source of information in the field of climatological research at various time and spatial scales. This has caused a huge development in the use of new sources of meteorological data in modern climatology. While many studies around the world still use meteorological data based on station data (in-situ), gridded data are increasingly the basis for analyses, especially spatial ones. This also facilitates the assimilation of such data for climatological analyzes using GIS (Ustrnul, 1997; Wyszkowski, 2001; Dyras et al., 2005; Ustrnul & Czekierda, 2005). Data values represent a specific grid point (node) or the entire area around a given grid (gridbox). The spatial (horizontal) relations between individual points are illustrated in Fig. 1.

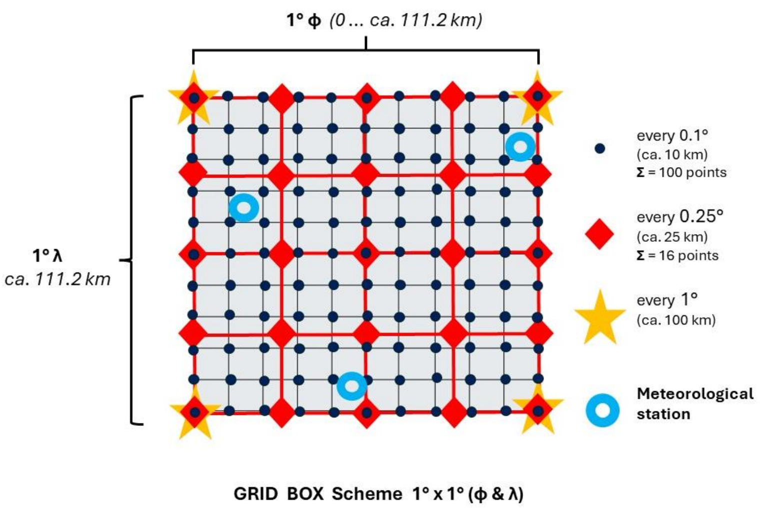

Fig. 1. Spatial resolution of selected gridded databases
Source: own study

So where does gridded data come from? In the case of climatological measurements, gridded data is the result of various interpolation methods, including statistical downscaling techniques. Meteorological models, especially forecasting ones, thanks to the numerical weather prediction methods, provide information on the most probable, past state of the atmosphere at precise locations. When including assimilation of the data obtained from various measurement sources they are called reanalyses. They are generated using models of a different advancement, including GIS spatialization methods. According to the ECMWF (European Center for Medium-Range Weather Forecasts) website, 'ECMWF uses its forecast models and data assimilation systems to 'reanalyse' archived observations, creating global data sets describing the recent history of the atmosphere, land surface, and oceans' (https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets). A slightly different, although very clear, explanation of the term 'reanalyses' can be found on the EU program website which says that they combine past observations with models to generate consistent time series of multiple climate variables. Reanalyses are among the most-used datasets in the geophysical sciences. They provide a comprehensive description of the observed climate as it has evolved during recent decades, on 3D grids at sub-daily intervals' (https://climate.copernicus.eu/climate-reanalysis).

In addition to the above-mentioned reanalyses, gridded databases can also be created using simpler, mainly geostatistical, models. Creating such data involves data gridding of previously acquired in-situ measurement data.

The most common contemporary climatological gridded databases.

As can be seen from many articles, reanalyses are very popular and used for monitoring climate change, in research and education, as well as for commercial applications (e.g. Domínguez-Pelosi et al., 2020). It even seems that there would be no modern climatology without the use of this type of data. As stated above, the history of creating and especially using gridded data in climatology is relatively short compared to the length of the series of meteorological instrumental measurements. The first databases, although still very poor, were created in the United States in the 1990s. Thanks to NOAA (National Oceanic Atmospheric Administration) and various teams operating within this powerful scientific institution, reanalyses were created covering data from various areas of atmospheric and environmental sciences (https://psl.noaa.gov/data/gridded/). The oldest reanalyses include various geophysical fields and have been available since the late 1990s. In a monumental work with thousands of citations in the literature, the fundamentals of this database was presented (Kalnay et al., 1996). This database, supplemented after a few years with another 10 years of data (Kistler et al., 2001), has become an inspiration for many global research teams that develop data assimilation methods and implement them in increasingly better generation of new databases. Moreover, in recent years, new databases have been established within NOAA which have significantly enriched the resources compared to the first version. This significant improvement is essentially an increase in spatial and temporal resolution and the inclusion of many new data parameters.

Most of them use modeling and provide ready-made products which can directly be further processed and used. The last significant expansion of these databases within NOAA, combined with structural changes, took place in 2020. Since that time Physical Sciences Laboratory and the three other NOAA laboratories in Boulder, Colorado (Chemical Sciences Laboratory – CSL, Global Monitoring Laboratory – GML, Global Systems Laboratory – GSL) continue close collaboration generating new data to improve understanding and ability to predict changes in atmosphere, weather and climate. Finally, it is worth mentioning that many climatological databases have a global dimension and their time resolutions range from individual measurement dates (usually every 6 hours) to daily or monthly values. Recently, a new gridded database has been made available dedicated to the reconstruction of climate conditions on a global scale since the first half of the 19th century (Slivinski et al., 2019; Slivinski et al. 2021; https://psl.noaa.gov/data/20thC_Rean/).

The United States used to be a world leader in possessing and sharing climatological data for various purposes. However, in recent years, thanks to cooperation under the European Union's Copernicus program, several professional gridded databases have been created also in Europe. In many respects, they are equal to or even superior to NOAA's reanalyses. This is largely due to the activities of the ECMWF consortium, which brings together various scientific institutions and meteorological services of many countries. Modern data assimilation methods, detailed spatial and temporal resolution and variety of meteorological variables set ECMWF's reanalyses among the best and the most often used also outside Europe. Currently, thanks to the ECMWF consortium, several gridded databases are available. They differ in the scope of data availability and temporal and spatial resolution. Their full list is available on the website with descriptions and links to them: https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets. The ERA5 database is considered the latest climatological database, in which climatological data are available from the current period back to 1940. Its basic horizontal resolution is 0.25° of longitude and latitude. The scope of data availability and their resolution depends on the size of the domain. The biggest one is for the entire Europe. The detailed scope of data availability changes very often, so it is difficult to determine its exact content, even in relation to meteorological fields. To obtain such information, please follow the web page address provided above. Although the climatological database with the above-mentioned resolution (0.25°) seems to be very good, its sister version ERA5-Land (only for land areas) has been prepared, where the resolution reaches 0.1°, i.e. about 10 km in the middle latitudes.

The recently developed and published ModE-RA reanalysis (https://www.wdc-climate.de/ui/project?acronym=ModE) contains slightly different data. It is used to assess changes and variability of climate over the last 600 years. Thanks to the use of various types of data, its creators have recreated the history of climate on a global scale, which is used for many analyzes with the help of various software tools (https://mode-ra.unibe.ch/climeapp/; Valler et al., 2024).

In addition to the above climatological databases, including the most famous and recognized NOAA/NCEP and ERA5, which are typical reanalyses, regional or local databases have been created in many countries, mainly in national meteorological services. They not only have a limited spatial dimension but also contain data on only some climate elements. At this point, however, it should be noted that some of these databases are not typical reanalyses, i.e. the data come from measurements and were most often interpolated using various geostatistical methods. However, the question arises to what extent modeling was carried out and what spatialization methods were included in generating data in grids. If these were, for example, physical downscaling methods, it can be considered that such data also have the features of reanalysis. Otherwise, the use of simple geostatistical methods (e.g. kriging, IDW, RBF) does not entitle such data to be called reanalyses, although in such cases we are dealing with a simple geostatistical model allowing the generation of gridded data.

Currently, there are many climatological gridded databases available in the world, which have not been created by any classic reanalyses. Due to the availability of data, two of them are worth mentioning: E-OBS dataset and HadCRUT4. The E-OBS gridded dataset database (https://www.ecad.eu/download/ensembles/download.php), also sometimes called ECA&D (European Climate Assessment and Dataset), was created in 1998 thanks to the European Climate Support Network (ECSN) initiative, which was to create a climatological database for Europe. Since its creation, this database has been constantly developed, improved and enriched with new data. Currently, this database, financially supported by the European Union and EUMETNET, contains many products, from classic gridded data to station measurement data (in-situ). This database, in addition to standard meteorological data of many elements, also includes pre-processed data that can be treated as climatological indicators (Cornes et al., 2018). The HadCRUT4 database (https://crudata.uea.ac.uk/cru/data/hrg/) is a British product prepared by the Hadley Center and Climate Research Unit consortium. It contains data for several climate elements dating back to 1901 with a resolution of 0.5° (Harris et al., 2020) or a database covering only air temperature for the entire globe from 1850 to the present, but with a grid resolution of 5° (Morice et al., 2021; Osborn et al., 2021).

Against the background of the above gridded databases with a regional or local scope are worth to be mentioned. First of all, we should mention the global database 'Global Precipitation Climatology Center (GPCC)' developed thanks to the activities of the Deutscher Wetterdienst (DWD) (https://www.dwd.de/EN/ourservices/gpcc/gpcc.html). Moreover the Climate Data Center (CDC) of the Deutscher Wetterdienst (DWD) has created other databases covering individual meteorological elements with different temporal and spatial resolutions (https://www.dwd.de/EN/ourservices/cdc/cdc_ueberblick-klimadaten_en.html). Among other databases that were created thanks to extensive international cooperation, the ALPCLIM database for the Alps area is worth mentioning (https://www.zamg.ac.at/cms/de/forschung/klima/zeitliche-klimaanalyse/alpclim). The ALPCLIM contains gridded values of atmospheric precipitation (Auer et al., 2001). The newer HISTALP database (https://www.zamg.ac.at/histalp/) covers several basic climate elements (Auer et al., 2007). Although both of these databases contain data only with monthly resolution, they constitute the basis for assessing climate variability in the Alps and adjacent areas dating back to the 18th century.

Other example databases are NORDCLIM (https://cds.climate.copernicus.eu/datasets/insitu-gridded-observations-nordic?tab=overview) and CARPATCLIM (http://www.carpatclim-eu.org/ pages/home/). They were created as a result of international cooperation based on measurement and observation data for Northern Europe and the Carpathians, respectively. In these databases, the values were gridded using GIS methods. In both databases, the temporal resolution of the data is daily and the spatial resolution is 1 km and 0.1°, respectively. Another example of a grid product is the recently released local database for Poland (PL1GD-T). Unfortunately, it contains data covering daily air temperature at a spatial resolution of 1 km for the period 1951–2020 (Jaczewski et al., 2024).

The above overview of various climatological gridded data databases does not cover many other local databases that are constantly being developed and improved. Despite this, it presents contemporary access to meteorological and climatological data, which is very wide and practically allows for conducting any analyzes of both scientific and purely applied importance. The reason for this state of affairs lies in the properties of gridded data, which have many advantages, among which it is worth mentioning:

- Regular spatial distribution of data facilitating further processing;
- Easy assimilation into GIS systems;
- Ensuring spatial and temporal continuity (there are usually no missing data in the databases);
- The existence of preliminary quality control and, in many cases, the existence of data homogeneity;
- Providing information on multiple meteorological fields;
- Relatively good temporal and spatial resolution.

Of course, grided data also has certain limitations that are worth remembering when using them. The most important thing is low accuracy of the data, especially in the case of intermittent meteorological fields, such as precipitation as well as detailed spatial and temporal resolution. Creating this data (regardless of whether we are dealing with reanalyses or other gridded data based on in-situ data) requires 'smoothing' the data and thus ignoring outliers, especially those occurring on a small scale. Despite these limitations, based on the above-mentioned review of gridded data, one can conclude that they are of great value and, therefore, can replace station (in-situ) data. It can even be said that the currently available gridded data makes it possible to abandon traditional data. However, this statement is only purely theoretical and, both in the light of the literature and the analyzes carried out for Poland, is incorrect (Miętus (ed.), 2009). When used professionally, these data require quality control and validation. In the literature you can find many examples of such analyzes that compare the results of in-situ data with gridded data (e.g. Hofstra et al., 2009; Behnke et al., 2016; Mourtzinis et al., 2017; Ahmed et al., 2019; Jiao et al., 2021; Pelosi et al., 2021) as well as compare the results of different gridded databases (e.g. Karger et al., 2020; Pelosi et al., 2020; Almeida & Coelho, 2023).

Material and methods

Validation of gridded data (based on the example of Poland).

The use of gridded data, like other spatial modeling results, should be preceded by their validation using in-situ data. In this study, two key meteorological elements were assessed, i.e. air temperature and precipitation totals. Validation was made on the basis of synoptic stations located in Poland (IMGW-PIB measurement and observation network, Fig. 2) and data from the currently most frequently used climatological reanalysis database, ERA5. The latest thirty-year research period (in climatology called the normal period), covering the years 1991–2020 was used.

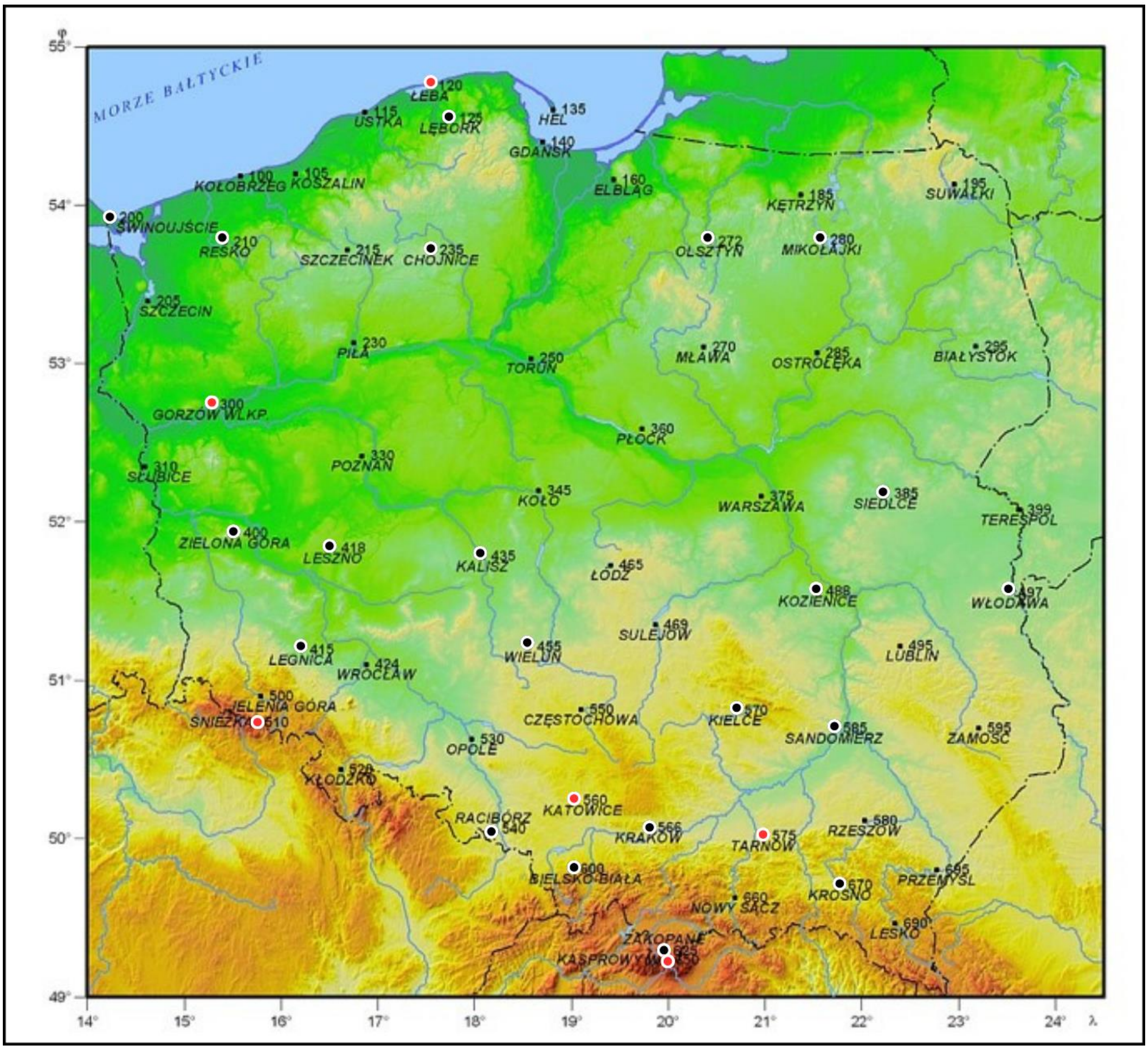

Fig. 2. Location of the synoptic stations used in the study with their nearest gridpoint neighbours information: red dots – distance < 5 km, black dots – distance < 10 km, subset for detailed analysis – marked by white halo
Source: own study

It is worth adding that in addition to weather dependent analysis, a whole range of different indicators can be used in this type of studies (Tveito et al., 2008). In this article root mean square error (RMSE) and the Pearson's correlation coefficient (R) have been used as the most frequently applied validation metrics (Ustrnul, 2006).

First, average values of daily air temperature and daily precipitation totals from the in-situ and grid series were also calculated for the points closest to the meteorological stations. As we know, both of these elements are treated as the leading ones and most often used in in climate studies. Detailed validation was carried out for 6 meteorological stations, where the horizontal distance between the station and the nearest grid point did not exceed 5 km. Independently, analyzes were also carried out taking into account 2 meteorological stations in Krakow (historical station: Krakow-Observatory (Krakow-Obs.) located in the city center and synoptic – airport station: Krakow-Balice, WMO no. 12566). The values from these 2 stations were considered as the reference and compared with gridded data from the ERA5 database and, additionally, ERA5 Land.

Results and discussion

As seen in Fig. 3, illustrating the differences in the average daily temperature in 2010 between the above-mentioned series, they may sometimes even exceed 2°C, which should be considered quite significant values. While most of the year their range does not exceed +/- 2°C, higher values occur in winter. Therefore, the values for this period were additionally compared over many years. Differences in daily rainfall sums were presented in a similar way for the same year. As could be expected, they are highest in the warm half-year, which should be associated with the convective nature of precipitation. Usually, they are intense but have a very limited spatial character.

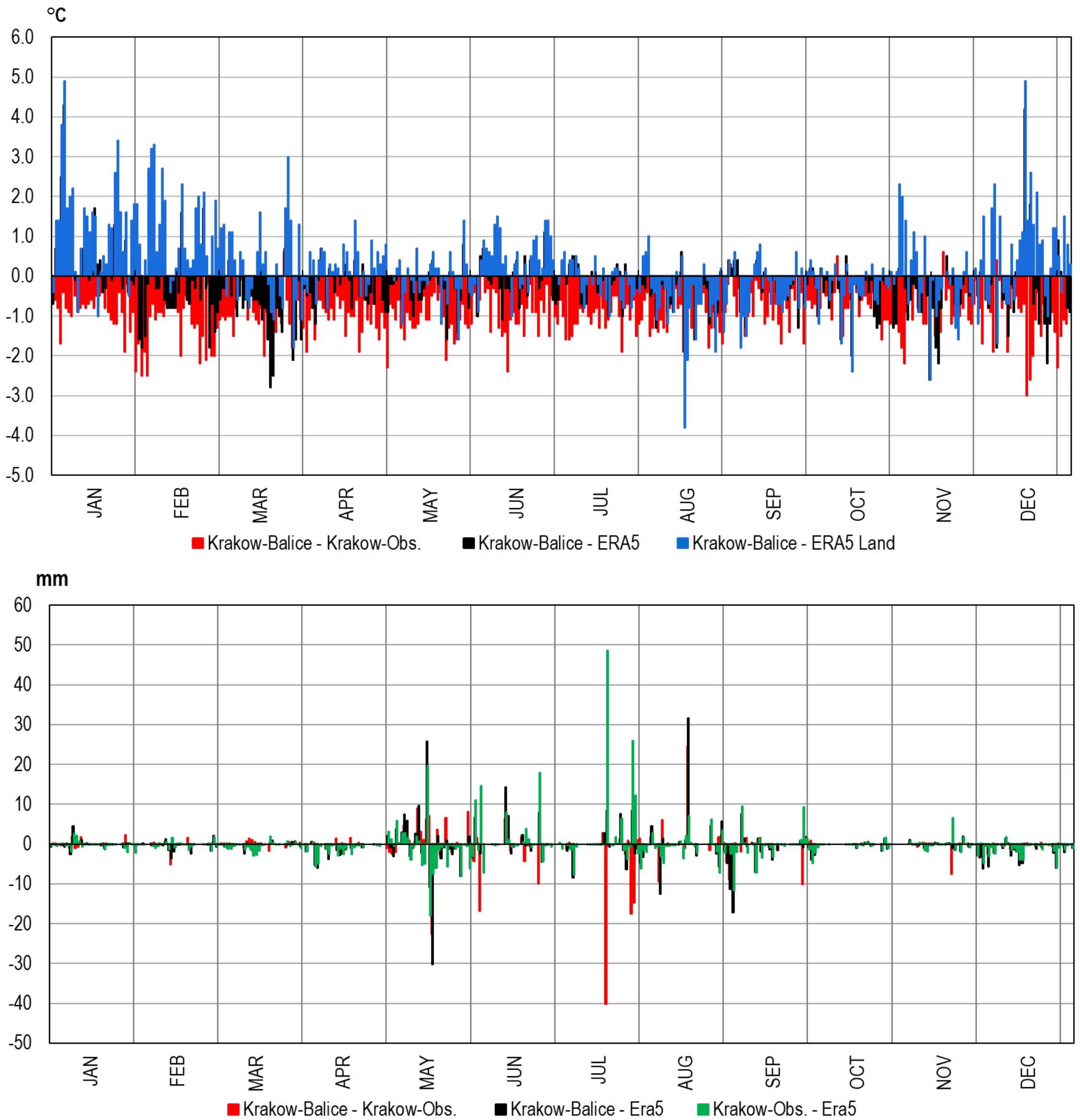

Fig. 3. Differences of mean daily air temperature and precipitation totals between the stations data and the gridded series – the example of 2010
Source: own study

For example, Fig. 4 shows the differences between the 2 stations Krakow-Obs. and Krakow-Balice. The average daily temperature between these stations may differ by up to 2.5°C, which is not the result of the horizontal distance between them (7.2 km) but of the location in completely different local conditions. The Krakow-Obs. station is an urban one with an influence of the urban heat island, while the other station is located beyond this influence. And although this last station is 10 km away from the grid point it is much more consistent with data from the ERA5 database. These differences are visible when assessing average values for the entire 30-year period 1991–2020. While in the case of the Krakow-Obs. station the annual average is higher than the grid average by 0.6°C (Table 1), in the case of the Kraków-Balice station there is no difference at all (Table 2). Both tables (Table 1 and 2) also include values for individual months and the range of average temperature differences calculated in individual years. In the case of precipitation, higher average monthly totals are noted at stations in winter, but in summer they are similar.

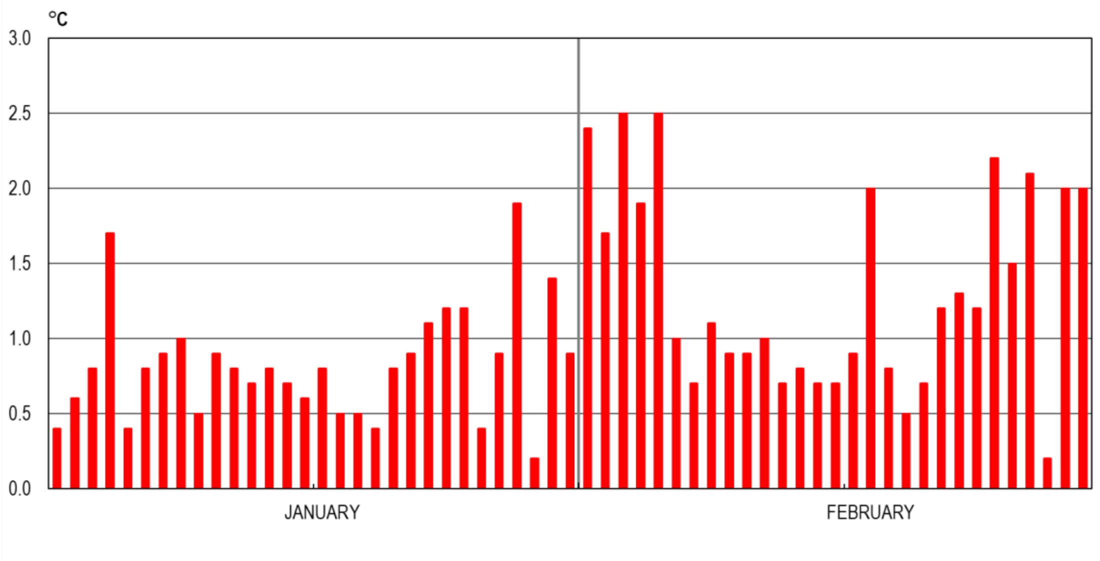

Fig. 4. Differences of mean daily air temperature values between the stations data (Krakow-Obs. and Krakow-Balice) – the example of January and February 2010
Source: own study

Finally, on the basis of 6 stations (located less than 5 km from the nearest grid point), correlation coefficients and RMSE values for the year, winter and summer were calculated for daily data (Table 3). The data is quite consistent. However, as could be expected, in the case of daily rainfall totals it is lower than in the case of air temperature. This is particularly visible in the summer, when convective and very local rainfall often occurs, which must be reflected in the calculated indicators.

Table 1. Differences (Δ, grid vs. observation) between mean monthly and annual air temperature (absolute, T) and precipitation totals (relative, RR) – the example of Krakow-Observatory station, 1991–2020

month	Temperature [°C]			Precipitation [%]		
	ΔT_{av}	ΔT_{max}	ΔT_{min}	ΔRR	ΔRR_{max}	ΔRR_{min}
January	-0.5	0.5	-1.4	134.9	227.4	97.1
February	-0.4	0.2	-1.0	155.5	317.8	93.1
March	-0.3	0.6	-0.9	151.4	231.5	110.4
April	-0.6	0.0	-1.0	130.5	1542.3	77.4
May	-0.9	-0.5	-1.3	116.7	233.6	64.8
June	-1.1	-0.6	-1.5	116.4	451.1	70.7
July	-1.0	-0.5	-1.4	109.5	269.2	48.3
August	-0.7	-0.1	-1.2	105.2	222.6	24.7
September	-0.4	0.2	-0.7	109.2	202.4	64.5
October	-0.3	-0.1	-0.6	119.6	249.6	90.8
November	-0.4	0.6	-0.9	125.0	240.1	86.7
December	-0.4	0.6	-1.3	151.9	237.7	90.3
YEAR	-0.6	-0.3	-0.8	121.8	146.2	101.2

Source: own study

Table 2. Differences (Δ, grid vs. observation) between mean monthly and annual air temperature (absolute, T) and precipitation totals (relative, RR) – the example of Krakow-Balice station, 1991–2020

month	Temperature [°C]			Precipitation [%]		
	ΔT_{av}	ΔT_{max}	ΔT_{min}	ΔRR	ΔRR_{max}	ΔRR_{min}
January	0.2	1.4	-0.8	134.6	303.2	99.4
February	0.2	1.0	-0.8	160.6	394.2	70.3
March	0.2	1.5	-0.5	152.6	322.1	98.4
April	-0.1	0.5	-0.7	136.1	396.0	90.5
May	-0.3	0.4	-0.8	122.0	275.5	58.3
June	-0.4	0.1	-0.9	122.7	1152.4	66.4
July	-0.3	0.3	-0.9	109.9	266.3	34.3
August	-0.2	0.5	-0.8	109.1	201.4	38.3
September	-0.1	0.5	-0.5	116.6	297.8	80.1
October	0.1	0.5	-0.4	124.1	275.3	88.2
November	0.1	0.9	-0.5	126.3	888.1	89.2
December	0.3	1.0	-0.8	147.8	446.8	85.2
YEAR	0.0	0.3	-0.3	125.4	157.3	106.5

Source: own study

Table 3. Pearson's correlation coefficient (R) and root mean square error (RMSE) values for daily air temperature and precipitation totals calculated for selected synoptic stations and relevant neighboring grids (red dots at Fig. 2) 1991–2020

season	Temperature		Precipitation	
	R	RMSE [°C]	R	RMSE [mm]
Year	0.998	1.2	0.976	2.4
Winter	0.991	1.2	0.981	1.7
Summer	0.999	0.9	0.924	3.1

Source: own study

Conclusions

A comprehensive review of the literature and the results of many works, including those obtained for Poland, allow the following conclusions to be formulated:

– Recent years provided new data opportunities for climatological analyses. Gridded data has become the basis for an increasing number of works at various spatial scales. These data are of increasingly better quality and spatial and temporal resolutions. The structure of these databases makes them easy to use in various Geographic Information Systems.
– The use of gridded data is very convenient and allows for very quick analyses regarding their formats and available software tools. In many cases, these data no longer require the search for interpolation (spatialization) methods.
– The preliminary assessments of air temperature and precipitation for Central Europe (now only for Poland) for the 30-year period 1991-2020 showed their generally good representativeness, i.e. compliance with traditional data.
– In the case of temperature, the data is exceptionally consistent in the warm half-year, deviations from station data generally do not exceed 1°C, R reaches >0.99, RMSE is below 0.9°C (summer) and 1.5°C (winter). There are slightly larger differences in winter, which result from the distribution of this element.
– However, the question arises which data (station or gridded) is more relevant? What needs to be considered is the aim of particular study. Station data are much more precise but they could represent very unique (particular) local conditions. Due to that sometimes they can not represent the larger spatial scales.
– Despite the above limitations, in-situ data constitute the basis for creating new gridded data sets and for their validation and calibration purposes.

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