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RESEARCH ARTICLE

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Evaluating long-term trends in annual precipitation: A temporal consistency analysis of ERA5 data in the Alps and Italy

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Abstract

Reanalyses are utilized for calculating climatological trends due to their focus on temporal consistency. ERA5 reanalysis family has proven to be a valuable and widely used product for trend extraction. This study specifically examines long-term trends in total annual precipitation across two climatic hotspots: the Alps and Italy. It is acknowledged by reanalysis producers that variations in the observational systems used for data assimilation impact water cycle components like precipitation. This understanding highlights the need of assessing to what extent temporal variations in ERA5 precipitation amounts are solely a result of climate variations and the influence of changes in the observational system impacting simulation accuracy. Our research examines the differences between ERA5 and similar reanalyses against homogenized, trend-focused observational datasets. We find that discerning the climatological signal within ERA5 adjustments for observational system variations is challenging. The trend in ERA5 from 1940 to 1970 shows distinct patterns over the Alps and, to a lesser extent, Italy, diverging from later ERA5 trends and those in other reanalyses. Notably, ERA5 shows an increasing, although nonlinear, trend in the deviation between ERA5 and the observational datasets. Improving future reanalysis interpretability could involve adopting a model-only integration for the same period, akin to the ERA-20C and ERA-20CM approach.

KEYWORDS

annual precipitation, climatological trends, ERA5, Greater Alpine region, Italy, LAPREC, reanalysis

1 | INTRODUCTION

Reanalyses are extensively utilized to reconstruct historical atmospheric states and monitor recent climate change. They have been used, for example, in the Sixth

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Abbreviations: GAR, Greater Alpine region; tp, total precipitation.

Assessment Report of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC), 2023, IPCC AR6), and in the European State of the Climate report by the Copernicus Climate Change Service (C3S) https://climate.copernicus.eu/ESOTC, last accessed January 27, 2024. Essentially, reanalyses involve a cyclical process that alternates between initializing the model via data assimilation and producing short-range forecasts, typically spanning a period of 6–12 h. Global reanalyses encompass the entire globe and span several decades, making them particularly suited for assessing long-term trends in climatological variables. In this article, we examine the annual precipitation totals simulated over Italy and the Greater Alpine region (GAR), focusing primarily on the state-of-the-art reanalysis ERA5 (Hersbach, Bell, Berrisford, Hirahara, et al., 2020), produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). While other global reanalyses will also be considered, they are mainly used as references to interpret the results from ERA5. Specifically, we address the question: to what extent are the temporal variations in precipitation amounts in ERA5 exclusively due to climate variations?

In any reanalysis system, the two primary components are the model and the observations. All reanalyses employ a fixed version of the numerical weather model throughout the entire simulation period. However, different reanalyses adopt varied strategies for assimilating observations, as reported in the comparison table at reanalysis.org (last accessed January 27, 2024). For example, ERA5 incorporates an increasing number of observations over time, significantly expanding with the advent of the satellite era. This raises an important question: What is the impact of a changing observational network on the simulated precipitation amounts?

Producers of global reanalyses assume that the continuous evolution of the observational network impacts the statistics of the quantities they simulate and this is true for components of the water cycle too (Bosilovich et al., 2017; Trenberth et al., 2011). To address this, ERA5, for instance, has certain components of its data assimilation cycle designed to adapt over time. This is done to enhance the reanalysis's performance by leveraging the growing volume of available observations. One such adaptive component is the background error covariance matrix **B**. This matrix specifies the flow-dependent uncertainty of the model in comparison to the observations within the assimilation scheme. As highlighted by Hersbach, Bell, Berrisford, Hirahara, et al. (2020), **B** is designed to “follow the evolution of the observing system.”

Global reanalyses typically do not incorporate in situ precipitation measurements. As a result, observational gridded datasets, which are derived from these in situ observations, serve as an independent source for validation. Importantly, datasets based on homogenized observations are designed to reconstruct climatological trends. As pointed out by Tveito (2023), homogenized time series result in more reliable gridded datasets for analysing climate trends and variability. In our study, we will analyze two such observational datasets based on homogenized data, specifically covering the GAR and the Italian peninsula. The time series of the difference between global reanalyses and observational data can provide valuable statistics. These statistics can be used to determine whether the climate signals reconstructed from the reanalyses are consistent with those observed.

The document is structured as follows: Section 2 details the reanalyses employed in this study, while Section 3 focuses on the reference observational data. The results are presented in Section 4. The article concludes with a summary of our key findings.

2 | REANALYSIS PRODUCTS

We utilized five reanalysis datasets produced by ECMWF and generated using different cycles of the integrated forecasting system (IFS). CERA-20C, ERA-20C, and ERA-20CM were developed both prior to and concurrently with the development of ERA5. When investigating the discrepancies among these reanalyses, we primarily attribute them to differences in model resolution, parameterizations, and the range of assimilated observational networks. It is our underlying assumption that the core dynamics of the model remain relatively consistent across the different versions of the IFS. A natural expansion of our study, which is not presented here, would involve conducting similar analyses using precipitation data from sources such as MERRA-2 Gelaro et al. (2017) and JRA-55 Kobayashi et al. (2015) reanalyses. In the discussion that follows, we distinguish between “model resolution” and “grid spacing.” These terms should not be considered interchangeable; their differences are elucidated, for example, in the work by Grasso (2000).

2.1 | ERA5 and ERA5-EDA

ERA5 (Hersbach, Bell, Berrisford, Hirahara, et al., 2020) is the most recent global reanalysis produced by ECMWF under C3S. We utilized both the high-resolution ERA5 fields and the coarser-resolution ERA5-EDA, a 10-member ensemble. The reanalyses were generated using the IFS cycle 41r2, operational in 2016, which employs 12-h windows for 4D-Var data assimilation. This process integrates a wide and time-varying array of observations. Indeed, ERA5 assimilates a greater number of observations compared with the other reanalyses considered in our study. For ERA5, we downloaded the hourly precipitation fields from 1940 to 2020 from Hersbach et al. (2023) (Accessed on January 24, 2024) on a regular grid with a spacing of 0.25°. The original resolution is ∼31 km in our areas of investigation, as per the ERA5 user guide. For ERA5-EDA, we used a grid spacing of 0.5°, roughly translating to a resolution of 63 km. In both reanalyses, we aggregated the hourly precipitation fields to calculate the annual precipitation totals.

In their study, Bandhauer et al. (2022) compared ERA5 daily precipitation fields with observational gridded datasets across Europe, finding a generally good agreement between ERA5 and the observational data. However, they noted that ERA5 tends to overestimate mean precipitation in all regions, a trend they attributed to the overestimation of the number of wet days. Furthermore, in their analysis, Lavers et al. (2022) supported the use of ERA5 for monitoring extratropical precipitation based on their examination of monthly precipitation data. They observed, however, that the accuracy of ERA5 decreases in tropical regions, with errors becoming more pronounced there. In their recent study, Lavers et al. (2023) compared daily precipitation estimates derived from the final trajectory of the ERA5 4D-Var data assimilation system with the standard ERA5 precipitation as previously described. Their analysis revealed that daily precipitation estimates obtained from the final 4D-Var trajectory are more accurate and precise. This enhancement in performance is due to the 4D-Var precipitation being more tightly constrained by observational data. However, it is important to note that our analysis in this document has focused on the standard ERA5 precipitation.

2.2 | CERA-20C

CERA-20C (Laloyaux et al., 2018) is a climate reanalysis dataset that spans from 1901 to 2010. This dataset is generated using the CERA coupled data assimilation system, which assimilates various observations including surface pressure, marine wind observations, and ocean temperature and salinity profiles. For our analysis, we used the 10-member ensemble available from the meteorological archival and retrieval system (MARS). CERA-20C was produced employing IFS cycle 41r2, which was implemented on March 8, 2016. We downloaded CERA-20C on a regular grid with a spacing of 0.5°. The original resolution of the hourly fields is ∼125 km in our areas of investigation.

2.3 | ERA-20C and ERA-20CM

ERA-20C (Poli et al., 2016) is a century-long deterministic climate reanalysis dataset that covers the period 1901–2010. Complementing this, ERA-20CM (Hersbach et al., 2015) is a 10-member ensemble model-only integration covering the same time period and featuring the same grid spacing. Both datasets are based on IFS cycle 38r1, implemented on June 19, 2012. In both ERA-20C and ERA-20CM, sea-surface temperature and sea-ice cover are prescribed based on the HadISST2 ensemble (Titchner & Rayner, 2014). Their model radiation scheme's forcing terms are aligned with CMIP5 recommendations (Taylor et al., 2012). A key difference between these datasets is that ERA-20C assimilates observations of surface pressure and marine winds, while ERA-20CM does not include any observation assimilation. As a result, ERA-20CM is expected to have lower accuracy and precision in simulating actual precipitation fields compared with ERA-20C and other reanalyses. However, its insensitivity to observational variations makes ERA-20CM a valuable reference for assessing the impact of such variations. For both datasets, we obtained the data from MARS on a regular grid with a 0.5° spacing. The original resolution of the datasets is ∼125 km in the areas we studied.

3 | OBSERVATIONAL DATASETS

We employed two observational datasets that covered distinct regions. The domains are shown in Figure 1. The area where these datasets overlap is also clearly recognizable and this information will be used in Section 4. Our main focus was to select temporally consistent observational datasets, which implies that the observations were subjected to quality checks and homogenization procedures.

3.1 | LAPrec1901

The long-term Alpine precipitation reconstruction (LAPrec) Isotta et al. (2024) provides gridded monthly precipitation fields spanning the Alpine region across eight countries. Our study focuses on the LAPrec1901

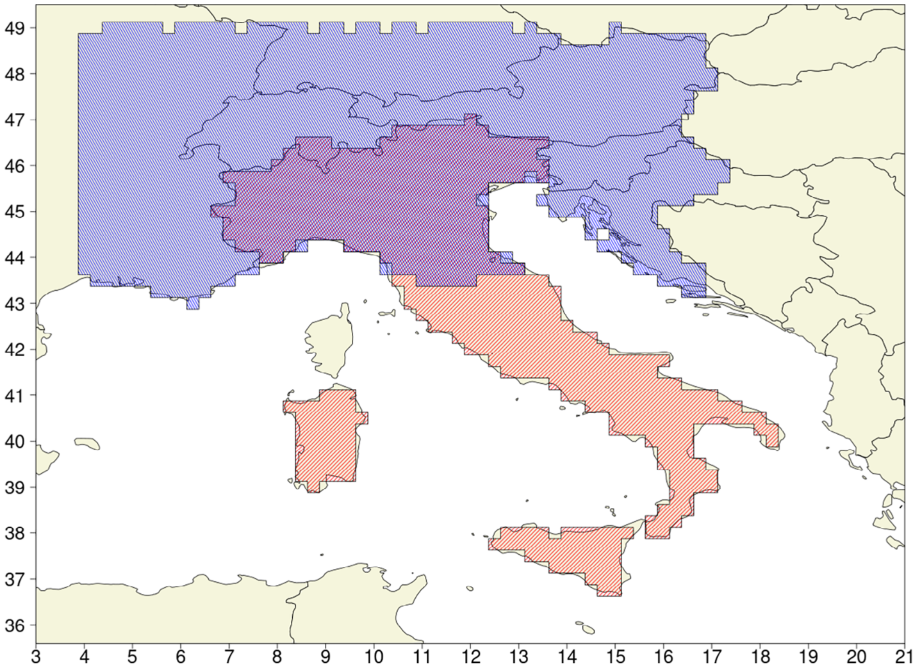

FIGURE 1 The domains of the observational datasets, with UniMi/ISAC-CNR outlined in red and LAPrec1901 in blue. The x-axis represents longitude, while the y-axis corresponds to latitude.

product, which begins in 1901 and is derived from 165 time series of data. The production of LAPrec involves the integration of two data sources: the recently revised Historical Instrumental Climatological Surface Time Series of the GAR (HISTALP, Chimani et al., 2023) and the Alpine Precipitation Grid Dataset (Isotta et al., 2014). LAPrec utilizes the reduced space optimal interpolation (Schiemann et al., 2010). This approach establishes a linear model between the input time series at point location and grid data. The method is calibrated during the period when both data types are available, incorporating a two-step process. First, it involves the principal component analysis of high-resolution grid data, followed by optimal interpolation using long-term station data.

Isotta et al. (2024) in section 3.3.2 of their publication present a study of residual inconsistencies within LAPrec. They focused on evaluating the mean absolute error (MAE) between LAPrec1871 and the homogenized data at the stations, employing a leave-one-out cross-validation approach. They found a gradual reduction in MAE over time, amounting to ~10% of the mean for the period 1871–2017. This translates to a reduction rate of about −0.7%/10 year. The authors consider this trend acceptable for a dataset that meets high standards of long-term consistency. Additionally, Isotta et al. (2024) demonstrate that various climatological datasets, including ERA5, exhibit notable differences in the trends of annual precipitation over the GAR (see their Figure 5). This variability is particularly evident at a local level.

3.2 | UniMi/ISAC-CNR

Monthly precipitation fields for Italy from 1921 to 2020 are developed using a large data set of quality controlled and homogenized stations across Italy and its northern neighboring regions. Specifically, precipitation fields are generated on a 30 arc-second resolution digital elevation model through the anomaly method (Mitchell & Jones, 2005), as described in Brunetti et al. (2012) and Crespi et al. (2018).

The technique is based on the independent reconstruction of monthly climatologies (i.e., the mean values estimated over a specific reference period) and anomalies (i.e., deviations with respect to the same baseline period). Climatologies are characterized by strong spatial gradients that need many weather stations (even if available for a short period) to be properly captured, together with an interpolation technique exploiting the dependence of climate variables on geographical parameters (Crespi et al., 2018). Anomalies, driven by climate change and variability, present higher spatial coherence and can be captured by a limited number of stations through simpler interpolation technique, but data homogenization is mandatory. Finally, monthly precipitation fields can be obtained by superimposition of the reconstructed climatologies and anomalies.

As climate normals we used the 30-arc-second resolution precipitation climatologies presented in Crespi et al. (2018), obtained from a data set of 6134 stations by performing a local weighted linear regression of the station precipitation normals versus elevation, where the weights associated to the stations involved in each grid cell estimation are computed on the basis of the level of similarity (in terms of horizontal and vertical distance, slope steepness and orientation, distance from the sea) between the stations and the grid cell itself.

Anomaly records are interpolated onto the same nodes of the 30 arc-second climatology and are obtained as weighted averages of the anomalies of the stations surrounding each grid point, with weights being a combination of a radial and a vertical weighting function, with the addition of an angular weight to take into account anisotropy in stations' distribution about the grid point (González-Hidalgo et al., 2011). 4969 stations' series contributed to the estimation of the anomaly fields over the 1921–2020 period (with the number of series simultaneously available remaining between 1200 and 4000 all over the whole considered period but 2020, when station number decreases to about 500–1000).

4 | RESULTS

Given that ERA5 is the focus of this study, we have upscaled the observational datasets to match the ERA5 grid. This was done by averaging all grid points that fall within an ERA5 cell. Conversely, we have downscaled other reanalyses using bilinear interpolation to align with the ERA5 grid resolution. Then, we analyzed the time series of deviations between the annual total precipitation from the reanalyses and the reference observational dataset. Specifically, for each year, we calculated the average deviation across the entire domain.

Generally, we expect that the time series of the deviations will consist of two overlapping components: a steady or slowly varying trend across the period, which reflects systematic deviations drifting over time, and a rapidly fluctuating component representing year-to-year variability. Additionally, a stable representativeness bias is expected over time, due to the differing effective resolutions between the reanalyses reconstructed precipitation fields and the observations. If climatological signals from reanalysis and observations align, the representativeness bias should be stable, with a likely flat trend component. Observing a slow-varying trend may suggest inconsistencies in the climatological trends between the two data sources. However, our study does not conclusively determine the cause of such trends, given the challenge in discerning whether they stem from representativeness bias variations or systematic shifts in model performance that impact predictions without changing the effective resolution.

As a reference for the comparison among reanalysis and observational dataset, in Figure 2, we present the time series of annual precipitation deviations between the two observational datasets on their overlapping region (see Figure 1). The average deviation is 4 mm, with a linear trend of +4 mm/10 year, leading to a century-long variation of about 40 mm, or 4% of the mean annual precipitation (1072 mm) according to the 1961–1990 climatology. Figure 3 displays maps of the

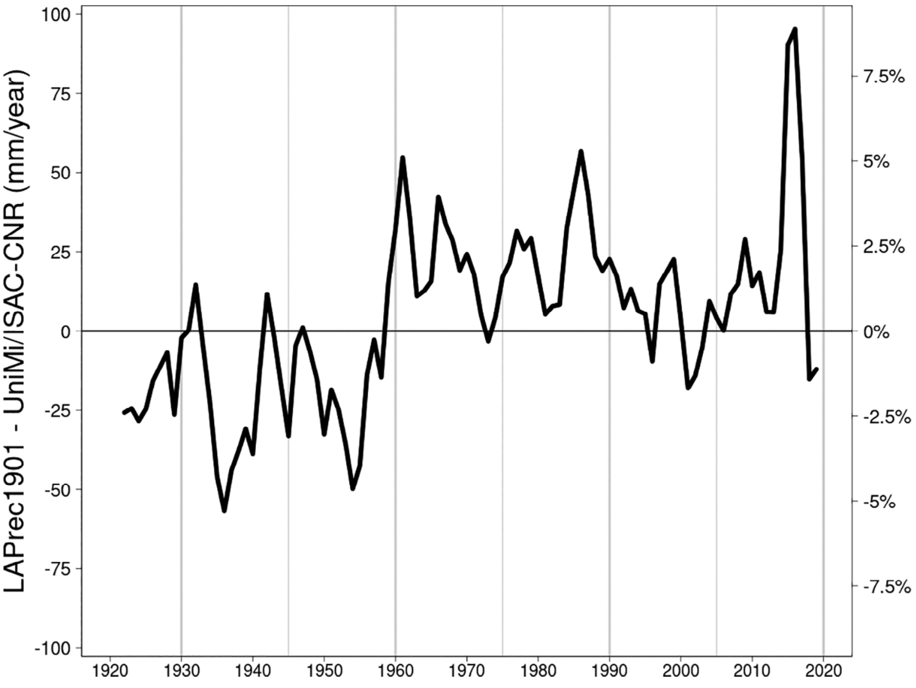

FIGURE 2 LAPrec1901 minus UniMi/ISAC-CNR annual precipitation averaged inside the common domain (Northern Italy) for the period 1921–2020. Time series were averaged over moving 3-year windows. The percent values are referred to the mean between the two observational precipitation 1961–1990 climatologies (1072 mm).

10-year averages of total annual precipitation. These same three decadal periods will also be utilized in subsequent analyses comparing reanalysis data and observations. A shift in the difference signs between LAPrec1901 and UniMi/ISAC-CNR datasets is evident in Figure 2. Prior to 1960, the UniMi/ISAC-CNR dataset, on average, recorded more precipitation than LAPrec1901, whereas post-1960, this trend reverses. Additionally, Figure 3 shows that the average precipitation deviation for the 1940–1949 decade exhibits distinct characteristics, particularly in the southeastern region of the study area. Here, the discrepancy between the two datasets significantly diverges from that observed in other periods. In this decade, the UniMi/ISAC-CNR dataset reports an increase in precipitation compared to LAPrec1901, covering an extensive area unlike in the subsequent periods evaluated. This discrepancy may arise from variations in the sets of observations utilized to create the two datasets during this decade, a divergence not observed post-1960. However, in the following, it will be shown that the differences observed between the two observational datasets consistently remain less pronounced than those observed between the observational datasets and the reanalysis data.

Figure 4 presents annual precipitation deviations between reanalyses and UniMi/ISAC-CNR averaged on the whole UniMi/ISAC-CNR domain, while Figure 5 compares reanalyses with LAPrec1901 in the GAR. Both figures use 3-year moving averages to filter out (part of) year-to-year variability. The summarized results for both comparisons are detailed in Tables 1 and 2. The figures and tables highlight: (i) ERA-20C and ERA-20CM show the highest representativeness biases, indicating they are "drier" than observations and other reanalyses; (ii) CERA-20C has a stable and statistically not significant bias trend; (iii) ERA5 and ERA5-EDA are consistently "wetter," likely due to higher effective resolution. ERA5 biases are more significant over the GAR than the Italian peninsula, while other reanalyses present greater biases over Italy. Additionally, our findings indicate that ERA5-EDA precipitation trends align more closely with observational datasets compared to ERA5.

The stabilizing effect of data assimilation is evident when comparing ERA-20CM and ERA-20C; ERA-20CM

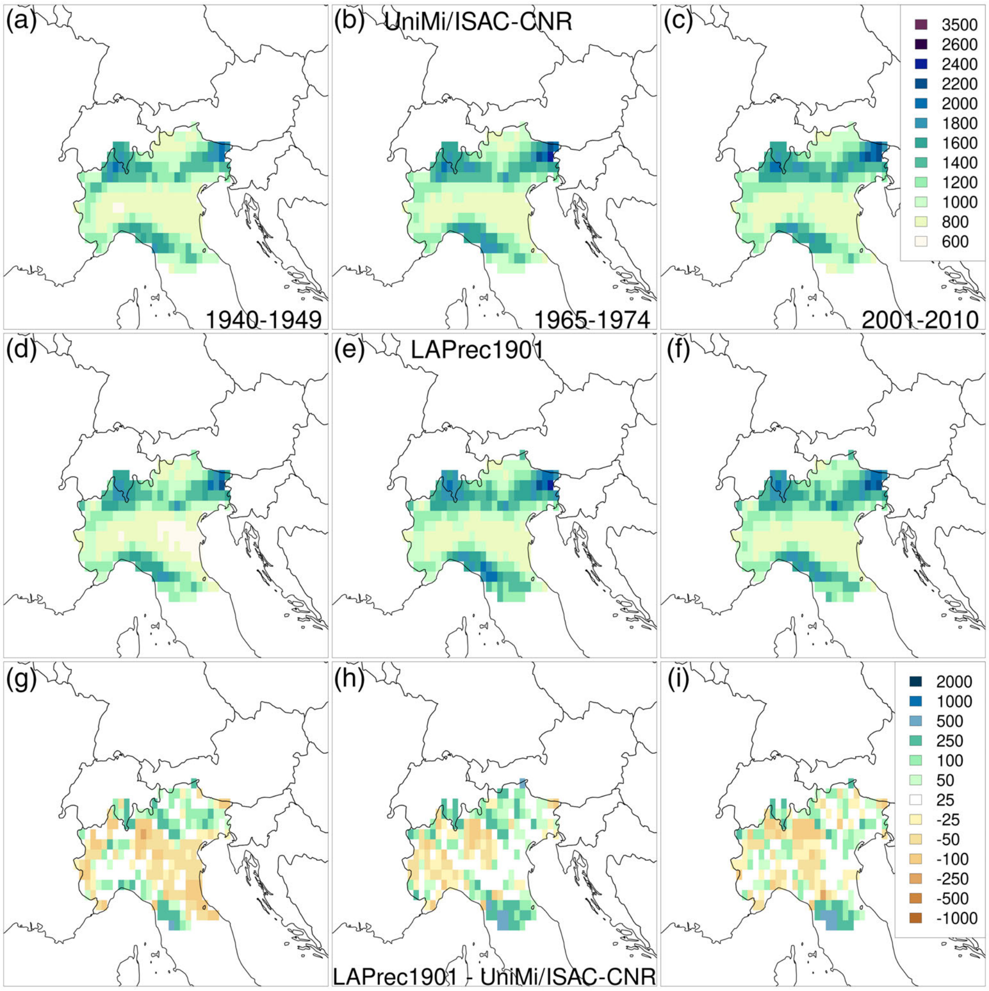

FIGURE 3 Comparison of total annual precipitation between LAPrec1901 and UniMi/ISAC-CNR, averaged over three distinct decades: 1940–1949 (panels a, d, and g), 1965–1974 (panels b, e, and h) and 2001–2020 (panels c, f, and i). The maps in the top row, marked by panels a, b, and c, represent LAPrec1901. The middle row, with panels d, e, and f, corresponds to UniMi/ISAC-CNR over Northern Italy. The bottom row, with panels g, h, and i, shows the difference between UniMi/ISAC-CNR and LAPrec1901. Each map displays the data aggregated to a grid cell resolution of 0.25°. The units are in mm/year. The legend values indicate "less than" the specified amount. For example, in panel g, the first value represents "<−1000 mm/year" and the second value indicates "<−500 mm/year (but ≥−1000 mm/year)."

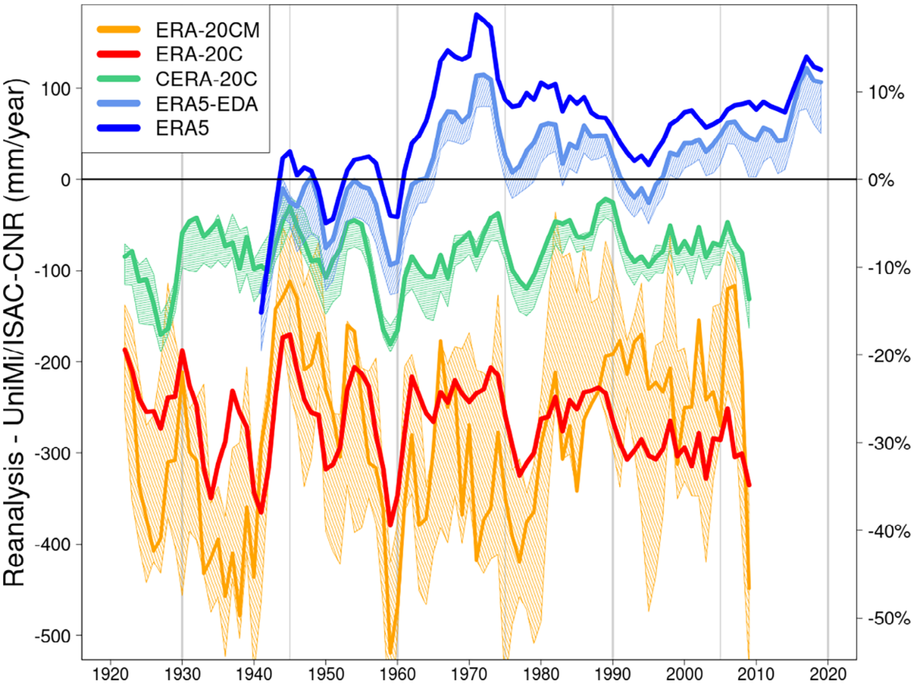

FIGURE 4 Deviations in annual precipitation between reanalyses and UniMi/ISAC-CNR over Italy for the period 1921–2020. The data are averaged over moving 3-year windows, and the ensemble spread is represented by polygons. Percent deviations are calculated with reference to the 1961–1990 UniMi/ISAC-CNR climatology, which is 962 mm/year.

TABLE 1 Statistics of the deviations in total annual precipitation between various reanalyses and the UniMi/ISAC-CNR dataset over its whole domain for the period 1940–2010.

Reanalysis	Mean bias (mm)	Trend (mm/10 year)	Trend (%/10 year)	*p*-Value
ERA5	50	12	1.4	<0.01
ERA5-EDA	−9 (−15,12)	14 (13,15)	1.6 (1.5,1.7)	<0.01
CERA20C	−90 (−94,−79)	0 (−1,2)	0 (−0.1,0.2)	0.3 (0.08,0.5)
ERA20CM	−278 (−302,−264)	3 (−4,8)	0.2 (−0.5,0.7)	0.4 (0.05,0.9)
ERA20C	−271	−7	−0.8	0.1

Note: For ensemble products, the mean value, along with the minimum and maximum values, are reported in the format: mean (min, max). Trends have been computed with Theil-Sen (median-slope) regression. *p*-values have been computed using the Mann-Kendall trend test.

exhibits broader variations and less stability due to its freedom from actual atmospheric conditions, unlike ERA-20C which, assimilating more data, better aligns with observations after adjusting for representativeness bias. Similarly, CERA-20C and ERA5-EDA show reduced ensemble spread respect to ERA-20CM, indicating more consistent predictions. This consistency is confirmed by the narrower range of trend values in Tables 1 and 2 for CERA-20C and ERA5-EDA than ERA-20CM, highlighting the benefits of data assimilation (trend ranges were defined by the difference between the minimum and maximum values reported under the "Trend" columns in brackets in the tables).

The most notable aspect observed in the data is the distinctive pattern in the time series of deviations for ERA5-EDA and, particularly, ERA5, which is absent in other reanalyses. This pattern is characterized by a gradual increase in bias from 1940 to 1970, followed by a decrease from 1970 to 1995, and then a subsequent increase from 1995 to 2020. This pattern is more pronounced over the GAR, as shown in Figure 5. If we analyze ERA5 over the 71-year period from 1940 to 2010, common to all reanalyses, the trends indicated in Tables 1 and 2 reveal an increase in deviations between ERA5 and the reference datasets. This increase amounts to approximately +10%/71 year (equivalent to 1.4%/10y × 71 year/10y) over Italy and +11%/71 year over the GAR. In contrast, within the same period, the trends in CERA-20C ensemble average deviations vary from −1%/71 year to +1%/71 year over Italy and from −3%/71 year to 0%/71 year over the GAR. For context, the deviation between the two observational datasets indicates an average change of +3%/71 year, based on the reported linear trend of +4 mm/10 year.

In the study by Hersbach, Bell, Berrisford, Hirahara, et al. (2020) it is reported that the **B** matrix in ERA5 uses

TABLE 2 Statistics of the deviations in total annual precipitation between various reanalyses and the LAPrec1901 dataset over its whole domain for the period 1940–2010.

Reanalysis	Mean bias (mm)	Trend (mm/10 year)	Trend (%/10 year)	*p*-Value
ERA5	99	17	1.6	<0.01
ERA5-EDA	52 (47,84)	18 (16,19)	1.7 (1.5,1.8)	<0.01
CERA20C	−29 (−35,−5)	−3 (−5,0)	−0.2 (−0.4,0)	0.3 (0.06,0.9)
ERA20CM	−101 (−111,−81)	−10 (−20,1)	−0.8 (−1.9,0.2)	0.4 (0.03,1)
ERA20C	−145	−6	−0.5	0.03

Note: Layout and methods as in Table 1.

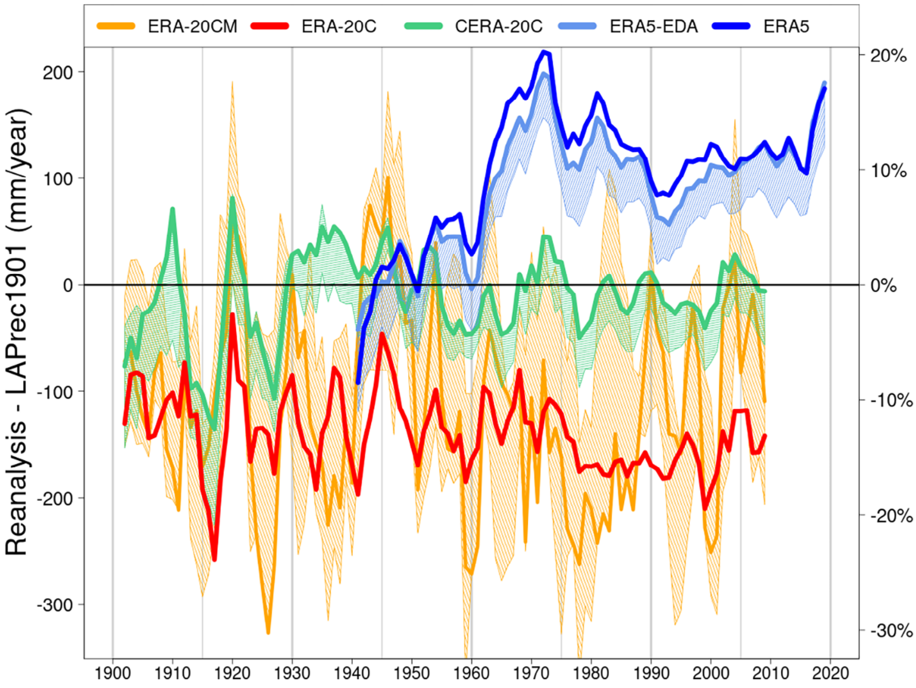

FIGURE 5 Deviations in annual precipitation between reanalyses and LAPrec1901 over the GAR for the period 1900–2020. The layout is similar to Figure 4. Percent deviations are calculated with reference to the 1961–1990 LAPrec1901 climatology, which is 1080 mm/year.

two definitions: one for 1979–1999 and another from 2000 onwards. Yet, further insights from Hersbach, Bell, Berrisford, Dahlgren, et al. (2020) reveal multiple updates to the **B** matrix definitions across periods: 1950–1973, 1974–1979, 1979–2006, and post-2006. Although the complexity of the climate system makes it difficult to directly connect changes in the **B** matrix to shifts in ERA5 trends, it appears that updates to the **B** matrix correspond with changes in the slope of the trend. It should be highlighted that our suggestion that the altered behavior of the mean state of ERA5 might correlate with changes in the **B** matrix lacks direct evidence. This hypothesis is proposed because, according to data assimilation theory, fluctuations in the **B** matrix can influence the effective resolution of the reconstructed fields. To empirically assess the mean state sensitivity to variations in the **B** matrix, one would need to plan reruns of the ERA5 production chain, an endeavor beyond our capacity.

Figure 6 compares ERA5 and UniMi/ISAC-CNR maps of 10-year average annual precipitation across the UniMi/ISAC-CNR domain for the same three periods illustrated in Figure 3, highlighting spatial precipitation distribution impacts seen in Figures 4 and 5. A similar comparison between ERA5 and LAPrec1901 over the GAR is shown in Figure 7. When comparing Figures 6 and 7 with Figure 3, one notes that the discrepancies between ERA5 and the two observational datasets are more pronounced than those within the observational datasets themselves. The spatial patterns of the differences between ERA5 and the observational datasets (panels g, h, and i) exhibit a highly variable structure, potentially reflecting the influence of topography and sea-land interactions. Exploring the underlying causes behind the systematic deviations observed in ERA5 precipitation fields is beyond the scope of this article. Pertinent to our study is that the comparative analysis across Figures 4 and 5 and Figures 6 and 7, using Figure 3 as a

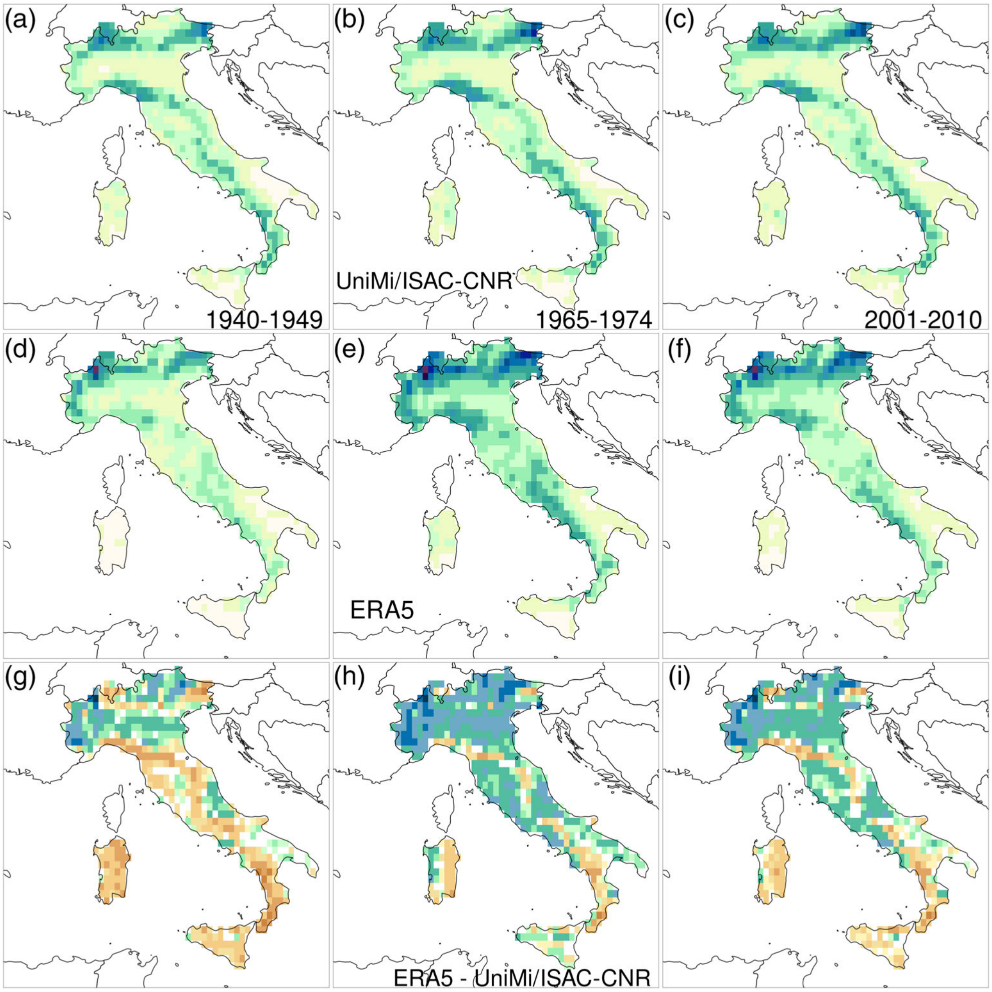

FIGURE 6 Comparison of total annual precipitation between ERA5 and UniMi/ISAC-CNR, averaged over three distinct decades: 1940–1949, 1965–1974, and 2001–2020. The layout and the legends are the same as Figure 3.

benchmark, complicates straightforward interpretations of ERA5 differences in total annual precipitation between different periods, such as attributing the 1940–1949 average annual precipitation to genuinely lower precipitation relative to later periods. It seems more plausible that the long-term average precipitation statistics in ERA5 are evolving, thereby complicating the comparison of 10-year average annual precipitation between the initial ERA5 period and later periods.

5 | CONCLUSIONS

The statistically significant trends and unique patterns observed in the time series of deviations between ERA5 products and observational gridded datasets, which are absent in other ECMWF reanalyses considered in this study, lead us to conclude that the climatological trends of total annual precipitation derived from ERA5 are likely influenced by factors beyond just climate change and climate variability.

Our results are valid for the two regions studied, the GAR and Italy. However, a preliminary analysis over Fennoscandia, not included here, suggests that ERA5 exhibits similar distinctive patterns, akin to those found in Figures 4 and 5, in other regions as well. An additional aim of our work is to encourage other researchers to evaluate ERA5 against other temporally consistent and well-verified observational data. This would help in investigating the applicability of our findings to other geographical areas.

One potential explanation for the observed discrepancies lies in the periodic recalibration of specific components within the ERA5 data assimilation system, such as variations in the definition of the **B** matrix. These adjustments may significantly affect precipitation amounts and, to a lesser extent, precipitation patterns. Adapting the data assimilation system to the continuously evolving observational network enables ERA5 to potentially reconstruct more accurate precipitation fields over time. This includes capturing smaller-scale precipitation features that may not be as well-represented in the

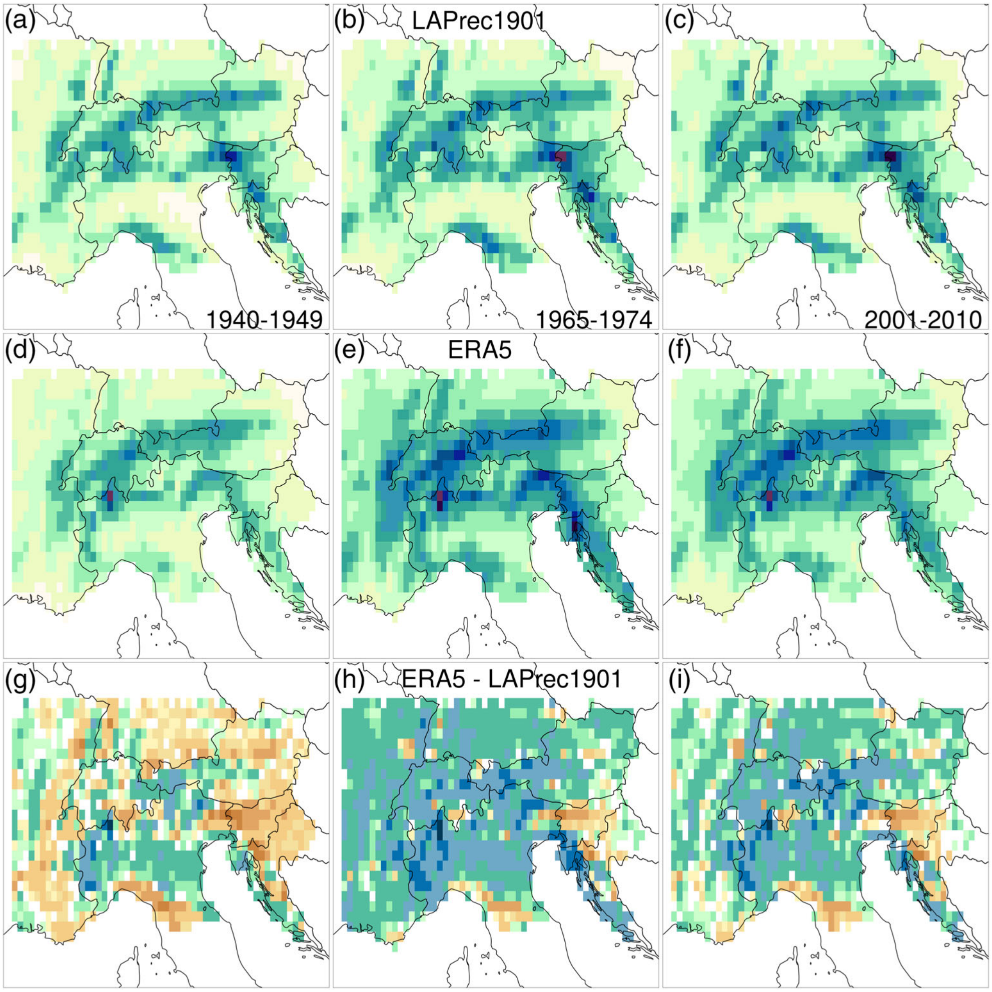

FIGURE 7 Comparison of total annual precipitation between ERA5 and LAPrec1901, averaged over three distinct decades: 1940–1949, 1965–1974, and 2001–2020. The layout and the legends are the same as Figure 3.

homogenized observational data used as a reference in our study. However, this adaptability also makes interpreting long-term trends from ERA5 more difficult, especially when compared with trends derived from reanalyses that are less sophisticated than ERA5.

For users of ERA5, it becomes a challenging task to unravel the multiple influences affecting the annual precipitation fields when comparing them against observations. These influences include the impact of a changing observational network, time-varying representativeness biases, their effects on model dynamics and parameterizations, and the consequent variations in the climate signal. For the production of future reanalyses, a useful approach to better understand the impact of the evolving observation base is to create complementary datasets like ERA-20C and ERA-20CM. The ensemble of model-only integration in ERA-20CM, in particular, provides a means to gauge the effect of data assimilation in ERA-20C. Overall, while the production of reanalyses would become a more costly endeavor, the extraction of temporal trends for key variables, such as total precipitation, and their comprehensive and transparent interpretation are objectives of such importance that they may justify the increased costs.

As a concluding recommendation for those utilizing ERA5 to analyze precipitation trends over the Alps or the Italian peninsula, we advise to be aware of the inherent uncertainties associated with these trends. The values presented in Tables 1 and 2 should be regarded as providing at least a range of this uncertainty. For a more comprehensive and reliable assessment of the statistical significance of these temporal trends, we recommend comparing ERA5 data with homogenized observational gridded datasets specific to the region of interest. This approach can offer a more solid basis for understanding and interpreting the observed precipitation patterns.

AUTHOR CONTRIBUTIONS

Cristian Lussana: Conceptualization; data curation; investigation; methodology; supervision; validation; writing – original draft. **Francesco Cavalleri:** Conceptualization; formal analysis; investigation; software; visualization; writing – original draft. **Michele Brunetti:** Data curation; investigation; writing – review and editing.

Veronica Manara: Data curation; investigation; writing – review and editing. **Maurizio Maugeri:** Data curation; investigation; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

The ERA5 and ERA5-EnDA data that support the findings of this study are openly available from Copernicus Climate Change Service (C3S) in the Climate Data Store (CDS): "ERA5 hourly data on single levels from 1940 to present" at http://doi.org/10.24381/cds.adbb2d47 (Accessed on 24-Jan-2024). The ERA-20C, ERA20-CM and CERA-20C data that support the findings of this study are available from the European Centre for Medium-Range Weather Forecasts (ECMWF) in the Meteorological Archival and Retrieval System (MARS). LAPrec1901 are openly available from Copernicus Climate Change Service, Climate Data Store, (2021): Alpine gridded monthly precipitation data since 1871 derived from in-situ observations. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.6a6d1bc3 (Accessed on 24-JAN-2024).The UniMi/ISAC-CNR data that support the findings of this study are available from the authors upon reasonable request.

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