nature portfolio

Peer Review File

Mediterranean precipitation variability is driven by complex atmospheric mechanisms beyond the North Atlantic Oscillation

Corresponding Author: Dr Marco Luppichini

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

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Dear Dr Luppichini,

Your manuscript titled "Beyond NAO: The Role of Mediterranean Cyclogenesis in Precipitation Patterns" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised substantial concerns that must be addressed. In light of these comments, extensive revisions will be required before we can further consider the manuscript for publication. We would, however, be interested in considering a revised version that fully addresses these serious concerns.

In particular, please ensure that the revised manuscript meets the following editorial thresholds:

1. Provide a physically sound and compelling interpretation of the mechanisms linking Mediterranean cyclones to precipitation, supported by robust analysis. If such support is lacking, consider moderating these claims while emphasising the influence of local climate indices and the results of the analysis of moisture sources through backward trajectories.
2. Ensure that all necessary data are presented to support your interpretations and conclusions. In particular, incorporate well-established observational or reanalysis datasets to support your analyses and/or validate the reconstructed monthly precipitation data.
3. Clearly articulate the motivation of the study and define its scope in relation to existing literature and current understanding, particularly regarding the influence of the NAO on Mediterranean cyclogenesis and, in turn, on precipitation.

We hope you will find the reviewers' comments useful as you decide how to proceed. If additional work allows you to either incorporate or refute these criticisms, we will be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers’ comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors’ comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,
Nicola

Nicola Colombo
Associate Editor
Communications Earth & Environment

EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

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An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript
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For your information, you can find some guidance regarding format requirements summarized on the following checklist: (https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript "Beyond NAO: The Role of Mediterranean Cyclogenesis in Precipitation Patterns" presents an interesting and valuable contribution, particularly through the following key points:

1. A significant effort was made to reconstruct a high-resolution precipitation dataset for Italy based on a long historical observational series originating from a census promoted by ISPRA.
2. The study offers a compelling analysis of Mediterranean dynamics using local climate indices, highlighting their strong influence on precipitation variability over the Italian Peninsula. This underscores the importance of regional-scale dynamics within the Mediterranean basin, in addition to large-scale mid-latitude circulation patterns, in shaping Mediterranean climate variability.
3. Finally, the analysis of air mass back-trajectories to identify moisture uptake regions contributing to precipitation over Italy provides novel insights into the mechanisms driving precipitation events across the country.

I believe the manuscript fits well within the scope of the journal and deserves publication. However, some specific issues should be addressed before it can be accepted for final publication.

Specific comments:

1) The paper places strong emphasis on Mediterranean cyclogenesis, starting from the title and throughout the results, suggesting a primary focus on the analysis of Mediterranean cyclones. However, a direct analysis of them and their specific impact on precipitation is not actually conducted.
Your study provides very interesting and valuable insights, particularly regarding the influence of local climate indices (MOI and WeMO) and the analysis of moisture sources through backward trajectories. It is important to focus the discussion and conclusions on these concrete results rather than placing too much emphasis on Mediterranean cyclones. Nevertheless, I

agree that cyclogenesis within the Mediterranean basin strongly affects climate variability and precipitation across the region, including Italy, and acknowledging this in the discussion is appropriate.
The MOI and WeMO indices indeed carry indirect information about cyclones developing in the basin, but to directly assess their impact requires cyclone detection and detailed statistical analysis, which is beyond the scope of this work. Therefore, it is appropriate to discuss cyclogenesis throughout your article. However, when referencing to specific physical mechanism or cyclogenesis regions (e.g., Genoa, Adriatic, North Africa), relevant literature should be cited to properly support these links. For example, in lines 350-352 and 357-359, you could refer to this work about Genoa cyclogenesis: Buzzi et al. 2020 (https://doi.org/10.1007/s42865-020-00021-6). Additionally in lines 393-397: you could include key studies on the role of Mediterranean cyclones on precipitation: Flaounas et al. 2016 (https://doi.org/10.1007/s00382-015-2622-1) and Portal et al. 2024 (https://doi.org/10.5194/wcd-5-1043-2024).
Finally, this study holds strong potential for future work. For example, a direct investigation of Mediterranean cyclones, such as through cyclone tracking, and combining it with your observational precipitation dataset. This could significantly advance understanding of how different cyclogenesis regions influence precipitation variability across Italy and provide valuable new insights.

2) If this is the first time that this machine learning-based reconstruction of precipitation is applied and published, it is essential to validate the reconstructed monthly precipitation data using other well-established observational or reanalysis datasets. This validation could include both the seasonal mean precipitation and the spatially averaged time series derived from the 10 km resolution map.

3) In Figure 5, the analysis of precipitation anomalies should be strengthened by assessing their statistical significance. For example, you could apply a bootstrapping method to test the significance of the anomalous precipitation term defined in the equation on line 201.

4) In lines 298-306 and lines 416-421, you highlight the important role of both the MOI and WeMO indices in shaping the spatial distribution of precipitation over Italy. However, based on Figure 5, the Mediterranean Oscillation Index (MOI) appears to exert a stronger influence than the Western Mediterranean Oscillation (WeMO). Given this substantial impact, it would be useful to provide a more detailed explanation of the physical mechanisms or regional dynamics driving the MOI–precipitation relationship.
Additionally, the East Atlantic (EA) index seems to have a greater influence than WeMO as well. For example, during NAO+ conditions, EA− has a more pronounced effect on precipitation than WeMO+, and similarly, during NAO−, EA+ appears more influential than WeMO+. You could strengthen the discussion by highlighting the role of the EA pattern in modulating precipitation variability over Italy.

5) In the Introduction, it would be beneficial to include references on Mediterranean cyclones and precipitation that are directly relevant to your study. For example, in lines 35–37, you could cite recent studies on the future evolution of cyclone-related precipitation over the Mediterranean, such as Reale et al. 2022 (https://doi.org/10.1007/s00382-021-06018-x) and Chericoni et al. 2025 (https://doi.org/10.1038/s41612-025-01121-w). Additionally, in lines 37–39, you might add references on the role of sea surface temperature (SST) in Mediterranean cyclogenesis, including Berthou et al. 2016 (https://doi.org/10.1002/qj.2717), Flaounas et al. 2018 (https://doi.org/10.1007/s00382-016-3398-7), Chericoni et al. 2025 (https://doi.org/10.5194/wcd-6-627-2025).

Minor comments:

1) In lines 405–408, I believe you meant to refer to NAO+ and EA−, rather than NAO− and EA+. Similarly, in lines 409–411, it seems you intended to refer to NAO− and EA+, not NAO+ and EA−. If this is not the case, please clarify, as the interpretation from the figure appears to suggest the opposite.

2) what do you mean with “the type of input data” in line L113-114?

3) In Figure 7, the low- and high-pressure systems appear to reflect synoptic-scale features rather than mesoscale structures.

4) Please specify which dataset was used to compute the sea-level pressure isobars shown in Figure 7.

5) Regarding the Back-trajectory analysis, please provide a map of the seven regions, perhaps as supplementary material, to help better visualize and understand the main moisture uptake areas.

6) In Figure 3, the models in version 2 are missing. Additionally, in the text (line 262), it is stated that the LSTM2STD model shows the best performance, but this model is not included in the figure.

7) Please provide which dataset was used to compute the indices and the SST trends in Figure 2.

8) In lines 429–431, it is unclear how the cited study (reference 56) supports this conclusion. Please elaborate on this point by referring to additional papers that specifically investigate cyclonic activity in the eastern Mediterranean. Consider having a look at Hochman et al. 2020 (https://doi.org/10.1007/s00382-019-05017-3) to strengthen the discussion.

Reviewer #2 (Remarks to the Author):

This manuscript presents a novel integration of deep learning (DL) for reconstructing historical precipitation data in Italy (1950–2020), analysis of atmospheric teleconnections (e.g., NAO, MOI, WeMO), and HYSPLIT-based back-trajectory modeling to identify moisture sources. The core argument—that Mediterranean cyclogenesis and regional indices (MOI, WeMO) exert a stronger influence on Italian precipitation than NAO alone—is well-supported and addresses a recognized gap in NAO-centric interpretations of Mediterranean hydroclimatology. The study leverages a massive dataset (>11,000 rain gauges) and demonstrates methodological innovation, particularly in using DL to handle data discontinuities.
The paper is timely, given ongoing debates on climate hotspots in the Mediterranean and the need for high-resolution historical reconstructions amid climate change. It contributes meaningfully to understanding spatial precipitation variability, with implications for paleoclimate proxies and future projections. However, minor issues include incomplete methodological comparisons, some editorial inconsistencies, and assumptions in modeling that could be better justified. Overall, the work is scientifically sound and suitable for publication with minor revisions.
Detailed comments:
- How were splits done spatially and temporally? If random over all station-months, spatial autocorrelation can inflate skill. Require spatially blocked and time-blocked cross-validation (e.g., leave-one-region-out; leave-years-out) to quantify true generalization.
- While DL models perform well (R^2 >0.90), no direct comparison to traditional interpolation (e.g., kriging, IDW) is provided. Recent studies benchmark ML against classical methods; this would strengthen claims of superiority for fragmented data.
- Report performance maps (R^2/MAE) by topography (Alps/Apennines/Islands) and climate regimes.
- Compare reconstructed monthly precipitation to E-OBS (and, if feasible, ARCIS for N Italy) at common grid and period (bias, RMSE, correlations, cycle & extremes). E-OBS is the de-facto observational baseline in Europe; its precipitation has known characteristics and documented evaluations.
- Discuss agreement/disagreement relative to recent Med/Italy precipitation reviews.
- Figures (e.g., 3–7) are well-described but could benefit from statistical significance tests (e.g., p-values for anomalies).
- While intro mentions GHG-driven changes, results/discussion underplay projections (e.g., how warming affects MOI/WeMO). Linking to CMIP6 downscaling (e.g., Statistical Downscaling over Italy, Sci Data, 2025) would enhance forward-looking value.

Reviewer #3 (Remarks to the Author):

Luppichini et al. addressed the question of precipitation variability in the Italian peninsula from the perspective of climatic indexes. They reached to a conclusion that cyclone systems play dominant role therein whereas North Atlantic Oscillation is insufficient to statistically explain it. The methodological approach is based on AI reconstructing rainfall time series from surface meteorological stations, then on the combined analysis of different teleconnection indexes and finally on moisture uptake diagnostics. I read the paper with great interest, but I have strong concerns on the content and approach that lead me to reject it for eventual publication. Right below I only outline 3 major issues that formed this decision:

Inconsistent datasets
1. The reconstruction of time series is certainly an interesting approach and leads to useful material. I am not sure however why surface stations were chosen for this study. Since the approach is based on a recent climatology and since the authors would like to link their results with regional dynamics (moisture uptakes and cyclone systems) why don't they use reanalysis datasets such as ERA5 instead of observations? This way, precipitation variability would be consistent with moisture uptake and large scale pressure patterns not to mention that there would be uncertainties in the results because of choosing representative grid points to perform the moisture uptake analysis. The authors would just have to run trajectory analysis from each grid point over the Italian peninsula. Finally, horizontal resolution of ERA5 would be more adequate for a relatively small region such as the Mediterranean than 1 degree used here.

2. Unsupported conclusions
There are several -if not many- papers addressing the question of cyclones' role in controlling Mediterranean precipitation. These papers usually perform explicit quantification of precipitation because of cyclone systems while in several of them there is also a quantification of moisture sources. All this knowledge is not discussed in the introduction and I find it a bit awkward that cyclones' contribution is implicitly determined because of climatological sea level pressure patterns. In these regards, I found the discussion rather weak and conclusions on cyclones' contribution rather unsupported. Finally, the distribution of moisture sources could be provided in a more direct way. Please consult past papers (there are many) that illustrate moisture uptakes in terms of maps and contours. In other words, I am not sure I can easily reach to the thirds concluding remark from Fig. 6.

3. From climatological patterns to regional dynamics
Actually, we already know that most of precipitation in the region is due to cyclone systems (a simple search in the scientific literature should be convincing), so I am not fully sure I follow the second bullet point on the conclusions. The whole motivation of this study seems to build on the argument that NAO is (not) explaining the variability of precipitation in Italy. However, I am not sure this is to be considered as a given in the state of the art. As far as I understand, NAO is statistically describing the Atlantic storm tracks' activity and thus is expected to have an influence on the frequency of Mediterranean cyclogenesis (there is a rich bibliography on the interconnection between Mediterranean and Atlantic storm tracks). As a result, NAO influences Mediterranean cyclogenesis and some impact should be expected on Mediterranean's precipitation variability. I guess that the discussion or scientific question could be based on how each index correlates with Mediterranean cyclones and in turn with precipitation variability. In this paper though given knowledge on the importance of

cyclone systems on precipitation variability is provided as a main result.

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Version 1:

Decision Letter:

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Dear Dr. Luppichini,

Your manuscript titled "Beyond the NAO: complex atmospheric mechanisms driving Mediterranean precipitation variability" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

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Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Nicola Colombo, PhD
Associate Editor, Communications Earth & Environment
Consulting Editor, Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have carefully addressed my comments. The manuscript has substantially improved compared to the earlier version, and I now consider it suitable for publication.

Reviewer #2 (Remarks to the Author):

The authors have thoroughly addressed all reviewers' comments, including those related to methodological clarification, comparative analyses, and editorial consistency. The revised manuscript demonstrates significant improvement in structure, clarity, and scientific rigor. The integration of deep learning for precipitation reconstruction, coupled with teleconnection analysis and moisture source identification, is now better justified and clearly articulated.
Overall, the paper is scientifically sound, methodologically robust, and contributes valuable insights into Mediterranean hydroclimatology. I find the revisions satisfactory, and I recommend the manuscript for publication in its current form.

Reviewer #3 (Remarks to the Author):

This is the second review of the paper "Beyond the NAO: complex atmospheric mechanisms driving Mediterranean precipitation variability" by Luppichini et al. The authors made a lot of effort to improve the manuscript and reply to the comments. I am afraid however that still the paper is not concise to proceed to publication. My main concern is about the results, the discussion and the presentation of the scientific content. There is certainly a lot of potential here but that the paper in its present form is not easy to reach to a well structured study. My recommendation would be to reject and reconsider a more focused submission.

Right below I list several comments that all point towards an important editing and revision of the paper. Please note that lines below refer to the marked-up document.

Introduction:
line 49: which patterns?
lines 49-50: I do not really understand the purpose of this phrase.

lines 63-78: Still I am not sure I follow the argumentation and the motivation about NAO. The two paragraphs in lines 63-78 seem a bit repetitive and I am not sure that they help to understand the importance of this study. I can understand that NAO should explain some part of the precipitation variability and perhaps a larger part could be explained by other kind of large-scale drivers or perhaps internal variability of the regional climate. To put it differently, a certain phase of NAO may favor a more frequent occurrence of Mediterranean cyclones. There will be certainly a large spread of regions to be affected by cyclones' precipitation. The (larger) smaller the area you focus your analysis, in this case the Italian peninsula, the (more) less NAO will be explaining the precipitation pattern. Please be more specific about what is missing from the state of the art and what is your contribution.

Line 90: The aim seems to be related to moisture sources alone but clearly all the above and the title point to different objectives. Also "these uncertainties" should be more elaborated.

Overall: I find the introduction a bit awkward. It starts with cyclones, then it discusses NAO and finally water sources but these do not seem to be connected between them, or to liaise with specific objectives.

Datasets:
In my first review, I am not claiming that ERA5 is more accurate or that resolution matters. I am arguing that for the purposes of this study ERA5 would be more appropriate despite its lack of accuracy (in terms of spatial resolution and precipitation amounts). After all, you are not discussing local precipitation (that would be of subgrid scales in ERA5), but subregional one, and more than that you compare precipitation with large scale patterns. Therefore, consistency between dynamics and precipitation would be quite important for your study. In any case, the authors did substantial work to validate their methods so most probably it is good to proceed this way.

Section 3.2:
The title of this section seems a bit generic. Please revise according to the content. The whole discussion here is quite hard to retain and I am not sure what we learn in the end. The section reads like: Several climate modes might partly explain variability of precipitation in Italy, but depending on the area, lack of statistical significance might render interpretations a bit difficult.

The discussion is actually a bit awkward: For instance, in lines 340-342, one learns that "significant positive precipitation anomalies are observed across much of the country.. the statistical assessment confirms that these signals are robust". I am not sure what we learn about local or overall precipitation in Italy. Also "robust" should be I guess "statistically significant" and I am not actually sure what "signals" refers to. Reading up to here, I think that one major issue with the whole paper is that in many places, there are generic mentions, few examples:
line 90: "these uncertainties", which ones? Here this phrase is mostly used as "all of the above"
line 342 "signals", what does this refer to?
line 336 "important role", in what?
line 345 "tends to increase", "generally observed", where, how much?
line 351 "the contribution of AMO appears relatively minor", contribution to what? relatively to what?
line 366: what is meant by "promote rainfall"?
line 378: what is "climatic forcings" here?
line 379: Indices nor statistical patterns (like NAO) interact to each other. Please revise.
line 434: "These findings"... which findings?

A careful editing to make the text more precise is certainly needed. I regard this issue as an important shortcoming of the paper.

Section 3.3
I find that the spatial variability of moisture uptake is rather similar in the four panels of Fig. 8. It is thus a bit hard to discuss differences between the different regions. In any case, this section seems a bit disconnected to the rest of the paper.

Discussion & Conclusions:
lines 448 - 460 come too late. This part should be in the methods. Regarding the analysis, I am not sure how the two main parts of this paper connect to each other (water sources & climate modes). Maybe I missed the point, but my impression is that the analysis on the climate modes could be stand as such without the water sources.

In lines 518-537, I find the discussion a bit weak. The association of different NAO phases with precipitation in the Mediterranean is rather known. I am not also sure I follow the argumentation that links SST with Mediterranean cyclogenesis (lines 523-526). The latter mainly depends on how many intrusions of troughs we have in the region. Higher SST may modulate the intensity of the cyclones by enhancing convection.

The second bullet point in the conclusions is unclear to me. What is meant by "NAO out of phase with other circulation modes"? How can two climate modes trigger "dipolar systems" (line 571). Also "Atlantic air masses" and "pressure systems" are generic mentions. Actually generic mentions like thses ones are repetititve in the text: e.g. "Mediterranean dynamics", "Atlantic circulation patterns", "Mediterranean regional dynamic".

Reviewer #1 (Remarks to the Author):

The manuscript "Beyond NAO: The Role of Mediterranean Cyclogenesis in Precipitation Patterns" presents an interesting and valuable contribution, particularly through the following key points:

1. A significant effort was made to reconstruct a high-resolution precipitation dataset for Italy based on a long historical observational series originating from a census promoted by ISPRA.
2. The study offers a compelling analysis of Mediterranean dynamics using local climate indices, highlighting their strong influence on precipitation variability over the Italian Peninsula. This underscores the importance of regional-scale dynamics within the Mediterranean basin, in addition to large-scale mid-latitude circulation patterns, in shaping Mediterranean climate variability.
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Specific comments:

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Your study provides very interesting and valuable insights, particularly regarding the influence of local climate indices (MOI and WeMO) and the analysis of moisture sources through backward trajectories. It is important to focus the discussion and conclusions on these concrete results rather than placing too much emphasis on Mediterranean cyclones. Nevertheless, I agree that cyclogenesis within the Mediterranean basin strongly affects climate variability and precipitation across the region, including Italy, and acknowledging this in the discussion is appropriate.

The MOI and WeMO indices indeed carry indirect information about cyclones developing in the basin, but to directly assess their impact requires cyclone detection and detailed statistical analysis, which is beyond the scope of this work. Therefore, it is appropriate to discuss cyclogenesis throughout your article. However, when referencing to specific physical mechanism or cyclogenesis regions (e.g., Genoa, Adriatic, North Africa), relevant literature should be cited to properly support these links.

For example, in lines 350-352 and 357-359, you could refer to this work about Genoa cyclogenesis: Buzzi et al. 2020 (https://doi.org/10.1007/s42865-020-00021-6). Additionally in lines 393-397: you could include key studies on the role of Mediterranean cyclones on precipitation: Flaounas et al. 2016 (https://doi.org/10.1007/s00382-015-2622-1) and Portal et al. 2024 (https://doi.org/10.5194/wcd-5-1043-2024).

Finally, this study holds strong potential for future work. For example, a direct investigation of Mediterranean cyclones, such as through cyclone tracking, and combining it with your observational precipitation dataset. This could significantly advance understanding of how different cyclogenesis regions influence precipitation variability across Italy and provide valuable new insights.

We sincerely thank the Reviewer for the constructive and insightful comments, which have greatly helped us to improve the clarity and focus of the manuscript.

Following the suggestions, we have changed the title to "Beyond NAO: complex atmospheric mechanisms driving Mediterranean precipitation variability", which better reflects the actual scope of the study.

We have also integrated the requested citations (Buzzi et al. 2020; Flaounas et al. 2016; Portal et al. 2024) in the relevant sections, and carefully revised the manuscript to ensure that the Results do not refer to Mediterranean cyclogenesis directly, but rather to the analysis of atmospheric indices and moisture source attribution, which represent the core of our work. Finally, we have modified the Conclusions by adding the suggested perspective on future research, explicitly highlighting the potential of combining direct cyclone tracking with our observational precipitation dataset to further advance the understanding of precipitation variability in relation to Mediterranean cyclogenesis.

In this framework, the reconstruction and analysis of atmospheric indices specifically tailored to the Mediterranean basin, alongside traditional indices like the NAO, and the direct tracking of Mediterranean cyclones combined with observational precipitation datasets, could be key to improving our understanding of past climate dynamics and the climate signals recorded in proxies.

We believe these revisions have strengthened the manuscript and improved its alignment with both the study objectives and the Reviewer's valuable recommendations.

2) If this is the first time that this machine learning-based reconstruction of precipitation is applied and published, it is essential to validate the reconstructed monthly precipitation data using other well-established observational or reanalysis datasets. This validation could include both the seasonal mean precipitation and the spatially averaged time series derived from the 10 km resolution map.

We thank the Reviewer for this valuable suggestion. Following the recommendation, we have added a validation analysis by comparing our reconstructed monthly precipitation dataset with ERA5 reanalysis data from the Copernicus Climate Change Service. Specifically, we computed both Spearman and Pearson correlation coefficients at the grid-cell level between the two datasets, and we evaluated the agreement through spatial correlation maps and summary statistics. The results show consistently high and statistically significant correlations ($p < 0.01$) across the entire Italian domain, despite the coarser spatial resolution of ERA5 (0.25° × 0.25°) compared to our 10 km reconstruction. This new analysis has been included in the Methods, Results, and illustrated in Figure 4.

In methods:

The reconstructed precipitation dataset was validated against ERA5 reanalysis data from the Copernicus Climate Change Service (https://climate.copernicus.eu/climate-reanalysis), which provides a widely used and well-established reference for climate and hydrological studies. To assess the consistency between the two datasets, we calculated both Spearman[41] and Pearson[42] correlation coefficients at a monthly scale over the common period of analysis. While Pearson's correlation measures the strength of the linear relationship, Spearman's correlation also accounts for monotonic but non-linear associations, offering a more comprehensive evaluation of agreement. The correlations were computed at each 10 km grid cell of the reconstructed dataset by comparing the corresponding spatially matched ERA5 time series.

In results:

The comparison with ERA5 reanalysis data shows that the reconstructed monthly precipitation dataset achieves very high correlations across most of the Italian domain (Figure 1). Both Spearman and Pearson coefficients display median values above 0.8, confirming the robustness of the reconstruction despite the coarser resolution of ERA5 (0.25° × 0.25°, corresponding to approximately 30–40 km) compared to the 10 km resolution of the reconstructed dataset. The spatial distribution of the correlations highlights locally lower values, particularly in some mountainous and coastal areas, where small-scale processes are not fully captured by ERA5. Nevertheless, correlations remain consistently significant across the entire domain. Importantly, all grid cells yielded p-values lower than 0.01, confirming the statistical robustness of the results.

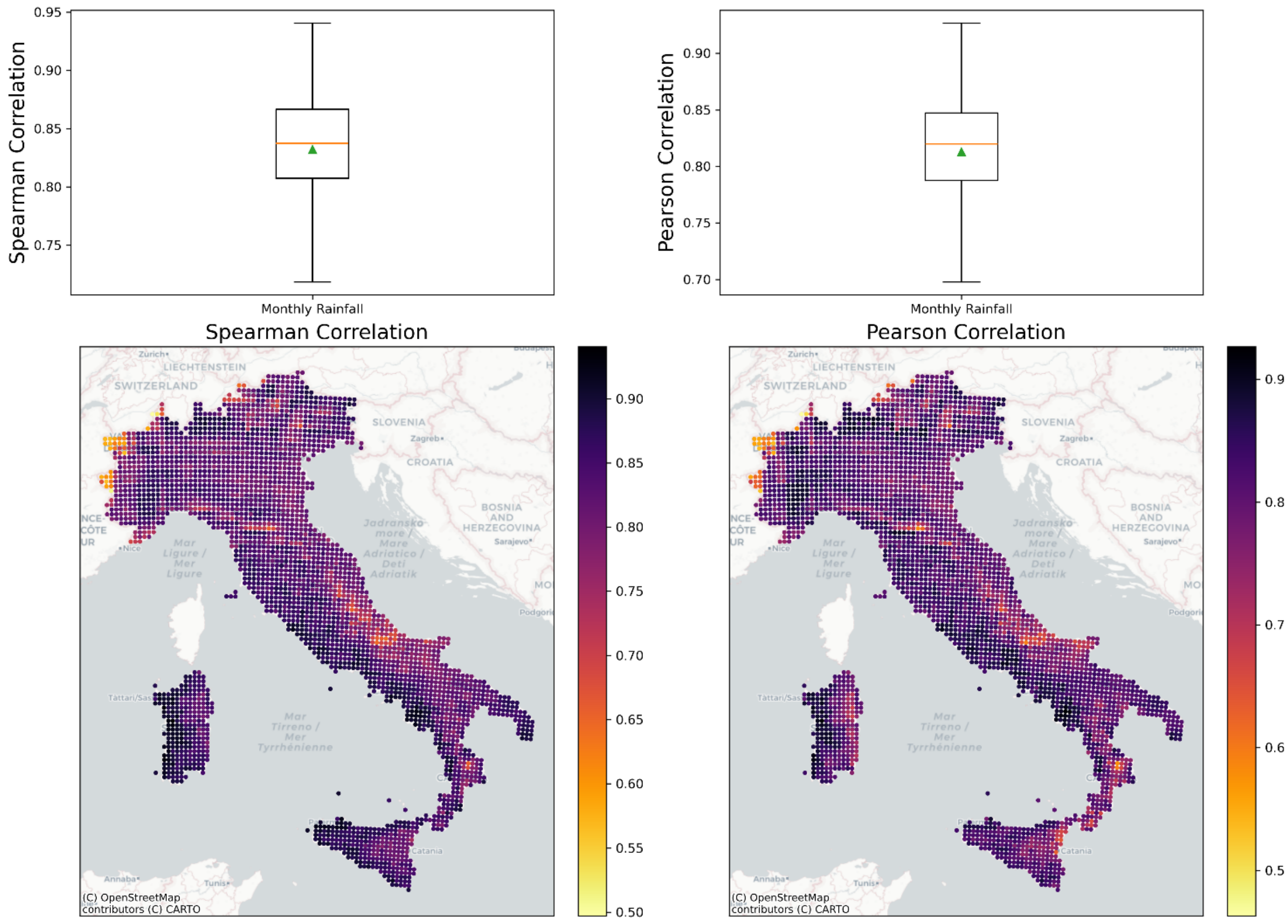


Figure 1 Validation of the reconstructed monthly precipitation against reference datasets. The boxplots (top) show the distribution of correlation coefficients across all grid cells at 10 km resolution, using both Spearman (left) and Pearson (right) metrics. The orange line indicates the median value, and the green triangle indicates the average. The maps (bottom) display the spatial distribution of the correlation values for Spearman (left) and Pearson (right), highlighting generally high and spatially consistent agreement across most of Italy, with local variations in mountainous and coastal areas. All recorded points have a significant statistic with a p-value < 0.01.

In discussions:

The historical series reconstructed in this study demonstrate how the integration of advanced methodologies makes it possible to effectively manage large climate databases and extract meaningful information from them. The consistency of the dataset produced was also verified through comparison with independent reanalysis data (ERA5), using statistical correlation analyses. The results confirm the robustness of the models and their ability to reproduce climate signals consistent with those reported in the literature, even for variables characterized by high spatial and temporal variability such as precipitation. Moreover, the use of this dataset has made it possible to overcome two main limitations of reanalysis products: i) the historical series reconstructed here are entirely based on statistical–probabilistic approaches, relying solely on observational data and not on physical models; ii) the spatial resolution achieved is about 7–8 times higher than that of ERA5, improving from approximately 0.25° × 0.25° (about 28 × 28 km) to 10 × 10 km in the dataset developed in this work.

3) In Figure 5, the analysis of precipitation anomalies should be strengthened by assessing their statistical significance. For example, you could apply a bootstrapping method to test the significance of the anomalous precipitation term defined in the equation on line 201.

We thank the Reviewer for this useful suggestion. Following the recommendation, we have implemented a statistical significance assessment of the precipitation anomalies shown in Figure 5. Specifically, we applied a non-parametric bootstrapping procedure to test the anomalous precipitation term defined in Equation (line 201). For each phase combination of the indices, the observed anomaly was compared against an empirical distribution obtained by resampling with replacement from the full dataset (5,000 iterations). The p-value was estimated as the proportion of bootstrap replicates yielding an anomaly equal to or greater than the observed one. The results of this analysis are presented in a new figure (Figure 7), where grid cells with p-values < 0.05 are highlighted as statistically significant. This additional validation confirms that the most robust anomalies occur under opposite-phase combinations of indices, while same-phase combinations generally yield non-significant results.

In methods

To assess the statistical significance of the precipitation anomalies associated with the different combinations of large-scale and regional circulation indices, we implemented a non-parametric bootstrapping approach. For each configuration (e.g., NAO+ | AMO–), we first computed the observed precipitation anomaly as the percentage deviation of the mean precipitation with respect to the climatological mean. Then, to evaluate whether this anomaly could arise by chance, we generated an empirical distribution by resampling with replacement from the full dataset, drawing the same number of years as in the target configuration. The anomaly was recalculated for each bootstrap sample, and this procedure was repeated 5,000 times to obtain a robust reference distribution. The p-value was then estimated as the proportion of bootstrap replicates yielding an anomaly of equal or greater magnitude than the observed one. Grid cells with p-values lower than 0.05 were considered statistically significant.

In results:

… and the statistical assessment confirms that these signals are robust over wide areas (Figure 7).

… although the significance analysis (Figure 7) highlights that when both indices share the same phase the anomalies are generally not significant across Italy, whereas opposite-phase combinations yield statistically robust signals.

However, as shown in Figure 7, only some of these anomalies reach statistical significance, underlining the need for caution when interpreting weak signals.

… and the significance analysis (Figure 7) confirms that these longitudinal contrasts are statistically robust.

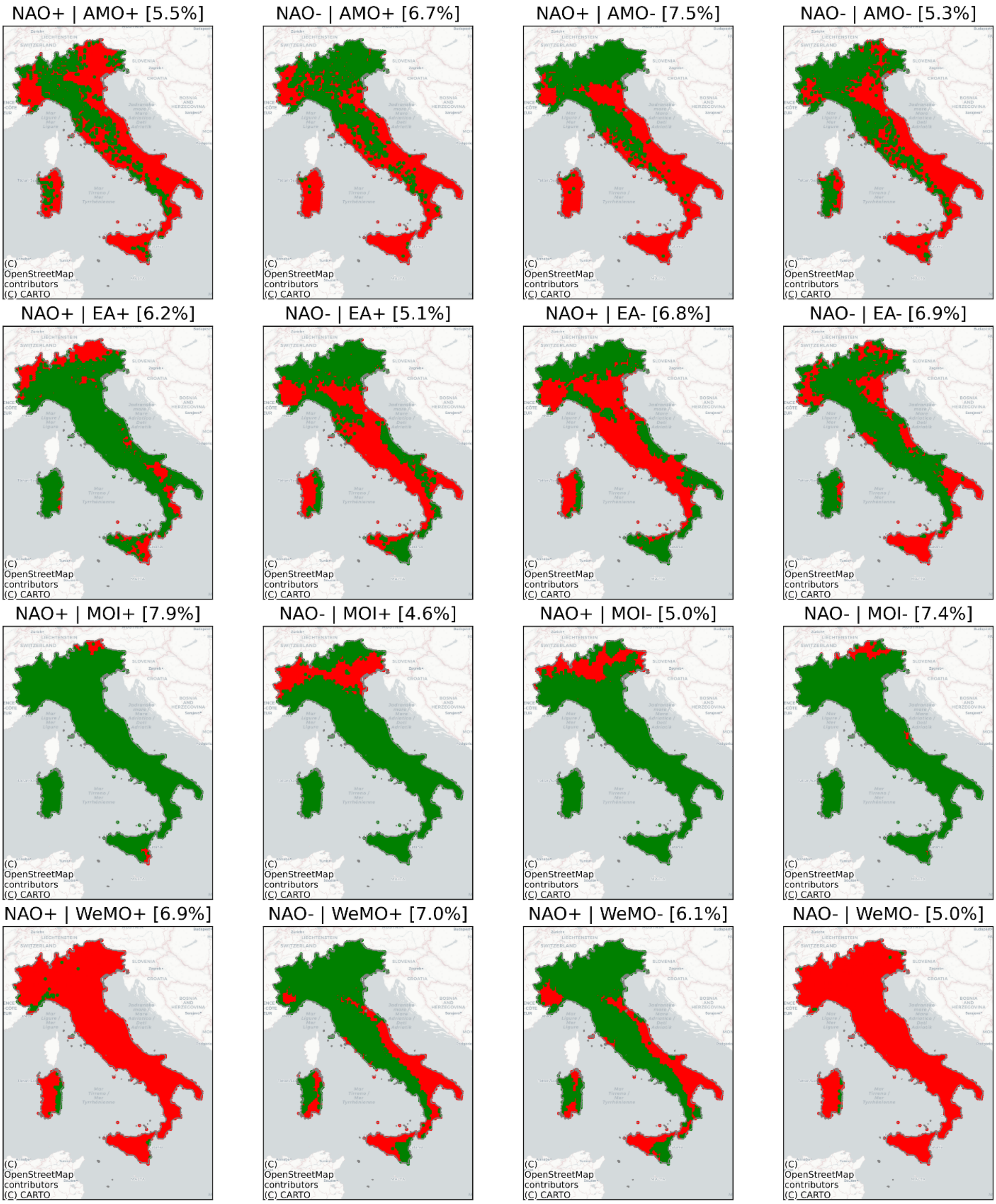


Figure 2 Spatial significance of precipitation anomalies under different NAO combinations with other climate indices. Green areas indicate grid cells where anomalies are statistically significant ($p < 0.05$), while red areas denote non-significant results. The percentage in square brackets indicates how often each specific configuration occurs within the time series.

4) In lines 298-306 and lines 416-421, you highlight the important role of both the MOI and WeMO indices in shaping the spatial distribution of precipitation over Italy. However, based on Figure 5, the Mediterranean Oscillation Index (MOI) appears to exert a stronger influence than the Western Mediterranean Oscillation (WeMO). Given this substantial impact, it would be useful to provide a more detailed explanation of the physical mechanisms or regional dynamics driving the MOI–precipitation relationship. Additionally, the East Atlantic (EA) index seems to have a greater influence than WeMO as well. For example, during NAO+ conditions, EA− has a more pronounced effect on precipitation than WeMO+, and similarly, during NAO−, EA+ appears more influential than WeMO+. You could strengthen the discussion by highlighting the role of the EA pattern in modulating precipitation variability over Italy.

We thank the Reviewer for this valuable comment. Following the suggestion, we have revised the Discussion to provide a more detailed explanation of the physical mechanisms underlying the relationship between the Mediterranean Oscillation Index (MOI) and precipitation variability. Specifically, we emphasise that the MOI reflects an east–west pressure gradient across the entire Mediterranean Basin, which exerts control on large-scale moisture advection pathways. Negative MOI phases are typically associated with cyclonic conditions over the central and eastern Mediterranean and North Africa, favouring the advection of moist air masses towards Italy, especially over the southern and Adriatic regions. In contrast, the WeMO represents a more regional dipole centred between the Iberian Peninsula and the Gulf of Genoa, whose influence is often confined to local circulation dynamics and extreme events. This explains why the MOI emerges as a more robust driver of precipitation variability across Italy.

In addition, we have expanded the discussion on the role of the East Atlantic (EA) index. Our results show that the EA can exert a stronger influence than the WeMO in modulating Italian precipitation, particularly in combination with NAO phases. For instance, under NAO+ conditions, EA− enhances precipitation anomalies more clearly than WeMO+, while under NAO− conditions, EA+ is more influential than WeMO+. These findings are consistent with recent literature highlighting the EA as a key modulator of North Atlantic and Mediterranean climate variability, and in some periods even as the leading mode of variability surpassing the NAO in its influence on precipitation over Western Europe.

The relatively stronger influence of the MOI compared to the WeMO can be interpreted in light of its synoptic nature and much broader spatial scale. The MOI is defined as the pressure difference between Algiers and Cairo and therefore expresses an east–west gradient that involves the entire Mediterranean Basin. Negative MOI phases have historically been associated with cyclonic conditions over the central and eastern Mediterranean or North Africa, which facilitate the advection of moist air toward Italy, particularly over the southern sector and the Adriatic coast[66]. In contrast, the WeMO describes a more regional pressure dipole between the Iberian Peninsula and the Gulf of Genoa, whose influence is especially evident in local dynamics such as Genoa cyclogenesis and in certain extreme precipitation events over the western Mediterranean[26]. This difference in spatial extent and temporal persistence provides a solid explanation for why the MOI emerges as a more robust and consistent index in modulating precipitation variability over Italy compared to the WeMO.

Our results suggest that the East Atlantic (EA) pattern exerts a stronger modulation of precipitation over Italy than the WeMO, particularly in combination with NAO phases. The EA is not only the second dominant mode of North Atlantic variability but, in some historical periods such as the early twentieth century, it even emerged as the leading mode, surpassing the NAO in its influence on European precipitation[70]. The physical mechanisms underlying this influence are linked to the EA's control over the position and intensity of the North Atlantic jet stream and the associated storm tracks, which explain up to one quarter of the interannual variability of European winter precipitation[71]. Long-term reconstructions further show that the EA interacts non-linearly with the NAO, with opposite-phase combinations producing the largest shifts in jet latitude and the most robust precipitation anomalies across the western and central Mediterranean[72]. Taken together, these findings reinforce the importance of considering the EA pattern, alongside NAO and MOI, as a key driver of hydro-climatic variability over Italy, while the WeMO remains more confined to regional dynamics.

5) In the Introduction, it would be beneficial to include references on Mediterranean cyclones and precipitation that are directly relevant to your study. For example, in lines 35–37, you could cite recent studies on the future evolution of cyclone-related precipitation over the Mediterranean, such as Reale et al. 2022 (https://doi.org/10.1007/s00382-021-06018-x) and Chericoni et al. 2025 (https://doi.org/10.1038/s41612-025-01121-w). Additionally, in lines 37–39, you might add references on the role of sea surface temperature (SST) in Mediterranean cyclogenesis, including Berthou et al. 2016 (https://doi.org/10.1002/qj.2717), Flaounas et al. 2018 (https://doi.org/10.1007/s00382-016-3398-7), Chericoni et al. 2025 (https://doi.org/10.5194/wcd-6-627-2025).

We thank you for this helpful suggestion. Following your recommendation, we have revised the Introduction to include the proposed references on Mediterranean cyclones and precipitation that are directly relevant to our study. Specifically, we now cite Reale et al. (2022) and Chericoni et al. (2025) when discussing the future evolution of cyclone-related precipitation over the Mediterranean, and we have also added references highlighting the role of sea surface temperature (SST) in Mediterranean cyclogenesis, namely Berthou et al. (2016), Flaounas et al. (2018), and Chericoni et al. (2025). We believe these additions strengthen the contextual framework of the study and improve the overall coherence of the Introduction.

Minor comments:

1) In lines 405–408, I believe you meant to refer to NAO+ and EA−, rather than NAO− and EA+. Similarly, in lines 409–411, it seems you intended to refer to NAO− and EA+, not NAO+ and EA−. If this is not the case, please clarify, as the interpretation from the figure appears to suggest the opposite.

We thank the Reviewer for pointing out this inconsistency. You are correct: in lines 405–408 the correct configuration is NAO+ and EA−, while in lines 409–411 it should be NAO− and EA+. We have revised the text accordingly to avoid confusion and ensure consistency with the interpretation from the figure.

2) what do you mean with "the type of input data" in line L113-114?

We thank the Reviewer for noticing this. The expression "the type of input data" was a leftover from an earlier draft and did not add relevant information in the current version of the manuscript. We have removed it from the text to avoid confusion.

3) In Figure 7, the low- and high-pressure systems appear to reflect synoptic-scale features rather than mesoscale structures.

We thank the Reviewer for this observation. You are correct that the pressure systems depicted in Figure 7 represent synoptic-scale rather than mesoscale features. We have therefore revised the caption accordingly, which now reads: *"Summary diagram of synoptic-scale circulation configurations and their effects on rainfall in Italy."*

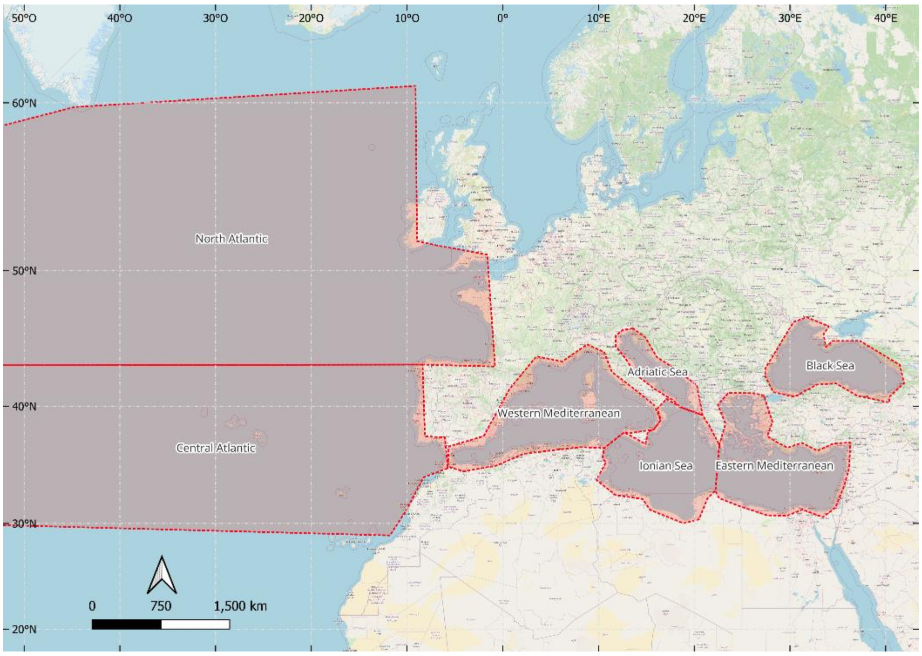
4) Please specify which dataset was used to compute the sea-level pressure isobars shown in Figure 7.

We thank the Reviewer for this comment. The sea-level pressure isobars shown in Figure 7 were computed using ERA5 Monthly data from the ECMWF, accessed through the Google Earth Engine platform (https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY?hl=it). This information has now been added to the figure caption for clarity.

5) Regarding the Back-trajectory analysis, please provide a map of the seven regions, perhaps as supplementary material, to help better visualize and understand the main moisture uptake areas.

We thank the Reviewer for this useful suggestion. Following the recommendation, we have added a supplementary figure (Supplementary Figure S1) showing the seven geographical domains used in the back-trajectory analysis. These regions (North Atlantic, Central Atlantic, Western Mediterranean, Adriatic Sea, Ionian Sea, Eastern Mediterranean, and Black Sea) are now described in the Supplementary Material to facilitate the interpretation of Figure 8 and to better visualize the main moisture uptake areas.

To quantify the origin of moisture contributing to precipitation over Italy, we identified seven geographical domains representing the main oceanic and regional sources. These include two large-scale oceanic regions (North Atlantic and Central Atlantic), four Mediterranean sub-basins (Western Mediterranean, Adriatic Sea, Ionian Sea, and Eastern Mediterranean), and the Black Sea. The delineation of these areas was based on the spatial distribution of air-mass back-trajectories intersecting the main water bodies surrounding the Italian Peninsula, as well as on previous studies of Mediterranean moisture recycling[1,2]. This classification allows for a consistent attribution of moisture uptake events, ensuring that each trajectory is assigned to the most relevant source region. By applying this scheme, we were able to estimate the relative contributions of oceanic and regional sources to precipitation over different parts of Italy. The inclusion of this map in the Supplementary Material (Supplementary Figure S1) provides a clear visualization of the domains used in Figure 8 of the main text and improves the reproducibility of the analysis.



6) In Figure 3, the models in version 2 are missing. Additionally, in the text (line 262), it is stated that the LSTM2STD model shows the best performance, but this model is not included in the figure.

We appreciate the Reviewer's careful observation. You are correct: the reference to the LSTM2STD model in line 262 was a mistake that remained from an earlier draft. The correct model is LSTM1STD, which is already included in Figure 3 and corresponds to the best-performing configuration. We have corrected the text accordingly to ensure consistency between the results and the figure.

7) Please provide which dataset was used to compute the indices and the SST trends in Figure 2.

We thank the Reviewer for this comment. The sea surface temperature indices and trends shown in Figure 2 were computed using data from the ERSST v5 dataset. This information has been added to the figure caption for clarity.

8) In lines 429–431, it is unclear how the cited study (reference 56) supports this conclusion. Please elaborate on this point by referring to additional papers that specifically investigate cyclonic activity in the eastern Mediterranean. Consider having a look at Hochman et al. 2020 (https://doi.org/10.1007/s00382-019-05017-3) to strengthen the discussion.

We thank the Reviewer for pointing out this issue. You are correct that the reference previously cited (Oza et al., 2022) is not the most appropriate to support this statement. We have now revised the text and included more relevant references that specifically address cyclonic activity in the Eastern Mediterranean, such as Hochman et al. (2020), to strengthen the discussion.

Reviewer #2 (Remarks to the Author):

This manuscript presents a novel integration of deep learning (DL) for reconstructing historical precipitation data in Italy (1950–2020), analysis of atmospheric teleconnections (e.g., NAO, MOI, WeMO), and HYSPLIT-based back-trajectory modeling to identify moisture sources. The core argument—that Mediterranean cyclogenesis and regional indices (MOI, WeMO) exert a stronger influence on Italian precipitation than NAO alone—is well-supported and addresses a recognized gap in NAO-centric interpretations of Mediterranean hydroclimatology. The study leverages a massive dataset (>11,000 rain gauges) and demonstrates methodological innovation, particularly in using DL to handle data discontinuities.
The paper is timely, given ongoing debates on climate hotspots in the Mediterranean and the need for high-resolution historical reconstructions amid climate change. It contributes meaningfully to understanding spatial precipitation variability, with implications for paleoclimate proxies and future projections. However, minor issues include incomplete methodological comparisons, some editorial inconsistencies, and assumptions in modeling that could be better justified. Overall, the work is scientifically sound and suitable for publication with minor revisions.
Detailed comments:

- How were splits done spatially and temporally? If random over all station-months, spatial autocorrelation can inflate skill. Require spatially blocked and time-blocked cross-validation (e.g., leave-one-region-out; leave-years-out) to quantify true generalization.

We thank the reviewer for this valuable comment. We fully agree that random splitting across all station-months could artificially inflate model performance due to spatial and temporal autocorrelation. For this reason, in addition to a standard random split, we implemented two dedicated cross-validation strategies to properly assess the generalization ability of the models.

(i) **Spatial blocking:** Stations were grouped into eight predefined climatic zones (Cantù et al., year; see Fig. S1). At each iteration, all stations within one climatic zone were excluded from training and used exclusively for testing, following a leave-one-region-out scheme. This approach allowed us to quantify the ability of the models to generalize to areas not seen during training.

(ii) **Temporal blocking:** The historical series was divided into contiguous three-year blocks. At each iteration, one block was excluded from training and used for testing (leave-years-out), while the remaining years formed the training set. This procedure enabled us to evaluate predictive skill on unseen time periods, simulating real-world application to future data.

The results of these experiments are reported in Supplementary Figures S2–S3 and described in the Supplementary Material. Both blocking strategies highlight the robustness of spatial transferability, while temporal generalization revealed clearer differences across model configurations.

In methods:

To properly assess model generalization, we applied both spatially blocked (leave-one-region-out) and temporally blocked (leave-years-out) cross-validation. The detailed procedure and results are reported in the Supplementary Material.

In supplementary material:

Cross-validation strategy

To evaluate the performance of the developed models, a cross-validation procedure was adopted that accounted for both the spatial and temporal dimensions of the data.

In the first case, spatial validation was implemented through a blocking approach (spatial blocking). Stations were associated with predefined climatic polygons[1,2] (Figure S3), and, in turn, all stations located within a given area were excluded from training and used as a test set. This procedure made it possible to verify the models' ability to generalize the learned relationships across different territorial contexts, including areas not involved in the training phase.

In parallel, a temporal validation (temporal blocking) was carried out by dividing the historical series into contiguous three-year blocks. Each block was excluded in rotation from the training phase and used as a test set, while the remaining years formed the training set. This approach allowed us to assess the stability of the models and their predictive skill in previously unseen historical phases, thus simulating their practical application to future periods.

Both procedures were applied to all model configurations (four different architectures combined with four different numbers of neighboring stations). In each case, the training set was further divided into training and validation subsets, in order to monitor the optimization process and reduce overfitting.

The Figure S4 reports the results of spatial and temporal cross-validation for the four model configurations.

For spatial validation, test performances are relatively similar across models, with R^2 values ranging approximately between 0.85 and 0.90 and RMSE values between 22 and 30. This indicates that the models can retain good predictive skill even when applied to climatic zones excluded from the training phase. Differences between architectures are limited, while the variability shown by the error bars mainly reflects the heterogeneous characteristics of the climatic regions.

For temporal validation, sharper contrasts emerge. The main distinction is related to the standardization of input data: models trained with standardized inputs (DL1STD and LSTM1STD) show lower and less stable R^2 values, with a clear deterioration in performance on the test sets. Conversely, non-standardized configurations (DL1 and LSTM1) achieve higher and more consistent R^2 values, particularly as the number of neighboring stations increases. RMSE values confirm this pattern, suggesting that input standardization did not improve model learning but instead reduced generalization to unseen temporal blocks.

Overall, the results highlight that spatial generalization is robust across all architectures, whereas temporal generalization reveals a clear negative effect of input standardization.

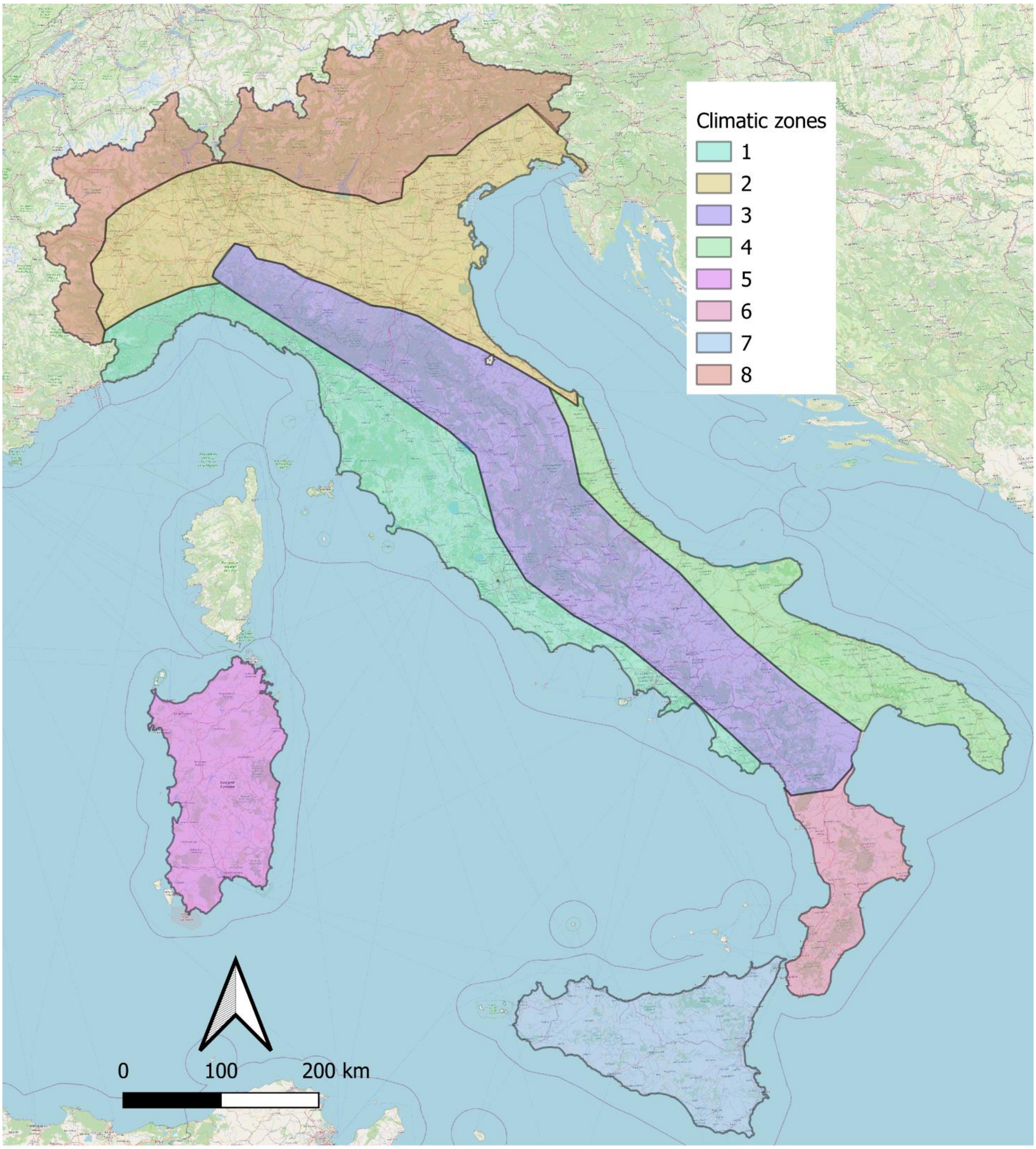


Figure S3 Climatic zones of Italy used for the spatial cross-validation procedure. The national territory was divided into eight climatic zones, following the classification proposed by [1,2]. For each iteration of the spatial blocking procedure, all stations within one zone were excluded from training and used exclusively as a test set, allowing the assessment of model performance in previously unseen areas.

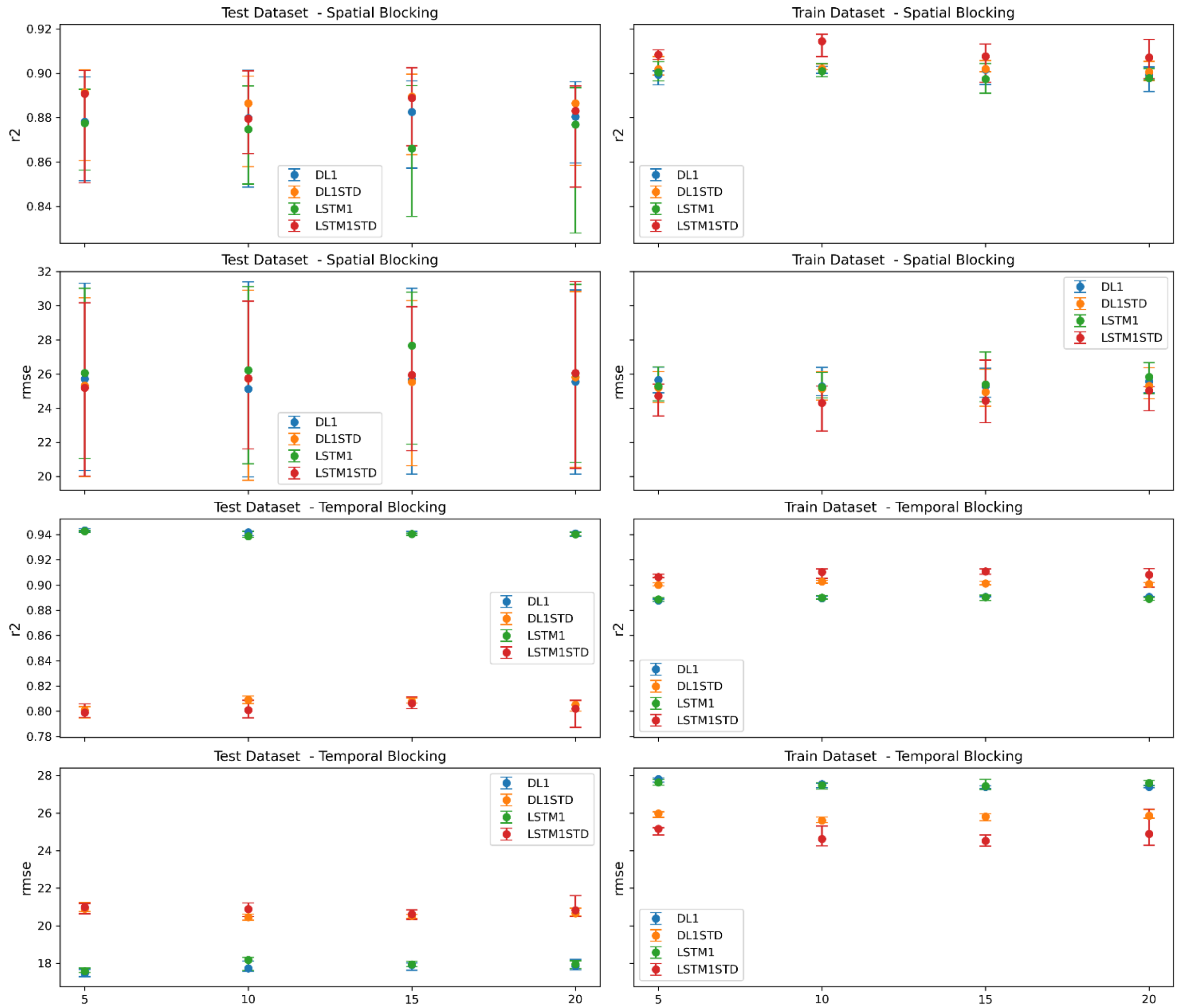


Figure S4 Performance of the four model configurations under spatial and temporal cross-validation.

The panels report R^2 and RMSE values for both training and test datasets.

- While DL models perform well (R^2 >0.90), no direct comparison to traditional interpolation (e.g., kriging, IDW) is provided. Recent studies benchmark ML against classical methods; this would strengthen claims of superiority for fragmented data.

We thank the Reviewer for this comment. We acknowledge that direct comparisons with classical interpolation methods (e.g., kriging, IDW) can be valuable, and several recent studies have indeed addressed this benchmarking. However, the primary aim of our work was not to identify the optimal interpolation technique but rather to produce a reliable, high-resolution dataset of precipitation over Italy. In this context, the adoption of deep learning models was motivated by their ability to efficiently handle and process very large and fragmented databases, which would be challenging to manage with traditional methods. We have clarified this point in the revised manuscript to better highlight the rationale behind our methodological choice.

In Discussion:

While classical interpolation techniques are widely used, the adoption of neural network models in this work primarily responds to the need for efficiently handling and exploiting large climate databases, rather than benchmarking model performance against simpler methods.

- Report performance maps (R^2/MAE) by topography (Alps/Apennines/Islands) and climate regimes.

We thank the Reviewer for this suggestion. Following the recommendation, we have expanded the validation by explicitly reporting model performance (R^2 and MAE) with respect to different topographic and climatic settings. In addition, we considered the main climatic regimes across the Italian territory. For each domain, we produced performance maps and summary statistics of R^2 and MAE.

The results confirm that the reconstruction performs consistently well across all regions, with no evidence of systematic biases linked to topography or climate. These additional maps and results are now provided in the Supplementary Material, as requested.

In the manuscript:

A more detailed assessment of model performance across the geospatial domain, including additional maps and correlation analyses, is provided in the Supplementary Material.

In Supplementary Material:

Spatial analysis of model errors

The validation of the reconstructed dataset generally shows excellent performance across the national territory, with high R^2 values and low MAE, as illustrated in the maps and detailed scatterplots (Figure S5, Figure S6, Figure S7). The spatial analysis does not reveal marked geographical patterns that could indicate systematic model biases in relation to latitude, longitude, or elevation (Figure S5). On the contrary, the distribution of accuracy values appears homogeneous, confirming the robustness of the reconstruction even in areas characterized by heterogeneous climatic and topographic conditions. Spearman correlations computed for the different models and configurations are generally very low, in many cases close to zero, suggesting the absence of strong or systematic relationships between performance and geographical parameters (Table S1).

The most consistent correlations concern elevation, which shows a weak but significant relationship with both indicators: R^2 tends to slightly decrease with increasing elevation (with coefficients between –0.04 and –0.07 depending on the model), while MAE shows a positive increase with altitude (with coefficients between 0.18 and 0.22, highly significant). These are nonetheless modest values, explaining only a very limited portion of the spatial variability, but they are consistent with the greater complexity of rainfall regimes in mountainous areas. For latitude and longitude, the signals are even weaker: in some cases, significant but very small correlations are observed, on the order of –0.02/–0.03 for R^2 and 0.14–0.16 for MAE with latitude, and –0.07/–0.09 for MAE with longitude. Once again, these are extremely weak relationships that do not outline real spatial gradients but only slight trends detectable thanks to the large number of observations.

Another relevant aspect is the relationship with observed rainfall. Results show that R^2 tends to increase slightly with increasing rainfall (with coefficients ~ 0.06–0.07, significant), while MAE increases more markedly (with coefficients ~ 0.22–0.27). This behavior is expected and does not indicate a deterioration of model performance, but simply reflects the percentage nature of the error and the relationship with the average rainfall. In other words, in stations or periods with higher rainfall, absolute error values increase, but relative accuracy remains unchanged or even improves, as confirmed by the increase in R^2 with precipitation amount.

Overall, the weak correlations observed, particularly with elevation and rainfall, do not reduce the solidity of the dataset but reflect intrinsic characteristics of rainfall variability. Therefore, the validation results confirm that the reconstruction is reliable on a national scale and suitable for climatic and hydrological studies that require a coherent and accurate representation of precipitation.

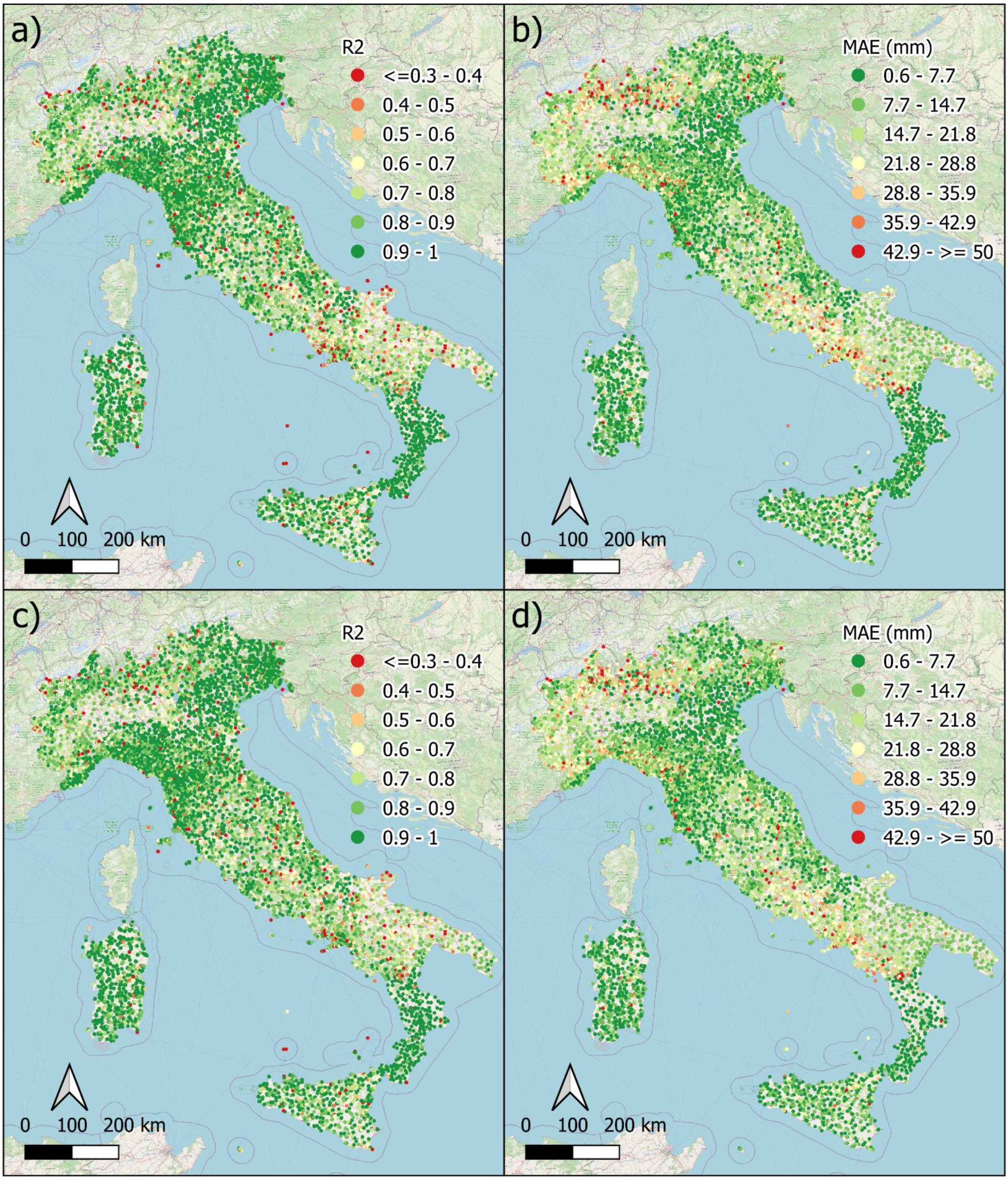


Figure S5 Spatial distribution of model performance across the Italian domain. Panels (a) and (b) refer to the DL1_n10 configuration, while panels (c) and (d) refer to the LSTM1_n10 configuration. Panels (a) and (c) show the coefficient of determination (R^2), and panels (b) and (d) display the mean absolute error (MAE, mm).

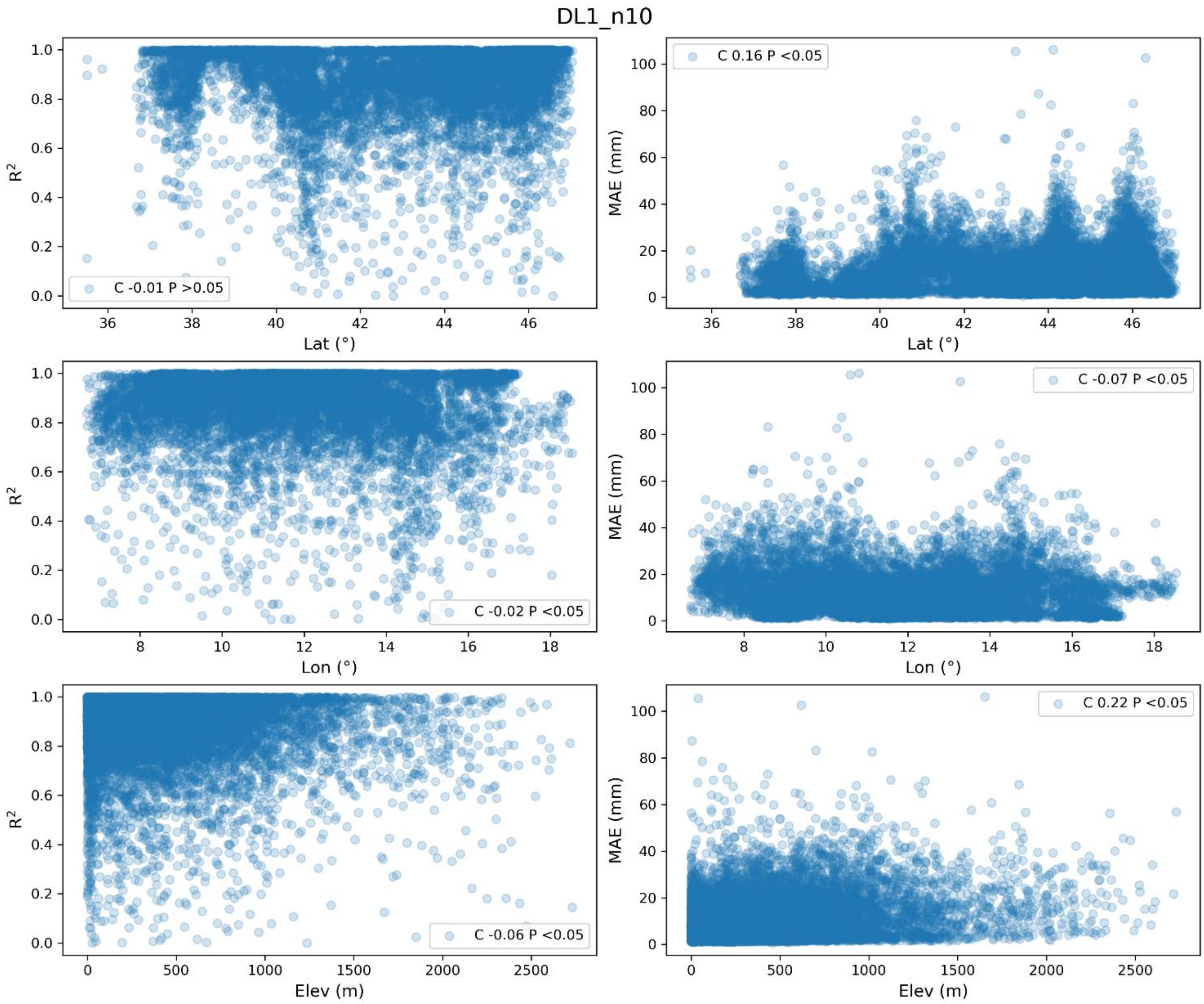


Figure S6 Spatial dependence of model performance for the DL1_n10 configuration. The scatterplots show the relationship between station latitude, longitude, and elevation with performance metrics: coefficient of determination (R^2, left column) and mean absolute error (MAE, right column). Reported Spearman's correlation coefficients (C) and associated p-values indicate the strength and significance of the dependence of performance on geographical location and elevation.

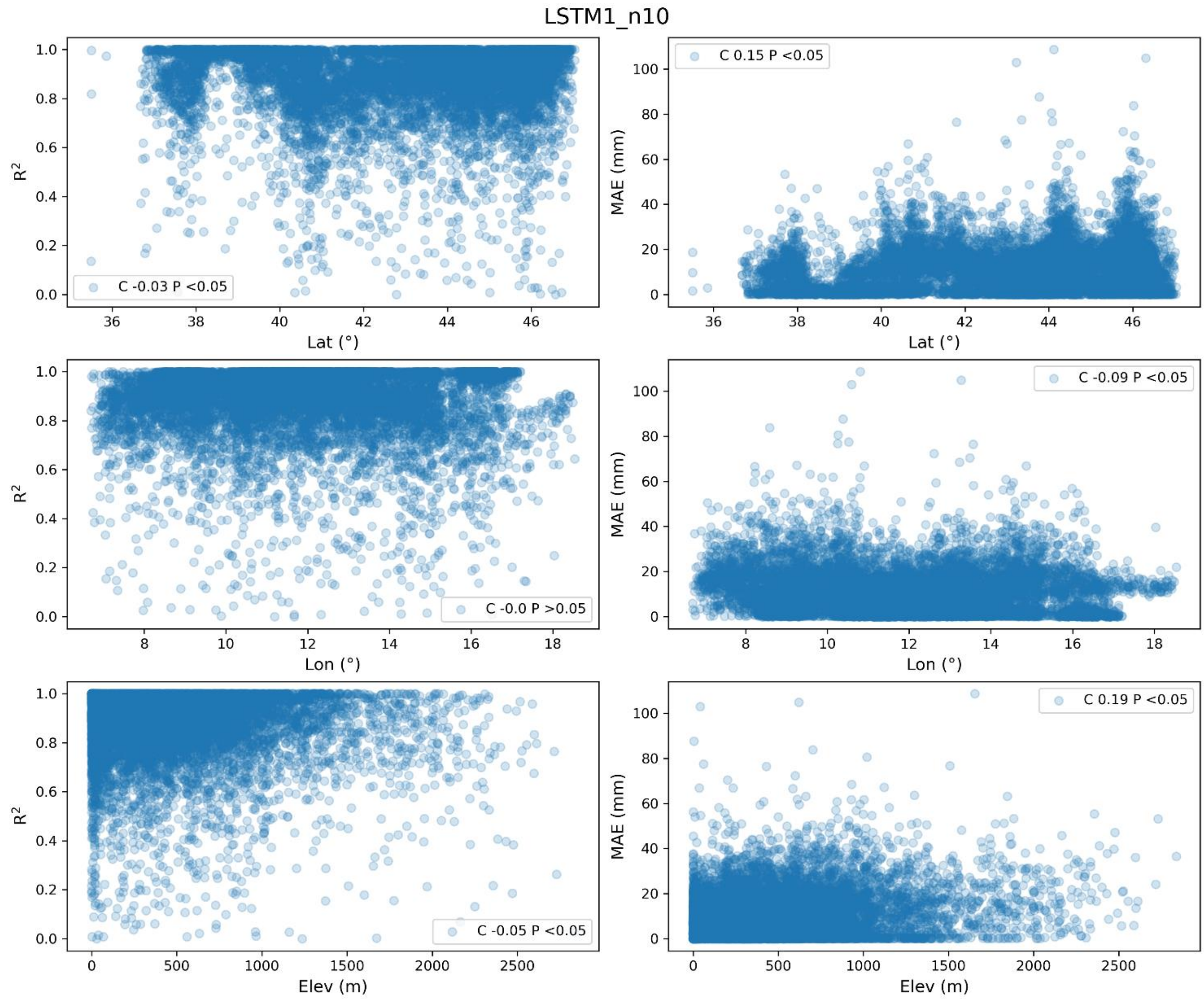


Figure S7 Spatial dependence of model performance for the LSTM1_n10 configuration. The scatterplots show the relationship between station latitude, longitude, and elevation with performance metrics: coefficient of determination (R^2, left column) and mean absolute error (MAE, right column). Reported Spearman's correlation coefficients (C) and associated p-values indicate the strength and significance of the dependence of performance on geographical location and elevation.

Table S1 Spearman correlation coefficients between model performance metrics (R^2 and MAE) and geographical or climatic predictors (latitude, longitude, elevation, and rainfall) for different model configurations. Asterisks indicate statistical significance (* $p < 0.05$, ** $p < 0.01$).

model	Lat - R2	Lat - MAE	Lon - R2	Lon - MAE	Elev - R2	Elev - MAE	R - R2	R - MAE
DL1_n10	-0.010	0.160**	-0.020*	-0.070**	-0.060**	0.220**	0.060**	0.270**
DL1STD_n10	-0.020	0.140**	-0.020	-0.070**	-0.070**	0.220**	0.060**	0.250**
LSTM1_n10	-0.030**	0.150**	0.000	-0.090**	-0.050**	0.190**	0.070**	0.230**
LSTM1STD_n10	-0.030**	0.150**	-0.010	-0.090**	-0.050**	0.180**	0.070**	0.220**
DL1_n15	-0.020	0.150**	-0.020	-0.070**	-0.050**	0.220**	0.070**	0.260**

DL1STD_n15	-0.020*	0.160**	-0.010	-0.080**	-0.060**	0.210**	0.060**	0.260**
LSTM1_n15	-0.030**	0.150**	-0.010	-0.090**	-0.050**	0.180**	0.070**	0.220**
LSTM1STD_n15	-0.030**	0.150**	-0.010	-0.080**	-0.050**	0.190**	0.070**	0.230**
DL1_n20	-0.020*	0.160**	-0.020*	-0.070**	-0.050**	0.220**	0.070**	0.270**
DL1STD_n20	-0.010	0.140**	-0.020	-0.080**	-0.060**	0.210**	0.070**	0.250**
LSTM1_n20	-0.030**	0.150**	-0.010	-0.090**	-0.040**	0.180**	0.070**	0.230**
LSTM1STD_n20	-0.030**	0.160**	-0.010	-0.090**	-0.050**	0.190**	0.070**	0.230**
DL1_n5	-0.020*	0.150**	-0.010	-0.080**	-0.060**	0.210**	0.060**	0.250**
DL1STD_n5	-0.020*	0.160**	-0.010	-0.090**	-0.060**	0.210**	0.050**	0.260**
LSTM1_n5	-0.030**	0.150**	0.000	-0.090**	-0.050**	0.190**	0.060**	0.230**
LSTM1STD_n5	-0.030**	0.150**	0.000	-0.090**	-0.050**	0.190**	0.070**	0.220**

- Compare reconstructed monthly precipitation to E-OBS (and, if feasible, ARCIS for N Italy) at common grid and period (bias, RMSE, correlations, cycle & extremes). E-OBS is the de-facto observational baseline in Europe; its precipitation has known characteristics and documented evaluations.

We thank the Reviewer for this suggestion. While we acknowledge the relevance of E-OBS (and ARCIS for Northern Italy) as observational baselines, we opted for ERA5 as the main reference dataset. ERA5 is widely recognized as a standard for climate and hydrological applications, provides homogeneous coverage of the entire Italian domain, and has been extensively validated in the literature. In contrast, E-OBS suffers from lower station density in parts of Italy and a similar spatial resolution to ERA5, while ARCIS is limited to Northern Italy only, making them less suitable for a comprehensive national-scale validation. For these reasons, we focused our validation on ERA5, computing both Spearman and Pearson correlations at the grid-cell level and summarizing the agreement through spatial correlation maps and statistics. This approach ensures a robust and spatially consistent assessment of the reconstructed dataset, confirming high and significant correlations across the domain ($p < 0.01$).

In methods:

The reconstructed precipitation dataset was validated against ERA5 reanalysis data from the Copernicus Climate Change Service (https://climate.copernicus.eu/climate-reanalysis), which provides a widely used and well-established reference for climate and hydrological studies. To assess the consistency between the two datasets, we calculated both Spearman[41] and Pearson[42] correlation coefficients at a monthly scale over the common period of analysis. While Pearson's correlation measures the strength of the linear relationship, Spearman's correlation also accounts for monotonic but non-linear associations, offering a more comprehensive evaluation of agreement. The correlations were computed at each 10 km grid cell of the reconstructed dataset by comparing the corresponding spatially matched ERA5 time series.

In results:

The comparison with ERA5 reanalysis data shows that the reconstructed monthly precipitation dataset achieves very high correlations across most of the Italian domain

(Figure 1). Both Spearman and Pearson coefficients display median values above 0.8, confirming the robustness of the reconstruction despite the coarser resolution of ERA5 (0.25° × 0.25°, corresponding to approximately 30–40 km) compared to the 10 km resolution of the reconstructed dataset. The spatial distribution of the correlations highlights locally lower values, particularly in some mountainous and coastal areas, where small-scale processes are not fully captured by ERA5. Nevertheless, correlations remain consistently significant across the entire domain. Importantly, all grid cells yielded p-values lower than 0.01, confirming the statistical robustness of the results.

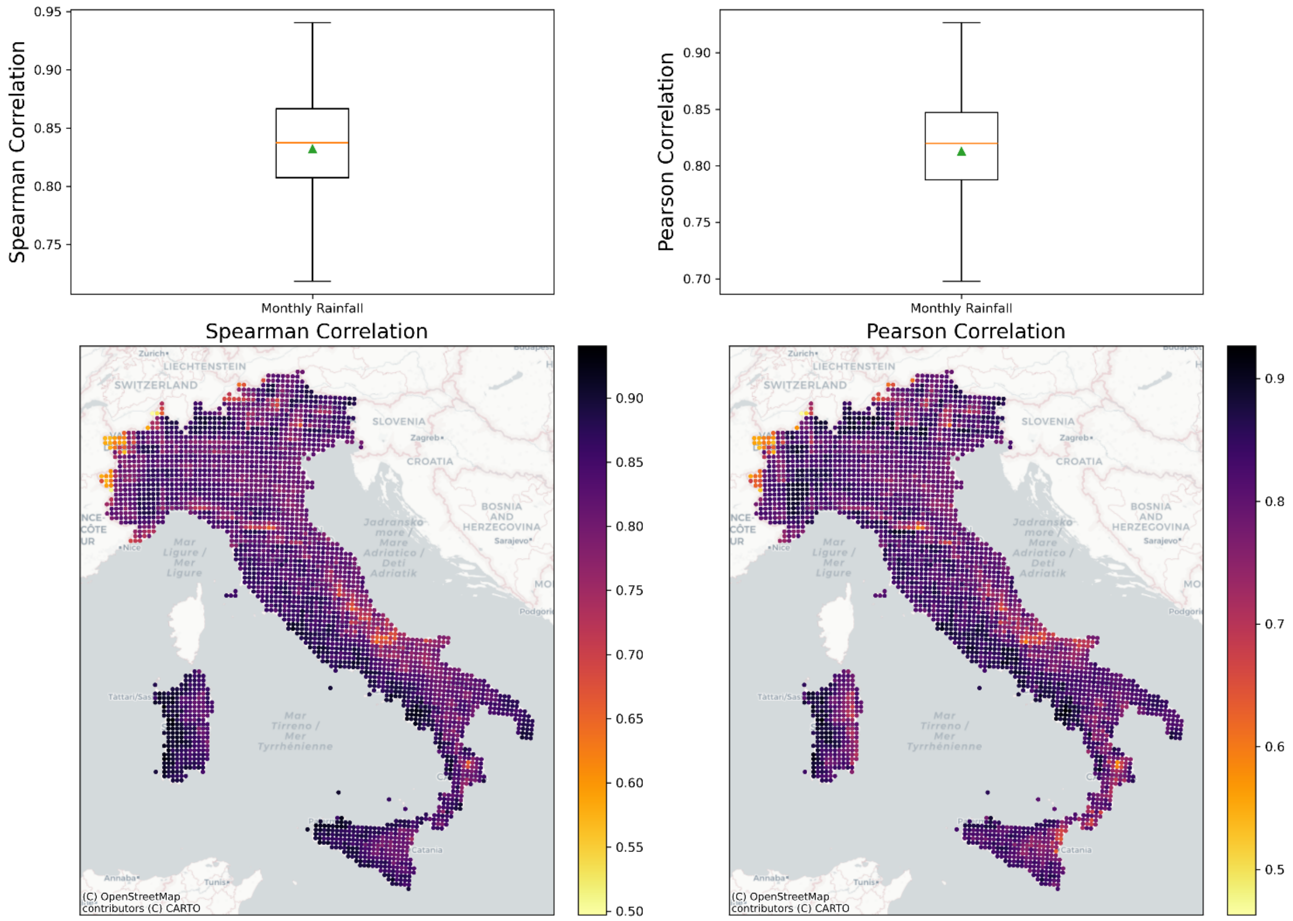


Figure 8 Validation of the reconstructed monthly precipitation against reference datasets. The boxplots (top) show the distribution of correlation coefficients across all grid cells at 10 km resolution, using both Spearman (left) and Pearson (right) metrics. The orange line indicates the median value, and the green triangle indicates the average. The maps (bottom) display the spatial distribution of the correlation values for Spearman (left) and Pearson (right), highlighting generally high and spatially consistent agreement across most of Italy, with local variations in mountainous and coastal areas. All recorded points have a significant statistic with a p-value < 0.01.

In discussions:

The historical series reconstructed in this study demonstrate how the integration of advanced methodologies makes it possible to effectively manage large climate databases and extract meaningful information from them. The consistency of the dataset produced was also verified through comparison with independent reanalysis data (ERA5), using statistical correlation analyses. The results confirm the robustness of the models and their ability to reproduce climate signals consistent with those reported in the literature, even for variables characterized by high spatial and temporal variability such as precipitation. Moreover, the use of this dataset has made it possible to overcome two main limitations of reanalysis products: i) the historical series reconstructed here are entirely based on statistical–probabilistic approaches, relying solely on observational data and not on physical models; ii) the spatial resolution achieved is about 7–8 times higher than that of ERA5, improving from approximately 0.25° × 0.25° (about 28 × 28 km) to 10 × 10 km in the dataset developed in this work.

- Discuss agreement/disagreement relative to recent Med/Italy precipitation reviews.

We thank the Editor for the helpful suggestion. In the revised version of the manuscript, we have expanded the *Discussion* section by adding a dedicated paragraph that validates the reconstructed dataset against independent reanalysis products (ERA5) and situates our results within the context of existing literature on Mediterranean and Italian precipitation. This addition highlights both the robustness of the reconstructed series and their ability to reproduce known climate signals, even for highly variable fields such as precipitation. Furthermore, the new text emphasizes the advantages of our dataset compared to reanalysis products, namely the exclusive reliance on observational data and the higher spatial resolution achieved. We believe that this addition addresses the comment raised and strengthens the scientific validity of our study.

In discussion:

The historical series reconstructed in this study demonstrate how the integration of advanced methodologies makes it possible to effectively manage large climate databases and extract meaningful information from them. The consistency of the dataset produced was also verified through comparison with independent reanalysis data (ERA5), using statistical correlation analyses. The results confirm the robustness of the models and their ability to reproduce climate signals consistent with those reported in the literature, even for variables characterized by high spatial and temporal variability such as precipitation. Moreover, the use of this dataset has made it possible to overcome two main limitations of reanalysis products: i) the historical series reconstructed here are entirely based on statistical–probabilistic approaches, relying solely on observational data and not on physical models; ii) the spatial resolution achieved is about 7–8 times higher than that of ERA5, improving from approximately 0.25° × 0.25° (about 28 × 28 km) to 10 × 10 km in the dataset developed in this work.

- Figures (e.g., 3–7) are well-described but could benefit from statistical significance tests (e.g., p-values for anomalies).

We thank the Reviewer for this useful suggestion. In agreement with the observation of the Reviewer 1, we have implemented a statistical significance assessment of the precipitation anomalies. Specifically, we applied a non-parametric bootstrapping procedure to test the anomalous precipitation term defined in Equation (line 201). For each phase combination of the indices, the observed anomaly was compared against an empirical distribution obtained by resampling with replacement from the full dataset (5,000 iterations). The p-value was estimated as the proportion of bootstrap replicates yielding an anomaly equal to or greater than the observed one. The results of this analysis are now presented in a new figure (Figure 7), where grid cells with p-values < 0.05 are highlighted as statistically significant. This additional validation confirms that the most robust anomalies occur under opposite-phase combinations of indices, while same-phase combinations generally yield non-significant results.

In methods

To assess the statistical significance of the precipitation anomalies associated with the different combinations of large-scale and regional circulation indices, we implemented a non-parametric bootstrapping approach. For each configuration (e.g., NAO+ | AMO–), we first computed the observed precipitation anomaly as the percentage deviation of the mean precipitation with respect to the climatological mean. Then, to evaluate whether this anomaly could arise by chance, we generated an empirical distribution by resampling with replacement from the full dataset, drawing the same number of years as in the target configuration. The anomaly was recalculated for each bootstrap sample, and this procedure was repeated 5,000 times to obtain a robust reference distribution. The p-value was then estimated as the proportion of bootstrap replicates yielding an anomaly of equal or greater magnitude than the observed one. Grid cells with p-values lower than 0.05 were considered statistically significant.

In results:

… and the statistical assessment confirms that these signals are robust over wide areas (Figure 7).

… although the significance analysis (Figure 7) highlights that when both indices share the same phase the anomalies are generally not significant across Italy, whereas opposite-phase combinations yield statistically robust signals.

However, as shown in Figure 7, only some of these anomalies reach statistical significance, underlining the need for caution when interpreting weak signals.

… and the significance analysis (Figure 7) confirms that these longitudinal contrasts are statistically robust.

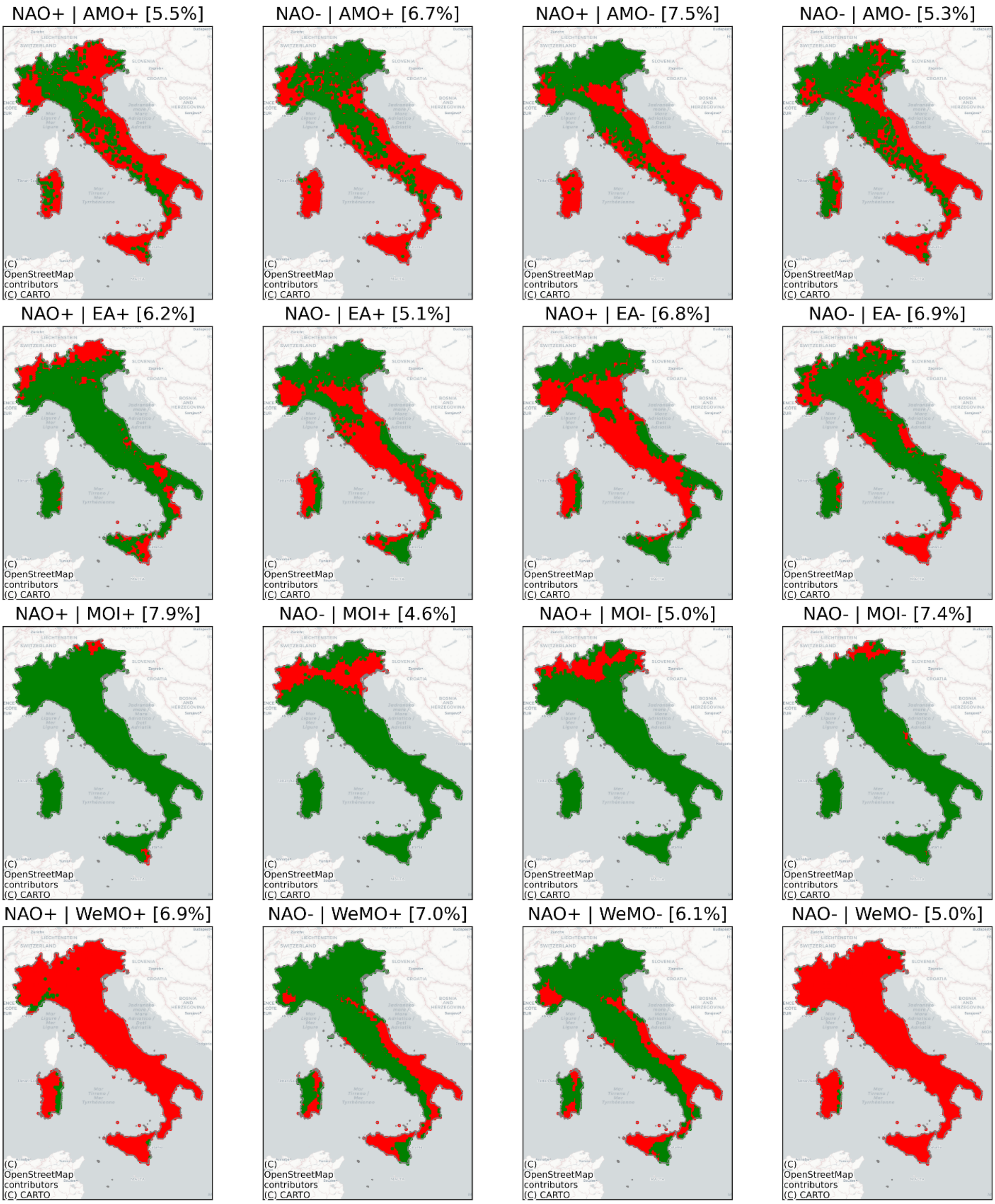


Figure 9 Spatial significance of precipitation anomalies under different NAO combinations with other climate indices. Green areas indicate grid cells where anomalies are statistically significant ($p < 0.05$), while red areas denote non-significant results. The percentage in square brackets indicates how often each specific configuration occurs within the time series.

- While intro mentions GHG-driven changes, results/discussion underplay projections (e.g., how warming affects MOI/WeMO). Linking to CMIP6 downscaling (e.g., Statistical Downscaling over Italy, Sci Data, 2025) would enhance forward-looking value.

We thank the Reviewer for this valuable comment. Following the suggestion, we have expanded the *Discussion* to explicitly connect our historical findings with future climate projections. In the revised manuscript we now emphasize that several studies suggest an increasing prevalence of positive NAO phases under greenhouse gas forcing, which are typically associated with drying trends across central and southern Italy. We also highlight the role of rising Mediterranean SSTs in weakening key cyclogenetic centers (e.g., the Icelandic Low and the Genoa Gulf Low) and in promoting greater atmospheric instability and extreme rainfall. In addition, we have integrated recent literature on the East Atlantic (EA) pattern, noting that in some historical periods it emerged as the leading mode of variability, underscoring its potential relevance for Mediterranean precipitation under future scenarios. Finally, to reinforce the forward-looking perspective of our study, we refer to the most recent statistical downscaling of CMIP6 simulations over Italy (Statistical Downscaling over Italy, Sci Data, 2025), which projects increased winter precipitation in the north but widespread reductions in other seasons. These additions strengthen the connection between past variability and future climate change, aligning our work with current research on Mediterranean precipitation trends.

In Discussion:

Recent studies suggest that the North Atlantic Oscillation (NAO) may become more frequently positive in the future[78,79], with direct implications for hydro-climatic regimes in the Mediterranean. Our analysis already shows that NAO+ phases are generally associated with reduced precipitation across much of Italy, particularly in central and southern regions, suggesting that a greater frequency of such conditions could intensify drying trends, especially if combined with a weakening of Mediterranean cyclogenetic areas. This dynamic is further reinforced by rising Mediterranean sea surface temperatures (SST), which according to the literature weaken both the Icelandic Low and the Genoa Gulf Low[80], resulting in reduced Mediterranean cyclogenesis[52]. The progressive intensification of negative WeMO phases can also be interpreted as a manifestation of this weakening, linked to the expansion of the Azores High and a background state more consistent with NAO+ conditions.

Taken together, these mechanisms are consistent with projections for Italy that indicate an increase in winter precipitation in the North but widespread reductions in other seasons, as highlighted by the most recent statistical downscaling experiments of CMIP6 simulations[81]. Moreover, while total precipitation is expected to decrease, rising Mediterranean SSTs promote greater atmospheric instability, fostering more frequent and intense extreme rainfall events[82–85] . These results reinforce the hypothesis that climate warming will intensify the "hydrological paradox" already observed in the Mediterranean: an overall reduction in annual totals accompanied by an increase in extreme events, placing our findings within a coherent trajectory from past to future.

Reviewer #3 (Remarks to the Author):

Luppichini et al. addressed the question of precipitation variability in the Italian peninsula from the perspective of climatic indexes. They reached to a conclusion that cyclone systems play dominant role therein whereas North Atlantic Oscillation is insufficient to statistically explain it. The methodological approach is based on AI reconstructing rainfall time series from surface meteorological stations, then on the combined analysis of different teleconnection indexes and finally on moisture uptake diagnostics. I read the paper with great interest, but I have strong concerns on the content and approach that lead me to reject it for eventual publication. Right below I only outline 3 major issues that formed this decision:

Inconsistent datasets

1. The reconstruction of time series is certainly an interesting approach and leads to useful material. I am not sure however why surface stations were chosen for this study. Since the approach is based on a recent climatology and since the authors would like to link their results with regional dynamics (moisture uptakes and cyclone systems) why don't they use reanalysis datasets such as ERA5 instead of observations? This way, precipitation variability would be consistent with moisture uptake and large scale pressure patterns not to mention that there would be uncertainties in the results because of choosing representative grid points to perform the moisture uptake analysis. The authors would just have to run trajectory analysis from each grid point over the Italian peninsula. Finally, horizontal resolution of ERA5 would be more adequate for a relatively small region such as the Mediterranean than 1 degree used here.

We thank the Reviewer for this important comment. We acknowledge the value of reanalysis products such as ERA5, but we chose to base our reconstruction on surface station observations for several reasons. First, ERA5 is a reanalysis product and, as such, remains a model-based dataset subject to biases and uncertainties, particularly in regions with complex topography such as Italy. In contrast, our reconstruction is entirely built on a statistical–probabilistic approach that relies solely on observed data, thus avoiding the dependence on physical models. Second, the spatial resolution of our dataset (10 × 10 km) is about 7–8 times higher than that of ERA5 (0.25° × 0.25°, approximately 28 × 28 km), which allows a much finer characterization of precipitation variability at the national scale. We have clarified this point explicitly in the revised Discussion.

In Discussion:

The historical series reconstructed in this study demonstrate how the integration of advanced methodologies makes it possible to effectively manage large climate databases and extract meaningful information from them. The consistency of the dataset produced was also verified through comparison with independent reanalysis data (ERA5), using statistical correlation analyses. The results confirm the robustness of the models and their ability to reproduce climate signals consistent with those reported in the literature, even for variables characterized by high spatial and temporal variability such as precipitation. Moreover, the use of this dataset has made it possible to overcome two main limitations of reanalysis products: i) the historical series reconstructed here are entirely based on statistical–probabilistic approaches, relying solely on observational data and not on physical models; ii) the spatial resolution achieved is about 7–8 times higher than that of ERA5, improving from approximately 0.25° × 0.25° (about 28 × 28 km) to 10 × 10 km in the dataset developed in this work.

Third, we performed a comprehensive comparison with ERA5 to ensure consistency and robustness of the reconstructed data. The validation included spatial correlation maps, summary statistics, and tests of statistical significance (p-values), confirming very high and significant agreement across the Italian domain.

In methods:

The reconstructed precipitation dataset was validated against ERA5 reanalysis data from the Copernicus Climate Change Service (https://climate.copernicus.eu/climate-reanalysis), which provides a widely used and well-established reference for climate and hydrological studies. To assess the consistency between the two datasets, we calculated both Spearman[41] and Pearson[42] correlation coefficients at a monthly scale over the common period of analysis. While Pearson's correlation measures the strength of the linear relationship, Spearman's correlation also accounts for monotonic but non-linear associations, offering a more comprehensive evaluation of agreement. The correlations were computed at each 10 km grid cell of the reconstructed dataset by comparing the corresponding spatially matched ERA5 time series.

In results:

The comparison with ERA5 reanalysis data shows that the reconstructed monthly precipitation dataset achieves very high correlations across most of the Italian domain (Figure 1). Both Spearman and Pearson coefficients display median values above 0.8, confirming the robustness of the reconstruction despite the coarser resolution of ERA5 (0.25° × 0.25°, corresponding to approximately 30–40 km) compared to the 10 km resolution of the reconstructed dataset. The spatial distribution of the correlations highlights locally lower values, particularly in some mountainous and coastal areas, where small-scale processes are not fully captured by ERA5. Nevertheless, correlations remain consistently significant across the entire domain. Importantly, all grid cells yielded p-values lower than 0.01, confirming the statistical robustness of the results.

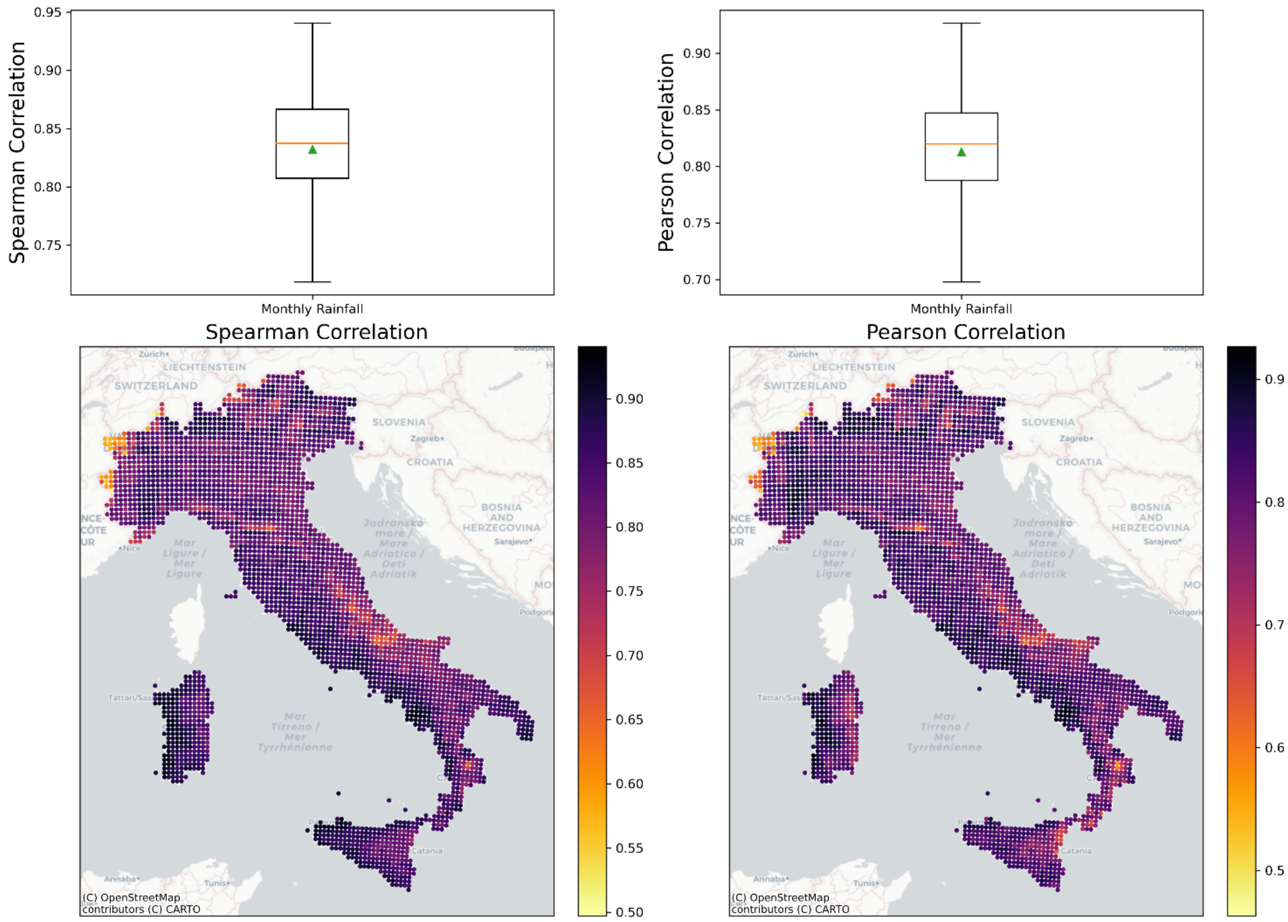


Figure 10 Validation of the reconstructed monthly precipitation against reference datasets. The boxplots (top) show the distribution of correlation coefficients across all grid cells at 10 km resolution, using both Spearman (left) and Pearson (right) metrics. The orange line indicates the median value, and the green triangle indicates the average. The maps (bottom) display the spatial distribution of the correlation values for Spearman (left) and Pearson (right), highlighting generally high and spatially consistent agreement across most of Italy, with local variations in mountainous and coastal areas. All recorded points have a significant statistic with a p-value < 0.01.

In discussions:

The historical series reconstructed in this study demonstrate how the integration of advanced methodologies makes it possible to effectively manage large climate databases and extract meaningful information from them. The consistency of the dataset produced was also verified through comparison with independent reanalysis data (ERA5), using statistical correlation analyses. The results confirm the robustness of the models and their ability to reproduce climate signals consistent with those reported in the literature, even for variables characterized by high spatial and temporal variability such as precipitation. Moreover, the use of this dataset has made it possible to overcome two main limitations of reanalysis products: i) the historical series reconstructed here are entirely based on statistical–probabilistic approaches, relying solely on observational data and not on physical models; ii) the spatial resolution achieved is about 7–8 times higher than that of ERA5, improving from approximately 0.25° × 0.25° (about 28 × 28 km) to 10 × 10 km in the dataset developed in this work.

Finally, in response to the comments of the other Reviewers, we substantially expanded the validation of the dataset, adding new analyses and figures both in the main text and in the Supplementary Material. We believe that these additions demonstrate the reliability of our reconstructed dataset while underlining its complementarity to reanalysis products such as ERA5.

In the manuscript:

A more detailed assessment of model performance across the geospatial domain, including additional maps and correlation analyses, is provided in the Supplementary Material.

In Supplementary Material:

Spatial analysis of model errors

The validation of the reconstructed dataset generally shows excellent performance across the national territory, with high R^2 values and low MAE, as illustrated in the maps and detailed scatterplots (Figure S5, Figure S6, Figure S7). The spatial analysis does not reveal marked geographical patterns that could indicate systematic model biases in relation to latitude, longitude, or elevation (Figure S5). On the contrary, the distribution of accuracy values appears homogeneous, confirming the robustness of the reconstruction even in areas characterized by heterogeneous climatic and topographic conditions. Spearman correlations computed for the different models and configurations are generally very low, in many cases close to zero, suggesting the absence of strong or systematic relationships between performance and geographical parameters (Table S1).

The most consistent correlations concern elevation, which shows a weak but significant relationship with both indicators: R^2 tends to slightly decrease with increasing elevation (with coefficients between –0.04 and –0.07 depending on the model), while MAE shows a positive increase with altitude (with coefficients between 0.18 and 0.22, highly significant). These are nonetheless modest values, explaining only a very limited portion of the spatial variability, but they are consistent with the greater complexity of rainfall regimes in mountainous areas. For latitude and longitude, the signals are even weaker: in some cases, significant but very small correlations are observed, on the order of –0.02/–0.03 for R^2 and 0.14–0.16 for MAE with latitude, and –0.07/–0.09 for MAE with longitude. Once again, these are extremely weak relationships that do not outline real spatial gradients but only slight trends detectable thanks to the large number of observations.

Another relevant aspect is the relationship with observed rainfall. Results show that R^2 tends to increase slightly with increasing rainfall (with coefficients ~ 0.06–0.07, significant), while MAE increases more markedly (with coefficients ~ 0.22–0.27). This behavior is expected and does not indicate a deterioration of model performance, but simply reflects the percentage nature of the error and the relationship with the average rainfall. In other words, in stations or periods with higher rainfall, absolute error values increase, but relative accuracy remains unchanged or even improves, as confirmed by the increase in R^2 with precipitation amount.

Overall, the weak correlations observed, particularly with elevation and rainfall, do not reduce the solidity of the dataset but reflect intrinsic characteristics of rainfall variability. Therefore, the validation results confirm that the reconstruction is reliable on a national scale and suitable for climatic and hydrological studies that require a coherent and accurate representation of precipitation.

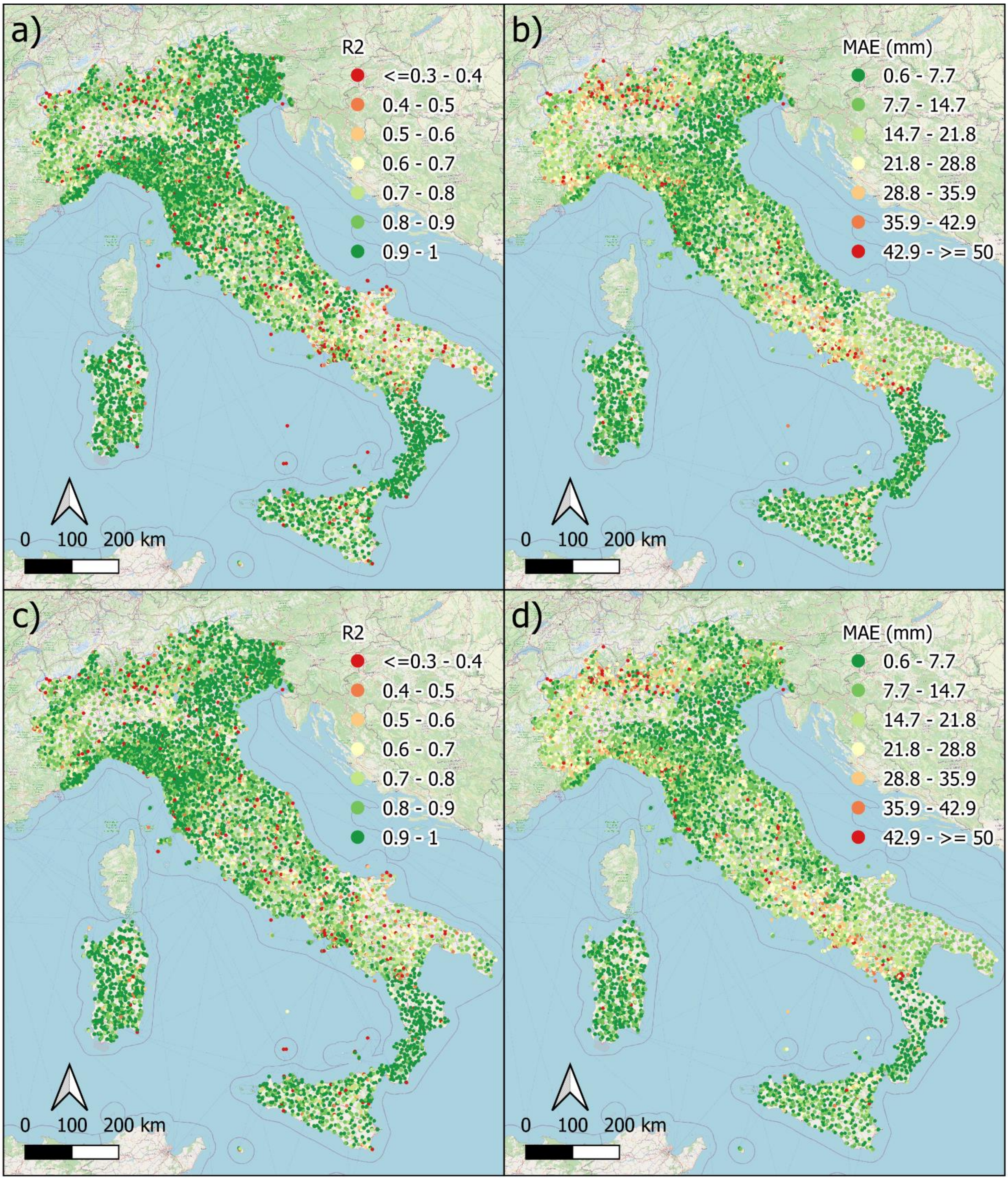


Figure S11 Spatial distribution of model performance across the Italian domain. Panels (a) and (b) refer to the DL1_n10 configuration, while panels (c) and (d) refer to the LSTM1_n10 configuration. Panels (a) and (c) show the coefficient of determination (R^2), and panels (b) and (d) display the mean absolute error (MAE, mm).

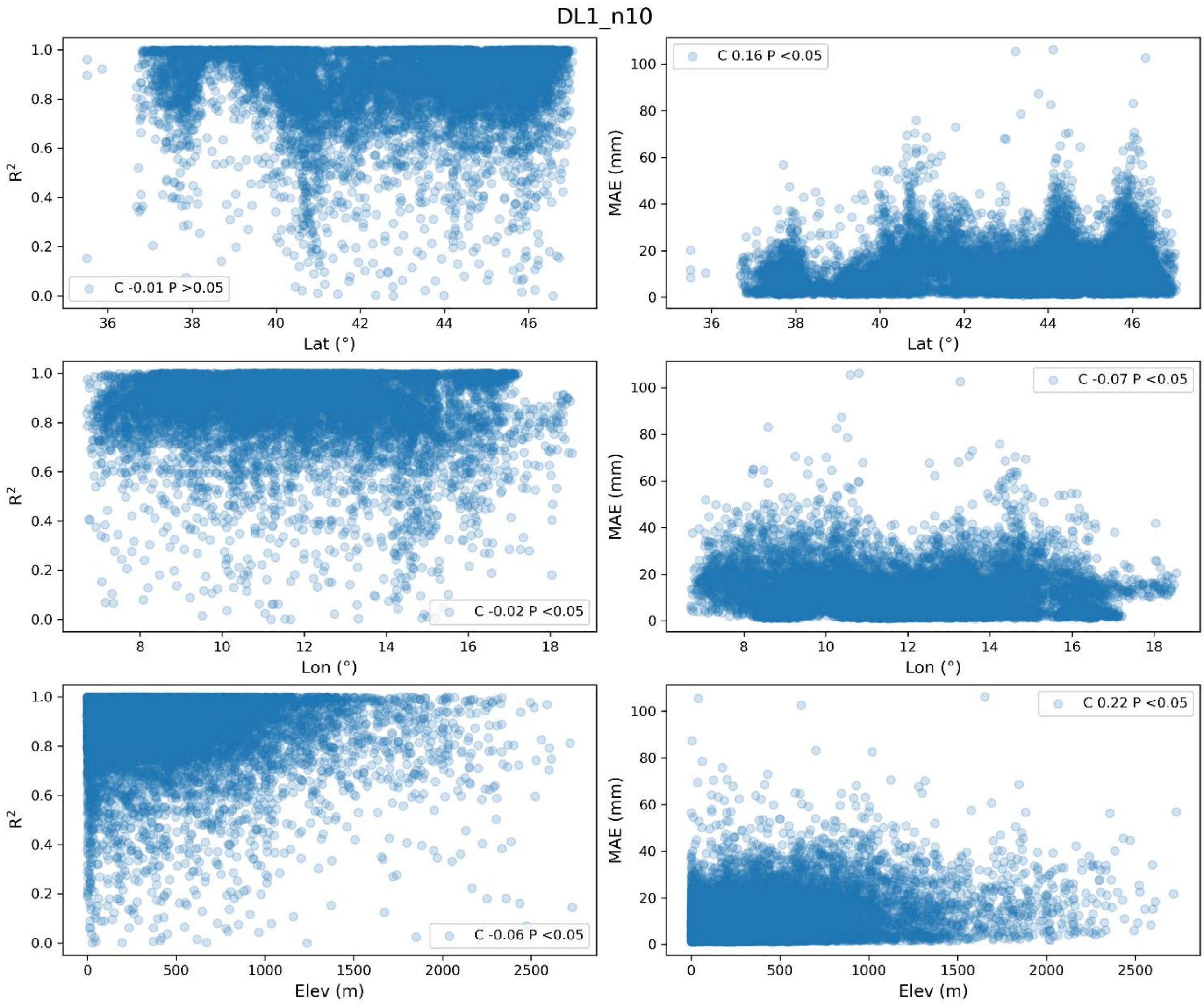


Figure S12 Spatial dependence of model performance for the DL1_n10 configuration. The scatterplots show the relationship between station latitude, longitude, and elevation with performance metrics: coefficient of determination (R^2, left column) and mean absolute error (MAE, right column). Reported Spearman's correlation coefficients (C) and associated p-values indicate the strength and significance of the dependence of performance on geographical location and elevation.

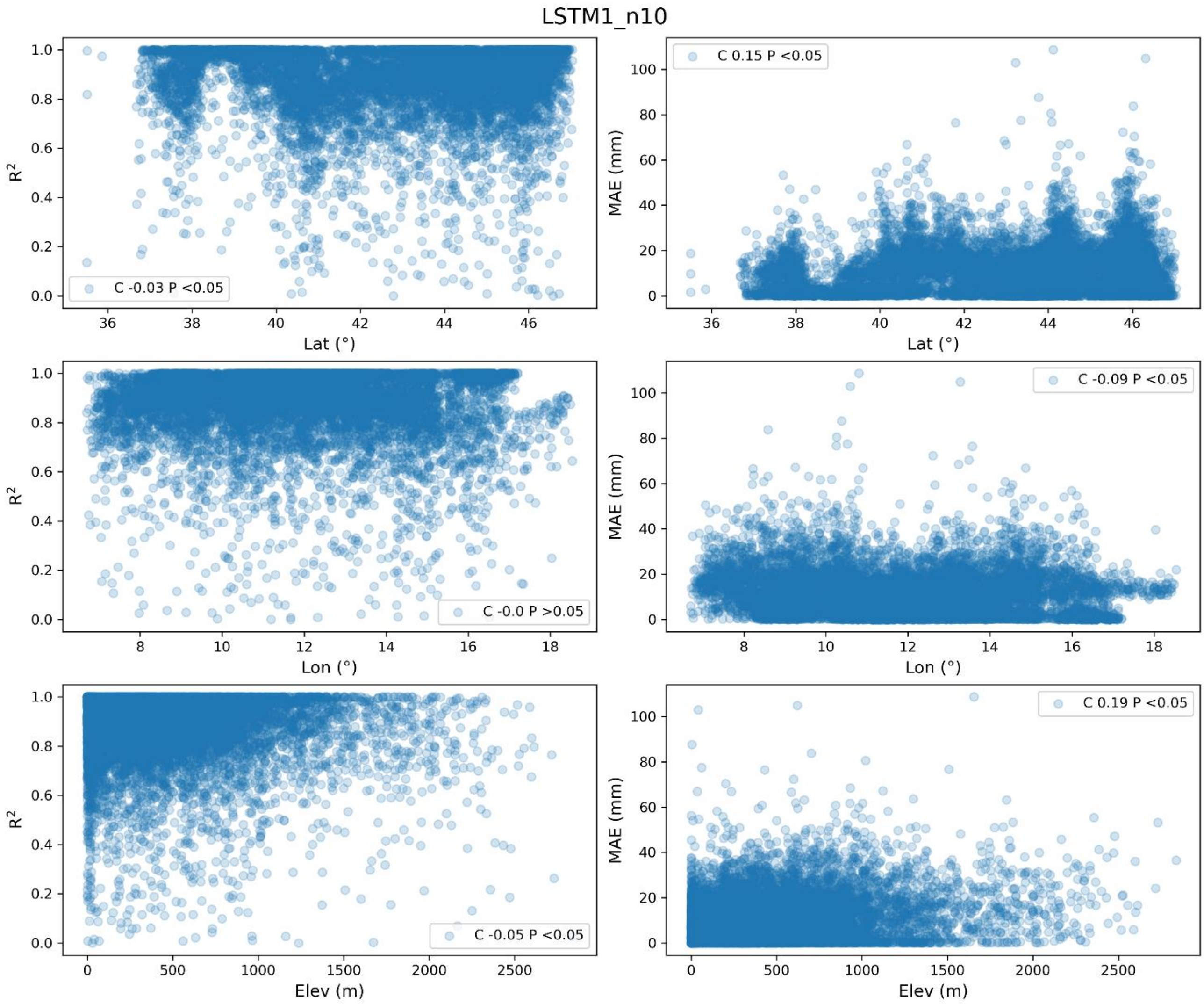


Figure S13 Spatial dependence of model performance for the LSTM1_n10 configuration. The scatterplots show the relationship between station latitude, longitude, and elevation with performance metrics: coefficient of determination (R^2, left column) and mean absolute error (MAE, right column). Reported Spearman's correlation coefficients (C) and associated p-values indicate the strength and significance of the dependence of performance on geographical location and elevation.

Table S2 Spearman correlation coefficients between model performance metrics (R^2 and MAE) and geographical or climatic predictors (latitude, longitude, elevation, and rainfall) for different model configurations. Asterisks indicate statistical significance (* $p < 0.05$, ** $p < 0.01$).

model	Lat - R2	Lat - MAE	Lon - R2	Lon - MAE	Elev - R2	Elev - MAE	R - R2	R - MAE
DL1_n10	-0.010	0.160**	-0.020*	-0.070**	-0.060**	0.220**	0.060**	0.270**
DL1STD_n10	-0.020	0.140**	-0.020	-0.070**	-0.070**	0.220**	0.060**	0.250**
LSTM1_n10	-0.030**	0.150**	0.000	-0.090**	-0.050**	0.190**	0.070**	0.230**
LSTM1STD_n10	-0.030**	0.150**	-0.010	-0.090**	-0.050**	0.180**	0.070**	0.220**
DL1_n15	-0.020	0.150**	-0.020	-0.070**	-0.050**	0.220**	0.070**	0.260**

DL1STD_n15	-0.020*	0.160**	-0.010	-0.080**	-0.060**	0.210**	0.060**	0.260**
LSTM1_n15	-0.030**	0.150**	-0.010	-0.090**	-0.050**	0.180**	0.070**	0.220**
LSTM1STD_n15	-0.030**	0.150**	-0.010	-0.080**	-0.050**	0.190**	0.070**	0.230**
DL1_n20	-0.020*	0.160**	-0.020*	-0.070**	-0.050**	0.220**	0.070**	0.270**
DL1STD_n20	-0.010	0.140**	-0.020	-0.080**	-0.060**	0.210**	0.070**	0.250**
LSTM1_n20	-0.030**	0.150**	-0.010	-0.090**	-0.040**	0.180**	0.070**	0.230**
LSTM1STD_n20	-0.030**	0.160**	-0.010	-0.090**	-0.050**	0.190**	0.070**	0.230**
DL1_n5	-0.020*	0.150**	-0.010	-0.080**	-0.060**	0.210**	0.060**	0.250**
DL1STD_n5	-0.020*	0.160**	-0.010	-0.090**	-0.060**	0.210**	0.050**	0.260**
LSTM1_n5	-0.030**	0.150**	0.000	-0.090**	-0.050**	0.190**	0.060**	0.230**
LSTM1STD_n5	-0.030**	0.150**	0.000	-0.090**	-0.050**	0.190**	0.070**	0.220**

2. Unsupported conclusions

There are several -if not many- papers addressing the question of cyclones' role in controlling Mediterranean precipitation. These papers usually perform explicit quantification of precipitation because of cyclone systems while in several of them there is also a quantification of moisture sources. All this knowledge is not discussed in the introduction and I find it a bit awkward that cyclones' contribution is implicitly determined because of climatological sea level pressure patterns. In these regards, I found the discussion rather weak and conclusions on cyclones' contribution rather unsupported. Finally, the distribution of moisture sources could be provided in a more direct way. Please consult past papers (there are many) that illustrate moisture uptakes in terms of maps and contours. In other words, I am not sure I can easily reach to the thirds concluding remark from Fig. 6.

We thank the reviewer for this constructive comment, which helped us improve the manuscript. We have addressed the points as follows:

Overall framing of cyclones in the paper:

We decided to soften the emphasis on cyclones in the manuscript by slightly **modifying the title and shifting the focus** toward broader circulation patterns and moisture sources. This avoids overstating a topic that is not the central scope of the study, while still acknowledging its importance.

"Beyond NAO: complex atmospheric mechanisms driving Mediterranean precipitation variability"

Role of cyclones in Mediterranean precipitation:

In the **Introduction**, we now explicitly discuss the central role of cyclonic systems in controlling Mediterranean precipitation, citing key studies that have quantified their contribution to rainfall and moisture transport.

"Mediterranean precipitation is strongly linked to cyclonic systems, which control both the intensity and spatial distribution of rainfall events. Several studies have quantified the contribution of cyclones to precipitation and moisture transport in the region, showing that extratropical and Mediterranean cyclones are responsible for a large fraction of rainfall variability[13–15]."

Explicit link between cyclones, precipitation, and moisture uptake:

In the **Discussion**, we added a dedicated passage to clarify that cyclonic systems represent the main physical drivers linking large-scale circulation to precipitation and moisture uptake in the Mediterranean, consistent with the broader literature.

In discussion:

The analysis of back-trajectories provides an additional interpretative layer, identifying the main moisture sources responsible for precipitation in Italy. Results show that the Western Mediterranean dominates in Central-Northern Italy, especially in the northwestern regions (e.g., Liguria, Tuscany, Piedmont), while the contribution from the Ionian Sea and the Eastern Mediterranean increases progressively toward the South and East, in agreement with previous observations [67,89] [8967]. The North Atlantic, despite being the origin of many frontal systems reaching Italy[90,91] contributes only marginally to the moisture associated with precipitation, and primarily in the western regions of the peninsula. These findings suggest that moisture sources largely follow the prevailing large-scale synoptic patterns typically associated with precipitation in different parts of Italy. Indeed, periods marked by enhanced subtropical or Eastern Mediterranean cyclogenesis have been shown to increase moisture contributions from basins such as the Ionian and Aegean Seas[92]. By contrast, the strong role of the Western Mediterranean reflects the influence of teleconnections such as the NAO and the MOI, which modulate both the frequency and intensity of cyclonic activity over this basin[93]. Overall, these results highlight that air mass trajectories and associated uptake points are highly sensitive to both the prevailing synoptic configuration, since pressure gradients, cyclonic systems, and associated temperature–humidity contrasts strongly modulate the pathways of air masses and the intensity of evaporation over different basins.

Direct representation of moisture sources:

As requested, we now provide a more direct visualization through a new figure (Figure 8), which reports the spatial distribution of average moisture uptake fields for four representative sites across Italy. This addition allows the reader to clearly identify the geographical patterns of source regions and strengthens the connection between the discussion and the supporting data.

In Results:

As an illustrative example, Figure 14 reports the average *moisture uptake* fields derived from back-trajectory analysis for four representative sites distributed across the Italian Peninsula. These points were selected to highlight the diversity of regional behaviours, with northern, central, southern, and insular locations showing distinct patterns of dominant source regions. The maps confirm that the relative contribution of the different basins is strongly modulated by geography and large-scale circulation, providing a useful framework before discussing the broader national-scale patterns.

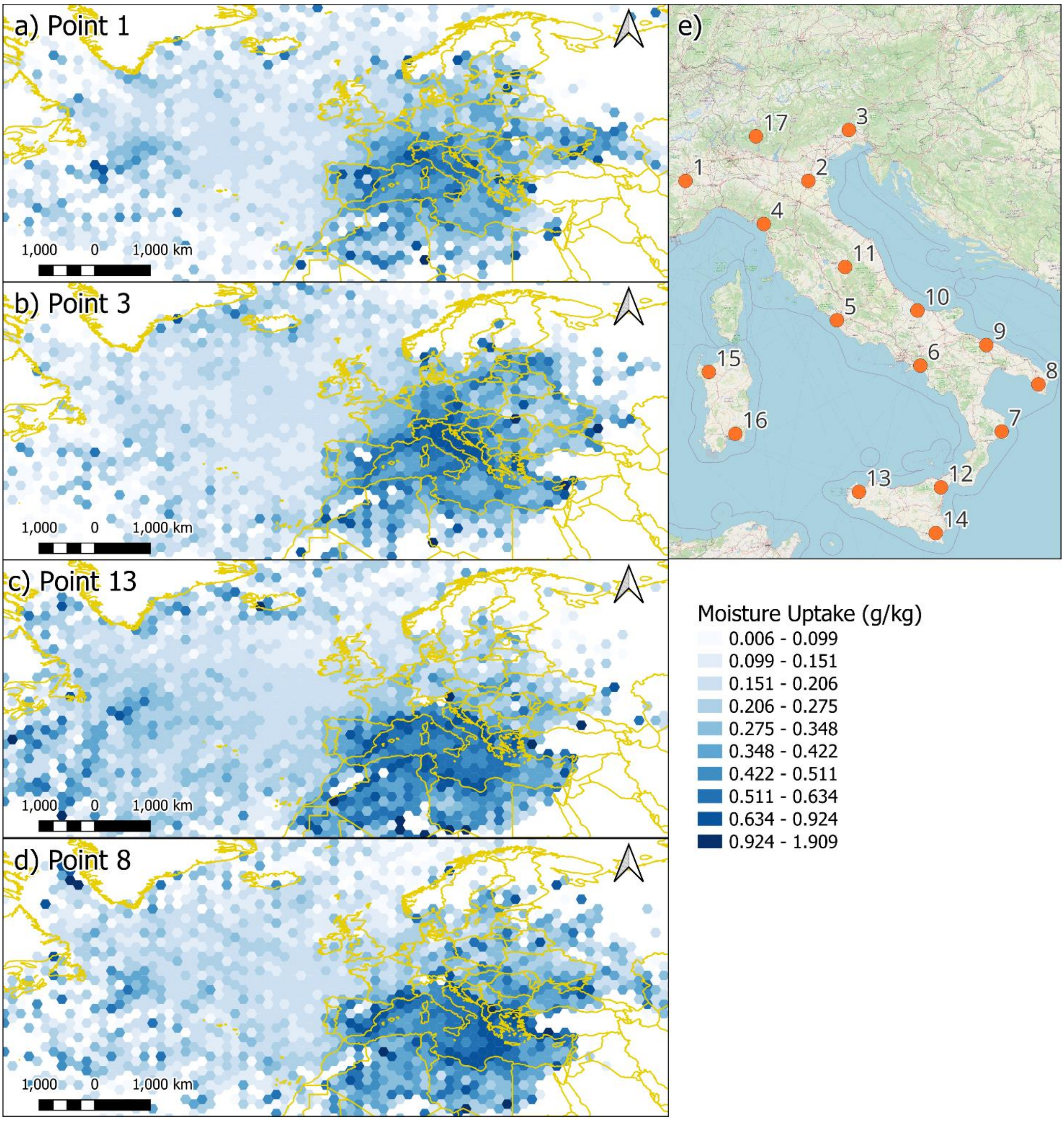


Figure 14 Mean moisture uptake cells (g/kg) calculated with the HYSPLIT model for four sites characterized by different behaviours: a) Point 1; b) Point 3; c) Point 13; d) Point 8. The maps show the spatial distribution of average moisture uptake along the back-trajectories associated with each site. Panel e) reports the map of the arrival locations of the trajectories considered in the analysis (1–17). The colour scale indicates the mean intensity of moisture uptake, from lower values (light blue) to higher values (dark blue).

We believe these changes substantially reinforce both the contextualization and robustness of our conclusions regarding the role of cyclones and the distribution of moisture sources, while keeping the overall focus of the manuscript coherent with its main objectives.

3. From climatological patterns to regional dynamics

Actually, we already know that most of precipitation in the region is due to cyclone systems (a simple search in the scientific literature should be convincing), so I am not fully sure I follow the second bullet point on the conclusions. The whole motivation of this study seems to build on the argument that NAO is (not) explaining the variability of precipitation in Italy. However, I am not sure this is to be considered as a given in the state of the art. As far as I understand, NAO is statistically describing the Atlantic storm tracks' activity and thus is expected to have an influence on the frequency of Mediterranean cyclogenesis (there is a rich bibliography on the interconnection between Mediterranean and Atlantic storm tracks). As a result, NAO influences Mediterranean cyclogenesis and some impact should be expected on Mediterranean's precipitation variability. I guess that the discussion or scientific question could be based on how each index correlates with Mediterranean cyclones and in turn with precipitation variability. In this paper though given knowledge on the importance of cyclone systems on precipitation variability is provided as a main result.

We thank the Reviewer for this important observation. We fully agree that the role of cyclones in controlling Mediterranean precipitation is well established in the literature, and we have therefore revised the second bullet point of the Conclusions, which previously could be interpreted as presenting this as a main result. In the revised version, we now focus less on Mediterranean cyclogenesis and more on the correlations between atmospheric indices and precipitation variability.

As correctly pointed out, the influence of the NAO on Mediterranean precipitation through its control of Atlantic storm tracks and Mediterranean cyclogenesis is well known and is introduced in the manuscript. What our study adds is the evidence that within the Italian domain the precipitation response is highly variable, with clear regional contrasts. In particular, our results highlight the occurrence of possible dipolar configurations that may arise when the NAO is not in phase with other indices (EA, MOI, WeMO). These configurations, which can be related to past episodes as discussed in the final part of the Conclusions, open promising avenues for future research.

We believe that this reorientation strengthens the manuscript. The study is now more clearly aligned with its real objectives, which were sometimes obscured by the previous framing. After several revisions and integrations, we are confident that the paper better reflects its innovative contribution: showing how multiple indices interact to shape precipitation variability over Italy and pointing to mechanisms that may explain the heterogeneity of hydro-climatic responses in the Mediterranean.

In Conclusions:

Dipolar configurations over Italy: At equal NAO configurations, precipitation patterns across Italy can diverge substantially when the NAO is not in phase with other indices. This mismatch generates dipolar systems in which the predominance of Atlantic air masses (or their absence) collides with baric structures developing over the central or eastern Mediterranean, producing contrasting regional hydro-climatic responses.

Reviewer #3 (Remarks to the Author):

This is the second review of the paper "Beyond the NAO: complex atmospheric mechanisms driving Mediterranean precipitation variability" by Luppichini et al. The authors made a lot of effort to improve the manuscript and reply to the comments. I am afraid however that still the paper is not concise to proceed to publication. My main concern is about the results, the discussion and the presentation of the scientific content. There is certainly a lot of potential here but that the paper in its present form is not easy to reach to a well structured study. My recommendation would be to reject and reconsider a more focused submission.
Right below I list several comments that all point towards an important editing and revision of the paper. Please note that lines below refer to the marked-up document.

We would like to sincerely thank the reviewer for taking the time to re-evaluate our manuscript *"Beyond the NAO: complex atmospheric mechanisms driving Mediterranean precipitation variability."*
We appreciate the constructive feedback and the thoughtful comments provided.

We fully understand the concern regarding the clarity and conciseness of the results, discussion, and overall structure. In this revised version, we have carefully addressed all comments and made substantial efforts to improve the organization, readability, and scientific focus of the paper.

We believe these revisions have significantly improved the clarity and focus of the paper, while preserving the scientific depth and originality of the study.
We are very grateful for the reviewer's insights, which have helped us to refine and strengthen the manuscript.

Below we provide a detailed, point-by-point response to each specific comment.

Introduction:
line 49: which patterns?

Thank you for the suggestion, we modified the sentence:

To fully understand these precipitation and atmospheric circulation patterns, […]

lines 49-50: I do not really understand the purpose of this phrase.
We thank the reviewer for this remark. The sentence was intended as an introductory link to the following section. To improve clarity, we have revised the paragraph structure and adjusted the phrasing to make its purpose clearer within the overall argument.

lines 63-78: Still I am not sure I follow the argumentation and the motivation about NAO. The two paragraphs in lines 63-78 seem a bit repetitive and I am not sure that they help to understand the importance of this study. I can understand that NAO should explain some part of the precipitation variability and perhaps a larger part could be explained by other kind of large-scale drivers or perhaps internal variability of the regional climate. To put it differently, a certain phase of NAO may favor a more frequent occurrence of Mediterranean cyclones. There will be certainly a large spread of regions to be affected by cyclones' precipitation. The (larger) smaller the area you focus your analysis, in this case the Italian peninsula, the (more) less NAO will be explaining the precipitation pattern. Please be more specific about what is missing from the state of the art and what is your contribution.

We thank the reviewer for this important comment. We clarify that the two paragraphs serve different purposes:

- The first paragraph discusses previous studies based on observed and recent precipitation data, focusing on statistical correlations between precipitation and large-scale atmospheric indices (e.g., NAO, EA, MOI, WeMO).
- The second paragraph, instead, introduces paleo-climatic studies exploring relationships between reconstructed NAO phases and long-term (centennial to millennial) rainfall or river-regime variations, highlighting inconsistencies in these relationships.

Thus, the two paragraphs address different temporal perspectives—modern observations vs. paleo-records—both necessary to introduce the rationale of our work.
We agree, however, that the scientific motivation of our study can be made clearer. To address this, we have revised the text by specifying the knowledge gap: the lack of integrated analyses combining long-term observational datasets and large-scale circulation indices to better capture the complex atmospheric mechanisms driving Mediterranean precipitation variability beyond the NAO framework.

The revised text now reads as follows:

Despite numerous studies, a clear understanding of how different large-scale circulation modes interact in modulating regional precipitation variability is still lacking. This highlights a knowledge gap that the present work aims to address through an integrated analysis combining long-term observational data and atmospheric circulation indices, in order to identify the mechanisms controlling Mediterranean rainfall variability beyond the traditional NAO framework.

Line 90: The aim seems to be related to moisture sources alone but clearly all the above and the title point to different objectives. Also "these uncertainties" should be more elaborated.

We modified the sentence:

This study aims to address the scientific gap identified through an innovative approach that integrates deep learning modeling of the largest national precipitation dataset to investigate the synoptic-scale atmospheric patterns associated with precipitation over the Mediterranean region.

Overall: I find the introduction a bit awkward. It starts with cyclones, then it discusses NAO and finally water sources but these do not seem to be connected between them, or to liaise with specific objectives.

Datasets:
In my first review, I am not claiming that ERA5 is more accurate or that resolution matters. I am arguing that for the purposes of this study ERA5 would be more appropriate despite its lack of accuracy (in terms of spatial resolution and precipitation amounts). After all, you are not discussing local precipitation (that would be of subgrid scales in ERA5), but subregional one, and more than that you compare precipitation with large scale patterns. Therefore, consistency between dynamics and precipitation would be quite important for your study. In any case, the authors did substantial work to validate their methods so most probably it is good to proceed this way.

We thank the reviewer for this thoughtful clarification and for acknowledging the effort devoted to data validation. We fully understand the reviewer's argument regarding the potential advantages of using ERA5 reanalysis data in terms of consistency between atmospheric dynamics and precipitation fields.

However, one of the main goals of this work was to move beyond the use of reanalysis datasets, which are constrained by model structures and parameterizations, and instead to develop and make available a new, observation-based national precipitation database, freely accessible to the scientific community. This dataset allows for a more direct and data-driven exploration of precipitation variability without the influence of model-dependent assumptions.

We acknowledge the reviewer's point, and we agree that the use of reanalysis products may offer complementary perspectives. Nevertheless, we believe that our observational approach is consistent with the study's objectives and provides a valuable contribution to understanding precipitation–circulation relationships in the Mediterranean context.

Section 3.2:
The title of this section seems a bit generic. Please revise according to the content. The whole discussion here is quite hard to retain and I am not sure what we learn in the end. The section reads like: Several climate modes might partly explain variability of precipitation in Italy, but depending on the area, lack of statistical significance might render interpretations a bit difficult.

We thank the reviewer for this helpful comment. We have revised the section title to “Combined Circulation Patterns”, which more accurately reflects the content and focus of the analysis.

In addition, we have modified the final summarizing sentence of the paragraph to make the main message clearer and more concise. The revised conclusion now highlights that precipitation variability over Italy results from the combined influence of multiple large-scale circulation modes and regional orographic effects, explaining both the spatial heterogeneity and the varying statistical significance observed across the country.

Overall, these results demonstrate that precipitation variability over Italy cannot be attributed to a single large-scale driver but emerges from the interplay between multiple circulation modes whose influence is further modulated by regional orography. This complexity explains the spatial heterogeneity and the limited statistical significance observed in some areas, highlighting the need for multi-index approaches to properly capture Mediterranean rainfall dynamics.

The discussion is actually a bit awkward: For instance, in lines 340-342, one learns that "significant positive precipitation anomalies are observed across much of the country.. the statistical assessment confirms that these signals are robust". I am not sure what we learn about local or overall precipitation in Italy. Also "robust" should be I guess "statistically significant" and I am not actually sure what "signals" refers to. Reading up to here, I think that one major issue with the whole paper is that in many places, there are generic mentions, few examples:

We modified the word “robust” with “statistically significant”

line 90: "these uncertainties", which ones? Here this phrase is mostly used as "all of the above"

We modified the sentence specifying

This study aims to address the scientific gap identified through an innovative approach that integrates deep learning modeling of the largest national precipitation dataset to investigate the synoptic-scale atmospheric patterns associated with precipitation over the Mediterranean region.

line 342 "signals", what does this refer to?

We modified with “results”

line 336 "important role", in what?

We modified the sentence

Although the NAO plays an important role on the regularization of the precipitation in Italy, but its effect is strongly modulated by interactions with the other indices.

line 345 "tends to increase", "generally observed", where, how much?

We thank the reviewer for this comment. The analysis presented in this section is qualitative, as it is based on the spatial correlation between precipitation anomalies and circulation indices, rather than on quantitative trend estimation. For this reason, it is not possible to specify "how much" precipitation changes in each phase.

However, we have clarified the spatial context in the text: during positive WeMO phases, precipitation tends to increase especially over the Apennine areas, while during negative WeMO phases, reductions are generally observed along the Ionian and eastern coastal regions.

The behaviour of the WeMO is especially distinctive: during positive WeMO phases, precipitation tends to increase, especially over the Apennine areas, while during negative WeMO phases, a reduction is generally observed along the Ionian and eastern coasts.

line 351 "the contribution of AMO appears relatively minor", contribution to what? relatively to what?

We thank the reviewer for this helpful observation. We have clarified in the text that the "contribution" refers to the influence of the AMO on precipitation amounts over Italy, and that it is minor compared to the other circulation indices analysed (NAO, EA, MOI, and WeMO).

The contribution of AMO to precipitation variability over Italy appears relatively minor, although a partial similarity with the EA pattern is observed.

line 366: what is meant by "promote rainfall"?

We modified with "favour precipitation development"

line 378: what is "climatic forcings" here?

We changed the sentence, now it is not present

line 379: Indices nor statistical patterns (like NAO) interact to each other. Please revise.

We modified the sentence

Overall, these results demonstrate that precipitation variability over Italy cannot be attributed to a single large-scale driver but emerges from the interplay between multiple circulation modes whose influence is further modulated by regional orography. This complexity explains the spatial heterogeneity and the limited statistical significance observed in some areas, highlighting the need for multi-index approaches to properly capture Mediterranean rainfall dynamics.

line 434: "These findings"... which findings?

We changed the sentences with "The results of this work"

A careful editing to make the text more precise is certainly needed. I regard this issue as an important shortcoming of the paper.

Section 3.3
I find that the spatial variability of moisture uptake is rather similar in the four panels of Fig. 8. It is thus a bit hard to discuss differences between the different regions. In any case, this section seems a bit disconnected to the rest of the paper.

Figure 8 was included following the suggestion raised during the first round of review, specifically to provide a direct comparison between the different regions as requested. We acknowledge that the figure is not entirely straightforward to interpret; this is precisely why we added Figure 9, which—although not a canonical choice in this type of study—proves particularly effective in this case for summarising and visualising the spatial differences in moisture uptake.

Regarding the comment on the possible disconnection from the rest of the paper, we agree that this section does not directly contribute to the interpretation of the atmospheric indices. However, we believe it still provides useful contextual information, as it highlights the spatial differences in the moisture source regions that contribute to the observed precipitation variability across the study area. This adds an interpretative layer that complements the overall framework, even if it remains somewhat peripheral to the main core of the analysis.

Discussion & Conclusions:
lines 448 - 460 come too late. This part should be in the methods. Regarding the analysis, I am not sure how the two main parts of this paper connect to each other (water sources & climate modes). Maybe I missed the point, but my impression is that the analysis on the climate modes could be stand as such without the water sources.

The decision to present the ERA5 comparison in lines 448–460 within the discussion section is intentional. In our view, this part does not constitute a methodological element per se, since the methods employed are standard and widely established in the literature. Our aim here is instead to verify and compare our findings with an independent data source, much as one would do in any other context when contrasting original results with reference or published datasets. For this reason, we consider it more appropriate to place this comparison in the discussion, where its implications can be assessed, rather than in the methods section.

Regarding the comment on the connection between the two main parts of the paper (water sources and climate modes), we reiterate what was stated in the previous response: we acknowledge that the two sections may appear only loosely connected, as the analysis of atmospheric indices forms the core of our interpretation, while the investigation of moisture sources plays a more complementary role. Nonetheless, the latter provides valuable spatial context on the mechanisms contributing to precipitation variability across the three regions, thus enriching the overall framework even if it remains somewhat secondary compared to the climate-mode analysis.

In lines 518-537, I find the discussion a bit weak. The association of different NAO phases with precipitation in the Mediterranean is rather known. I am not also sure I follow the argumentation that links SST with Mediterranean cyclogenesis (lines 523-526). The latter mainly depends on how many intrusions of troughs we have in the region. Higher SST may modulate the intensity of the cyclones by enhancing convection.

Thank you for this valuable comment, which gives us the opportunity to clarify the reasoning behind our discussion. We fully acknowledge that the association between NAO phases and Mediterranean precipitation is well established in the literature. In this section, our aim was not to present a novel result, but rather to place the outcomes of our analysis within the broader synoptic framework already documented. For this reason, we briefly recall the NAO–precipitation relationship to link it with the observed patterns over Italy.

Regarding the connection between Mediterranean SSTs and cyclogenesis, we agree that Mediterranean cyclone formation fundamentally depends on the frequency and depth of upper-level trough intrusions. In the text, we do not intend to imply that SSTs control this frequency. Instead, following the literature we cite, we refer to the modulatory role of warm SSTs on the Icelandic Low and the Gulf of Genoa Low, which can weaken the efficiency of these classical cyclogenetic areas. At the same time, as also stated later in the discussion, higher SSTs can intensify the cyclones that do occur by enhancing convective instability.

Therefore, our intention is to highlight that SST increases act as a modulating rather than a primary driver of cyclogenesis, while large-scale teleconnections (NAO/WeMO) chiefly determine the occurrence of the relevant synoptic intrusions. We hope this clarification makes the logic of the discussion clearer.

The second bullet point in the conclusions is unclear to me. What is meant by "NAO out of phase with other circulation modes"? How can two climate modes trigger "dipolar systems" (line 571). Also "Atlantic air masses" and "pressure systems" are generic mentions.

Actually generic mentions like thses ones are repetititve in the text: e.g. "Mediterranean dynamics", "Atlantic circulation patterns", "Mediterranean regional dynamic".

By *“NAO out of phase with other circulation modes”*, we refer to situations in which the NAO exhibits a given phase (e.g., NAO+), while other large-scale modes relevant to the Mediterranean — such as EA or WeMO — display an opposite or non-coherent phase. This condition is well documented to alter both the position and the intensity of synoptic disturbances approaching Italy, resulting in markedly different precipitation responses even under the same NAO phase.

The term *“dipolar systems”* is used here to describe these strong regional contrasts — for example, enhanced precipitation on one side of the peninsula and reduced precipitation on the other — driven by the interaction between Atlantic frontal intrusions and pressure anomalies developing over the central or eastern Mediterranean.

We also acknowledge that expressions such as “Atlantic air masses” or “pressure systems” may appear generic, and we have refined the phrasing to make the description more specific and less repetitive, while preserving the original meaning.

We hope these clarifications improve the clarity and readability of this conclusion point.

Dipolar precipitation configurations over Italy: Precipitation patterns can diverge substantially when the NAO is in an opposite phase compared with other circulation modes such as EA or WeMO. These non-coherent configurations alter the trajectory and intensity of synoptic disturbances entering the Mediterranean, generating *dipolar* responses through the interaction between Atlantic frontal systems and pressure anomalies developing over the central or eastern Mediterranean.