

Comment on:

**“Mediterranean drying by a positive North Atlantic Oscillation trend over the last 65 years is an extreme outlier in the CMIP6 multimodel ensemble”
by R. Seager et al. Journal of Climate 39 (2): 785-804. 10.1175/JCLI-D-25-0359.1**

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Abstract: This Comment addresses the interpretation of recent findings reported by Seager et al. (2026), who identify widespread winter drying across the Mediterranean region during 1959–2023 and link this signal to a positive trend in the North Atlantic Oscillation (NAO), characterized as an extreme outlier in the CMIP6 multimodel ensemble. Given the strong interannual and multidecadal variability that typifies Mediterranean hydroclimate, we argue that these conclusions require careful reassessment within a broader temporal and dynamical framework. Using evidence from high-density homogenized station observations, instrumental NAO indices extending back to the early nineteenth century, CMIP6 historical and pre-industrial control simulations, and multiple paleoclimate NAO reconstructions, we evaluate the robustness of both the reported precipitation and NAO trends. We show that the winter drying identified for

the 1959–2023 period is highly sensitive to the choice of the starting decade and largely reflects the influence of anomalously wet conditions during the 1960s. When longer records are considered, Mediterranean winter precipitation is dominated by variability rather than by a persistent basin-wide trend. Similarly, the positive NAO trend over the last 65 years is shown to be consistent with internal atmospheric variability. Comparable multidecadal NAO trends and decades with strongly negative NAO values occur repeatedly in unforced model simulations and in proxy-based reconstructions over the last several centuries, indicating that the recent evolution of the NAO is not exceptional in a long-term context. This Comment emphasizes the importance of distinguishing short-term variability from long-term change when interpreting observational trends in highly variable regions. We stress that recent observations should not be overinterpreted as evidence of an unprecedented or forced shift in Mediterranean winter precipitation or NAO behavior.

1. The dynamics of the Mediterranean precipitation

The temporal dynamics of precipitation in the Mediterranean region have been debated for several decades. Some studies have supported a drying trend across the region (Hoerling et al. 2012; Caloiero et al. 2018; Seager et al. 2019; Dai 2021), while others have gone further and attributed this trend to anthropogenic climate change (Gudmundsson and Seneviratne 2016; Christidis and Stott 2022).

In a recent contribution, Seager et al. (2026), using data from different databases between 1959 and 2023, report a “widespread drying across most of the Mediterranean region in winter”. In one section of their study, the authors describe the evolution over the analysis period as “a long-term drying that the Mediterranean has experienced”. As this study appears to align with earlier work supporting a drying trend in the region, we consider it necessary to provide a clarification on this issue. The notion of a persistent Mediterranean drying has increasingly shaped the assessment of precipitation trends in the region in spite of articles highlighting that interdecadal

and decadal variability prevents the identification of sustained long-term trends (Cherif et al. 2020; Peña-Angulo et al. 2020; Lionello and Scarascia 2018). In fact, recent studies based on high-quality, long-term observational data highlight the need to reconsider the presence of past drying trends in the Mediterranean region.

In this comment, we present arguments showing that a long-term drying of the Mediterranean cannot be robustly inferred from data analysed over a specific, limited period, and we emphasise the need to place any hypothesised short-term drying within a longer temporal context in a region characterised by pronounced interannual and decadal variability.

Two recent studies have analysed in depth the dynamics of precipitation in the Mediterranean region. In particular, the review by González-Hidalgo and Vicente-Serrano (2025) synthesised the published literature on this topic over the last four decades based on more than 300 studies ranging from large-scale analyses to local and regional studies across all Mediterranean countries. According to this comprehensive review, precipitation in the Mediterranean is characterised by strong spatial and interannual variability, but no robust regional-scale drying trends emerge from the literature, even for the winter season that is the focus of Seager et al. (2026). Although some studies report significant trends, these are restricted to specific regions and limited time periods, consistent with the pronounced temporal (annual and decadal) variability that characterises Mediterranean precipitation.

Other recent research has reached a similar conclusion based on observational data. In particular, Vicente-Serrano et al. (2025a) analyzed all available precipitation series across the broader Mediterranean region using a homogenized dataset comprising more than 25,000 monthly series, spanning multiple time windows from the late nineteenth century to the present. Their results indicate that precipitation in the basin is characterized by strong multidecadal variability rather than consistent long-term drying trends. The study also illustrates how trend estimates can be biased by period selection; for example, a negative trend may arise

when the analysis begins during anomalously wet decades and concludes during a comparatively dry period.

1.1. Analysing Mediterranean precipitation trends

Here, we draw on the observational dataset from Vicente-Serrano et al. (2025a), which provides unprecedented quality, spatial density and temporal coverage. Using this and other alternative datasets, we reassess the long-term behaviour of Mediterranean winter precipitation to evaluate the robustness of the drying signal reported by Seager et al. (2026). Throughout the analyses presented below, we refer to this dataset as VS2025 and to its various constituent databases, which encompass different sets of meteorological stations over varying observation periods.

Given the data restrictions described in Vicente-Serrano et al. (2025a), it is not possible to obtain station-level data for the exact period 1959–2023 analysed by Seager et al. (2026). However, analyses conducted over close alternative periods clearly illustrate that in all cases there is a clear dominance of stations exhibiting no statistically significant trends (Figure 1). The number of available meteorological stations varies substantially depending on the study period. For the longest period considered (1872–2020), winter precipitation data from 307 stations were available. Based on the Mann–Kendall test (see Vicente-Serrano et al. (2025a) for methodological details), 17.2% of these stations exhibited statistically significant positive trends ($p < 0.05$), 3.6% showed significant negative trends, and the remaining 79.2% exhibited no significant trend. For the period 1902–2020, spatial coverage increased to 912 stations, of which 9.5% showed significant positive trends, 6.7% significant negative trends, and 83.8% no statistically significant trends. During 1952–2020, 5,441 stations were available; 11.4% displayed significant negative trends and 0.5% significant positive trends, while the remaining 88.1% showed non-significant trends. Finally, for 1982–2020, the 7,151 available series indicated that

6.7% exhibited significant positive trends, 1.6% significant negative trends, and 91.7% non-significant trends.

The dominance of non-statistically significant trends, derived from the most robust precipitation database ever developed for the Mediterranean region, can be explained by the strong temporal variability that characterises precipitation, which clearly overwhelms both long- and short-term trends (see below).

1.2. The relevance of the selected precipitation database

There is, however, an important issue that warrants caution regarding the observational data used in the analysis by Seager et al. (2026). Their study relied on three precipitation databases that present substantial limitations for trend analysis in the Mediterranean region:

i) The first one is the E-OBS daily observational gridded dataset. This data set has known issues

that prevent its use for trend analysis as it is explained by the data providers at:

https://surfobs.climate.copernicus.eu/userguidance/known_issues_eobs.php:

"The underlying stations timeseries used as input to the interpolation of E-OBS are usually not corrected for inhomogeneities (except for E-OBSv19.0eHOM). Also, the station density is not constant through time. Trend analyses should therefore be treated with caution." This likely explains the stronger drying trends reported using this dataset in comparison with denser and quality controlled ones in some areas of the Mediterranean such as the Iberian Peninsula (Peña-Angulo et al. 2020).

ii) The second dataset they used is ERA5, a reanalysis product that does not assimilate precipitation observations (Lavers et al. 2022), and is therefore prone to significant biases when analysing precipitation trends. Seager et al. (2026) are aware of this limitation but they consider its use for consistency with other meteorological variables used in the study: "ERA5 does not assimilate precipitation data this provides a check that in-situ precipitation data are physically consistent with the

assimilated atmospheric state”. In the Mediterranean region, ERA5 is affected by strong temporal inhomogeneities that can distort trend assessments in the region (Lussana et al. 2024). Further analysis on this issue over the whole Mediterranean region can be found at Figures 21-24 in <https://www.nature.com/articles/s41586-024-08576-6#peer-review>.

iii) The third database used by Seager et al. (2026) is the 0.5° observational gridded dataset produced by the Climatic Research Unit (CRU) (Harris et al., 2020). This dataset is more suitable for assessing long-term trends than the other two, as it incorporates quality-control and homogenisation procedures. Accordingly, the standardized regional series obtained by averaging the data for the western, central, eastern, and entire Mediterranean regions—following the approach of Seager et al. (2026)—are very similar when derived from the VS2025 database and from CRU for the overlapping period 1952–2020 (Figure 2a). Standardisation was performed using the reference period 1952–2020 and the most appropriate three-parameter distribution, selected according to the Akaike Information Criterion (AIC) (Vicente-Serrano et al. 2025b). This close agreement provides high confidence in the use of the CRU database for regional trend analyses, as it closely matches a dataset based on 5,441 stations over the period 1952–2020. However, spatial assessments based on this low-spatial-resolution gridded dataset may be subject to substantial uncertainties. Figure 2b shows the spatial distribution of the magnitude of winter precipitation change between 1952 and 2020 and the statistical significance of trends derived from both the CRU gridded data and the VS2025 station dataset. This comparison reveals spatial mismatches, particularly in regions exhibiting stronger precipitation declines during this period, such as the Iberian Peninsula, Italy, and the western Balkans. It also highlights excessive spatial generalisation in areas where patterns are inferred from a very limited number of stations, such as

Morocco, Algeria, and Libya. Moreover, low-resolution gridded datasets are inherently affected by spatial variations in station density, a well-known limitation of gridded products that can substantially influence trend analyses (Beguería et al. 2016).

1.3. The relevance of the selected period of analysis

In any case, the drying trend reported for the Mediterranean by Seager et al. (2026) and by other previous studies is not caused by the database used. Instead, it arose from methodological choices; critically, the length and timing of the analysis period. Trend analysis is particularly sensitive to the strong temporal variability that characterises Mediterranean precipitation. In this context, the selection of an analysis period beginning in 1959 corresponds to a phase of declining precipitation within the broader multidecadal variability of the region. In contrast, long-term analyses using different databases do not reveal statistically significant trends (Camuffo et al. 2013; Vicente-Serrano et al. 2025a).

This strong sensitivity to the selected analysis period is illustrated in Figure 3 for the sub-regions defined in Seager et al. (2026), as well as for the regional mean of the entire Mediterranean basin. The figure shows the magnitude of change in standardized winter precipitation regional series calculated over periods of increasing length, with a minimum duration of 30 years. Across all datasets, the subpanels reveal a broadly consistent behavior: both the magnitude and the statistical significance of precipitation trends vary markedly depending on the chosen time window, despite being derived from the same underlying regional time series.

For records extending back to the early twentieth century and earlier, and irrespective of the region considered, the results indicate that long-term trends are not statistically significant. Across datasets, a generally dominant positive trend in winter precipitation emerges for periods starting between the 1870s and the 1940s and ending in the 1970s. In contrast, series beginning in the 1950s–1960s exhibit negative trends toward the end of the analysis period; however,

these negative trends are no longer evident when the analysis is restricted to periods starting after the 1970s.

Consequently, when an analysis period coincides with one of these phases of declining precipitation—such as the period considered by Seager et al. (2026)—predominantly negative trends are expected to emerge. When longer time spans are examined, however, the overall behaviour of Mediterranean winter precipitation is stationary. Given the availability of extended observational records, analyses based on longer time windows provide a more robust characterisation of long-term behaviour by reducing the influence of pronounced temporal variability.

In light of the evidence presented here, the winter drying over the Mediterranean region claimed by Seager et al. (2026) must be placed within a longer-term context. The negative trend identified over their analysed period should be interpreted as the initiation of the analysis during the particularly wet conditions of the 1960s. This interpretation follows directly from the temporal structure of Mediterranean long-term stationarity, as demonstrated through analyses of extended periods, and is further supported by three-century precipitation observations available for the north-western part of the basin (Camuffo et al. 2013).

2. The dynamics of the North Atlantic Oscillation

The second aspect analysed by Seager et al. (2026) concerns the variability of the North Atlantic Oscillation (NAO) as the main driver of precipitation dynamics in the Mediterranean, an issue that has been extensively documented in previous studies (Kelley et al. 2012; Trigo et al. 2002). Seager et al. (2026) identify a positive trend in the NAO, which they identify consistently across different NAO indices. Accordingly, they link the drying trend reported for the 1959–2023 period with the concurrent positive trend in the NAO.

This issue must also be placed within a temporal framework of long-term decadal variability, as it may otherwise be misinterpreted. In particular, interpreting an apparently unprecedented

positive NAO trend as the driver of an unprecedented drying trend raises the risk of implicitly attributing anthropogenic forcing to the NAO signal and, consequently, to Mediterranean precipitation drying. Although Seager et al. (2026) do not explicitly make such a claim, they state that “...it is possible that the NAO and Mediterranean drying trends have been generated by natural multidecadal variability. According to the models, this is possible but very unlikely.” Clarifying this issue is therefore highly relevant. For this reason, we provide here a detailed assessment showing that analysing the positive NAO trend over the 1959–2023 period does not yield robust insights into climate dynamics or potential precipitation changes in the Mediterranean region. By placing NAO observations within a broader temporal context, we show that recent NAO behaviour is consistent with long-term natural climate variability, in line with the most recent IPCC Assessment Report (Gulev et al. 2021).

The next step is to illustrate the role of the NAO in Mediterranean precipitation and to assess how rare or unprecedented the NAO increase reported by Seager et al. (2026) over the 1959–2023 period actually is. To this end, we employ three complementary approaches. First, we analyse observational NAO time series extending back to the 1820s. Second, we evaluate NAO data from climate model simulations that incorporate internal variability, anthropogenic forcing, and long-term natural forcing. Third, we examine proxy-based NAO reconstructions.

2.1. The quantification of a North Atlantic Oscillation index

There are different approaches to characterising NAO dynamics. Some pioneering studies defined the NAO as an index derived from the first empirical orthogonal function (EOF) of sea-level pressure or 500 hPa geopotential height fields over the North Atlantic region (Barnston and Livezey 1987). Other approaches demonstrated that the dynamics of this oscillation can be effectively characterised using pressure data from two locations near the centres of action of the North Atlantic dipole, located in the northern and southern parts of the basin (Hurrell 1995).

Seager et al. (2026) derived a specific NAO index based on the leading Empirical Orthogonal Function (EOF) of DJF 700-hPa geopotential height anomalies over the domain 90°W–50°E and 10°N–70°N, after removing the area-weighted global mean, using ERA5 as the data source. The temporal evolution of this index closely resembles that of the CPC NAO index (Dool et al. 2000), which is obtained from an EOF analysis of Northern Hemisphere 500-hPa geopotential height fields. It is also highly consistent with an NAO index derived from NCEP/NCAR R1 reanalysis sea-level pressure, as well as with the Gibraltar–Iceland station-based CRU NAO index (see details below). The correlation between the CRU and CPC NAO indices is 0.83, while correlations between the CRU and NCEP/NCAR indices and between the CPC and NCEP/NCAR indices are both 0.90. The 700-hPa NAO index developed by Seager et al. (2026) is likewise strongly correlated with the CRU, CPC, and NCEP/NCAR indices, with correlation coefficients of 0.89, 0.92, and 0.98, respectively (Figure 4). At first glance, the use of 700-hPa geopotential height fields to construct an NAO index, as in Seager et al. (2026), may appear appropriate. However, there is an important limitation to this approach: a station-based NAO index can be extended back nearly two centuries, owing to the availability of long-term surface pressure records at key locations (Jones et al. 1997). This allows recent NAO behaviour to be evaluated within a much longer historical context. For this reason, we adopt the station-based approach in the present analysis.

Here we describe in greater detail how the NAO index used in this study was calculated, in order to fully clarify this issue. The CRU NAO index is available at <https://crudata.uea.ac.uk/cru/data/nao/>. This website provides both a monthly NAO index and the monthly mean sea-level pressure records from the Gibraltar station (southwestern Europe) and in southwestern Iceland. Details on the calculation of the NAO index from these station pressure data are given in Jones et al. (1997).

In the CRU dataset, independent standardized indices are computed by considering the mean and standard deviation of each monthly series, and the December, January, and February values

are then averaged to obtain a DJF (winter) NAO index. In this study, for comparative purposes, we adopted an improved standardization approach to ensure that the standardized series has a median of zero and a standard deviation of one. Figure 5a shows the winter NAO index obtained directly from the averaged CRU monthly NAO values. Its temporal evolution is very similar to that of a winter NAO index calculated from the average of the monthly standardized differences between Gibraltar and Iceland sea-level pressures, using the 1951–1980 period as a reference. In this latter case, standardization is performed using a three-parameter probability distribution that provides a better fit to each monthly series, thereby ensuring a more accurate standardization (Vicente-Serrano et al. 2025b). The resulting NAO series exhibits a mean value greater than zero over the whole period, mainly because the 1951–1980 period was anomalously negative (see below). The use of such a short reference period is not advisable, both for statistical reasons and because it complicates comparability with other NAO indices (e.g. those derived from climate model outputs or paleoclimatic reconstructions). For this reason, we standardized the differences between the DJF-mean sea-level pressures at Gibraltar and Iceland using the full length of the series as the reference period (Figure 5b). This approach yields a NAO index based on a robust estimation of the distribution parameters, taking advantage of the long-term record, and ensures that the standardized series has a mean of zero and a standard deviation of one. The resulting index is very similar to averaging the monthly NAO values calculated using the same methodology, but the approach adopted here guarantees greater statistical consistency.

2.2. The influence of the NAO on the Mediterranean precipitation

We first examine the relationship between winter NAO variability and winter precipitation across the Mediterranean region. Although the NAO represents the dominant mode of atmospheric circulation affecting the basin, its influence is far from being spatially uniform. Large areas of the Mediterranean exhibit weak or no significant correlations between winter

precipitation and the NAO (Figure 6), revealing a spatial pattern that is considerably more complex than the statement by Seager et al. (2026) that the “influence (of the NAO) wanes from west to east.” Instead, the observed NAO–precipitation correlation pattern reflects the combined effects of complex topography and the contribution of other atmospheric modes (Trigo et al. 2002; Luppichini et al. 2025). Consequently, basin-wide generalisations based on spatially averaged time series can be misleading, as they obscure substantial subregional variability.

At the same time, when precipitation is averaged over the entire Mediterranean basin (see details on the method in Figure 2), a statistically significant relationship with the NAO does emerge (Figure 7). The correlations between winter NAO index and Mediterranean-mean winter precipitation are consistently negative across the different datasets, despite their different time coverage. This highlights an important distinction: while the NAO does not uniformly control precipitation at local or subregional scales, its signal can nonetheless dominate the variability of basin-averaged precipitation through the aggregation of regionally coherent responses.

2.3. Long-term NAO observed dynamics

Much like the precipitation data, the temporal dynamics of the NAO are characterized by high inter-decadal variability (Figure 8). Observational series beginning in the 1820s do not exhibit a significant long-term trend; instead, they show a slight negative tendency when ending in the 1960s. This is due to the predominantly negative values recorded during the 1960s relative to the rest of the record (Figure 5b). While a statistically significant positive trend emerges after 1960, this largely represents a recovery to the baseline values and dynamics observed prior to that decade. Consequently, series beginning after 1975 show no significant trend. These patterns are entirely consistent with the regional Mediterranean precipitation trends shown in Figure 3. This suggests that the NAO positive trend from 1959 to 2023 is primarily a recovery from the extreme lows of the 1960s toward a mean oscillating around zero. We could

then interpret that the recent positive trend does not mean that the NAO is drifting toward a permanently positive state; rather, it reflects a return to pre-1950 conditions following the 1960s anomaly (Figure 9). Ultimately, the anomaly lies not in the recent trend but in the exceptionally low values of the 1960s, which—when used as a starting point—can make subsequent trends appear extraordinary.

2.4. The 1959-2023 NAO trend in model simulations

The central question is whether the anomalous NAO trend between 1959 and 2023—quantified linearly as 0.165 z-units per decade—or, more importantly, the occurrence of a decade as extreme as the 1960s (with a mean winter NAO value of -0.87) is truly exceptional. To address this, we calculated the NAO from climate models using the exact approach applied to the CRU NAO, selecting modeled sea-level pressure (SLP) values at grid points corresponding to Iceland and Gibraltar.

Monthly SLP data were obtained from all available simulations within the CMIP6 archive (<https://esgf-node.ipsl.upmc.fr/search/cmip6-ipsl/>). Our analysis included 609 historical simulations and 50 pre-industrial control (piControl) simulations from 40 different models. While the historical simulations incorporate the full suite of observed natural and anthropogenic forcings, the piControl simulations do not include any type of forcing. For each piControl realization, we selected the final 165 years to match the length of the historical period (1850–2014) with other experiments. Furthermore, to isolate the climate sensitivity to specific drivers, we analyzed 214 natural-only (hist-nat) simulations—driven exclusively by solar and volcanic forcing—and 203 greenhouse-gas-only (hist-GHG) simulations. Table 1 summarizes the CMIP6 simulations used, with further technical details available in the CMIP6 protocol documentation (CMIP, 2025).

In addition to the CMIP6 ensemble, we utilized the PMIP4 Tier-1 “past1000” experiment (850–1849 CE) and the Tier-3 “past2k” experiment, which spans the full Common Era. Five models (EC-EARTH3-LR, EC-EARTH3-Veg-LR, INM-CM4-8, MIROC-ES2L, and MRI-ESM2-0) provided simulations for the “past1000” experiment, while MPI-ESM1-2-LR contributed to the past2k experiment. These PMIP4 simulations utilize the same forcing sets as their historical CMIP6 counterparts (Jungclaus et al. 2017). For all model outputs, the NAO index was derived using the optimized standardization approach described by Vicente-Serrano et al. (2025b).

Figure 10 displays examples of these model simulations across the different experiments, illustrating that the inter-annual NAO variability is generally high and certainly comparable to the characteristic variability observed in the NAO record over the past 200 years (Figure 5b). When examining 65-year trends for 1959–2023, all experiments show comparable values. Although such trends are uncommon, many cases exhibit NAO increases greater than 0.165 z-units per decade (Figure 11), accounting for about 0.5% of all analyzed periods (Table 2). Importantly, their frequency and magnitude do not differ between experiments with observed greenhouse gas forcing and those with no or natural-only forcing, nor when compared with long-term paleoclimate simulations (past2k, past1000). The key question, however, is whether models also reproduce the origin of this rare trend—a decade of strongly negative NAO values as it was recorded in the 1960s.

When examining decades with mean NAO values below -0.85 , like the 1960s record, we find that although this value is exceptionally low, models reproduce such events under all forcings. Simulations show that strongly negative NAO years can cluster into persistent negative phases (Table 3), which can generate positive trends without a shift toward dominant positive values. Consequently, both phenomena—the pronounced short-term trend and the presence of persistent negative (or positive) anomalies—appear to be a plausible characteristic of modeled NAO variability. Because these features emerge independently of the specific forcing used, they likely reflect internal atmospheric dynamics rather than a forced climate response.

2.5. The 1959-2023 NAO trend in reconstructions

We also analyzed short-term variability using several paleoclimate reconstructions of winter NAO based on different proxies, methods, and time periods (Table 4). All records were standardized using the same approach applied to instrumental data and CMIP6 simulations (Vicente-Serrano et al., 2025b). The standardized reconstructions show strong interannual variability (Figure 12), comparable to that in both observations and models.

Moving-window trends from NAO reconstructions over 65-year periods also reveal intervals in which the trend exceeds 0.165 z-units per decade, matching the rate observed for 1959–2023 (Figure 13). These cases account for a substantial fraction of all analyzed periods within some of the reconstruction records (Table 5). Moreover, the different reconstructions display a highly convergent pattern in the evolution of 65-year trends since the early 17th century, which greatly strengthens the robustness of this assessment.

A similar consistency is found in the frequency of extreme negative decades: decades with mean NAO values below -0.85 occur at frequencies comparable to, or even higher than, those observed in the CRU instrumental record across most reconstructions (Table 6).

Taken together, evidence from long-term observations, model simulations, and paleoclimate reconstructions indicates that recent NAO dynamics are stationary on long timescales and strongly supports the interpretation that the most recent NAO trend reflects a return to “normal” conditions following a decade of exceptionally negative values. The behavior observed during 1959–2023 is fully consistent with patterns documented during pre-industrial periods, as demonstrated by both instrumental data and multiple independent NAO reconstructions.

3- Conclusions

The aim of this comment has been to clarify, using high-quality observations, model experiments, and paleoclimate reconstructions, some conclusions reached by Seager et al. (2026), considering a broader perspective.

Future projections consistently indicate that the Mediterranean is one of the regions most likely to experience declining precipitation during the 21st century. This has led part of the scientific community to place increased emphasis on identifying observational evidence that is consistent with these projections. As a result, many studies emphasize decreasing Mediterranean precipitation based on relatively short observational periods, often starting in the 1950s or 1960s (Piervitali et al. 1997; Mariotti 2010; Tanarhte et al. 2012; Barkhordarian et al. 2013; Caloiero et al. 2018) (Piervitali et al., 1997; Mariotti, 2010; Tanarhte et al., 2012; Barkhordarian et al. 2013; Caloiero et al., 2018), as in Seager et al. (2026).

Since Hoerling et al. (2012) attributed a declining precipitation trend to climate change using CMIP3 simulations, which showed strong historical drying in the Mediterranean, some studies have sought to reinforce this message by attributing observed declines to anthropogenic forcing through comparisons between forced and unforced model experiments (Gudmundsson and Seneviratne 2016; Christidis and Stott 2022, 2021). More recently, attention has shifted toward identifying the dynamic mechanisms underlying the precipitation variability (Zappa et al. 2015; Seager et al. 2019; Tuel and Eltahir 2021). In this context, Seager et al. (2026) link a negative precipitation trend from 1950 to 2023 with a positive NAO trend over the same period and hypothesize about the role of internal atmospheric variability and human forcing on these trends.

However, an analysis based on the full length of available precipitation and NAO records reveals a markedly different picture, consistent with dominant long-term variability rather than persistent trends, as highlighted in recent studies (Vicente-Serrano et al. 2025a; González-Hidalgo and Vicente-Serrano 2025). From this longer perspective, the interpretation is straightforward: the precipitation decline since the 1960s is mostly associated with high

precipitation linked to the exceptionally negative NAO phase of that decade, while the subsequent positive NAO trend simply reflects a return to more frequent positive values, comparable to those commonly observed between the 1820s and 1950s. Consequently, it is difficult to hypothesize a potential influence of human forcing on NAO trends.

The prevailing hypothesis for future winter drying in the Mediterranean suggests that high-pressure systems will become more frequent and intense due to a poleward expansion of the Hadley cell driven by Arctic amplification (Staten et al. 2018; Tuel and Eltahir 2020). Yet, this mechanism is not clearly detectable. Arctic amplification presently has a limited influence on northern mid-latitudes (Dai and Song 2020), and the poleward extent of the Hadley circulation in the Euro-Africa sector is characterized by strong decadal variability rather than a robust long-term trend (Bronnimann et al. 2015; Grise et al. 2019; Lionello et al. 2024). Model projections further indicate that a consistent Hadley cell expansion emerges mainly under high-emission scenarios toward the end of the century (D'Agostino et al. 2020). Consequently, the main dynamical mechanisms governing winter precipitation in the Mediterranean appear largely stable over at least the last two centuries—and likely longer, as suggested by paleoclimate reconstructions.

At the same time, the Mediterranean is unquestionably experiencing profound hydroclimatic and ecological changes driven by strong warming affecting the region (Urdiales-Flores et al. 2023). These include increased atmospheric evaporative demand (Tomas-Burguera et al. 2021; Vicente-Serrano et al. 2020), which enhanced evaporation from water bodies (Lorenzo-Lacruz et al. 2025), and irrigated areas (Vicente-Serrano et al. 2017), as well as heightened plant water stress (Colangelo et al. 2017; Peñuelas et al. 2018) and caused widespread tree decline and mortality (Carnicer et al. 2011; Navarro-Cerrillo et al. 2019). Warming has also strongly affected snow cover and melt processes (Alonso-González et al. 2020; López-Moreno et al. 2020), with major implications for water availability and management. However, these impacts are primarily linked to thermodynamic changes during the warm season rather than to shifts in cold season

large-scale atmospheric circulation or precipitation dynamics, which both remain broadly stable, as emphasized in the latest IPCC assessment (Gulev et al. 2021; Gutiérrez et al. 2021). Future projections consistently indicate a decline in precipitation across the Mediterranean region (Lionello and Scarascia 2018), based on CMIP6 models that have demonstrated a high degree of agreement between simulated and observed trends (Vicente-Serrano et al., 2025a), thereby conferring strong reliability on these projections. Nevertheless, to date, precipitation has remained stationary, and overall highly variable, over the long term, consistent with the absence of clear trends in the main atmospheric circulation mechanisms governing the Mediterranean, particularly the North Atlantic Oscillation.

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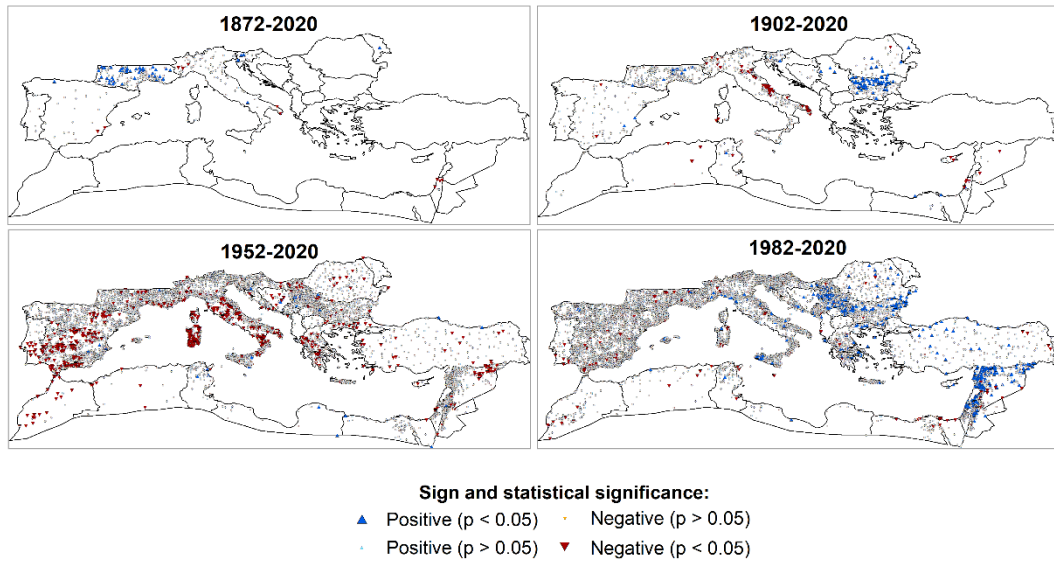


Figure 1: Stations showing statistically significant positive and negative DJF precipitation trends for different periods ending in 2020. Details on the data and methods can be consulted in Vicente-Serrano et al. (2025a).

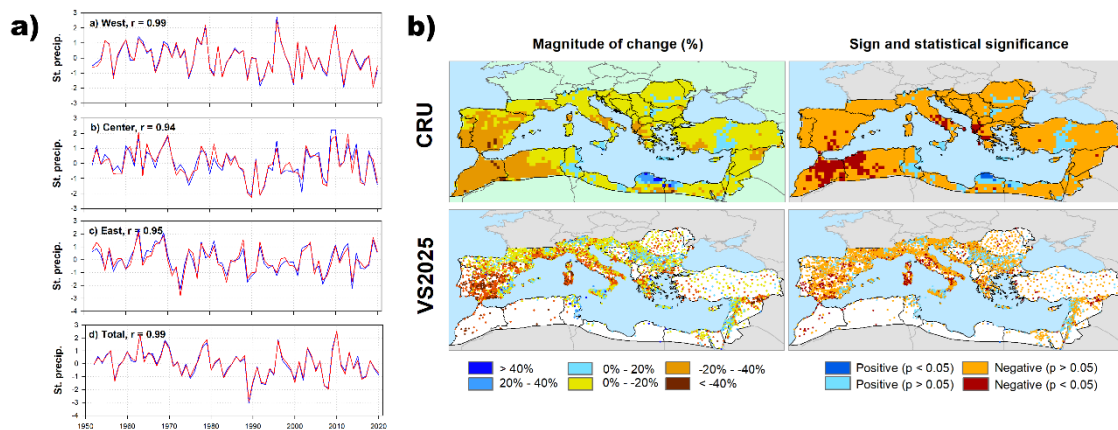


Figure 2. (a) Red lines: Evolution of standardized winter (DJF) precipitation averaged over the Mediterranean region for the period 1952–2020, derived from the CRU gridded dataset for land areas in the western (10°W–10°E, 30°N–46°N), central (10°E–30°E, 30°N–46°N), eastern (30°E–45°E, 30°N–46°N), and entire Mediterranean region (10°W–45°E, 30°N–46°N), following Seager et al. (2026). Blue lines: Corresponding standardized winter (DJF) precipitation series from the VS2025 station database. The western regional series was constructed as a surface-area-weighted average of the regional series for Spain, France, Portugal, Morocco, and Algeria. The same approach was applied to the central region, including Italy, Slovenia, Croatia, Greece, Serbia, Albania, North Macedonia, Montenegro, Bosnia and Herzegovina, Malta, Tunisia, Libya, Moldova, Romania, and Bulgaria. The eastern regional series includes Türkiye, Israel, Cyprus, Egypt, Syria, Jordan, and Lebanon. (b) Trend analysis of winter precipitation based on the CRU (upper panels) and VS2025 (lower panels) datasets. Left panels show the magnitude of change (expressed as a percentage over the study period), and right panels indicate the statistical significance of the trends. Trend magnitudes were estimated using the robust non-parametric Sen’s slope estimator, and statistical significance was assessed using the non-parametric Mann–Kendall test with correction for annual temporal autocorrelation prior to trend estimation (see details in Vicente-Serrano et al. (2025a)).

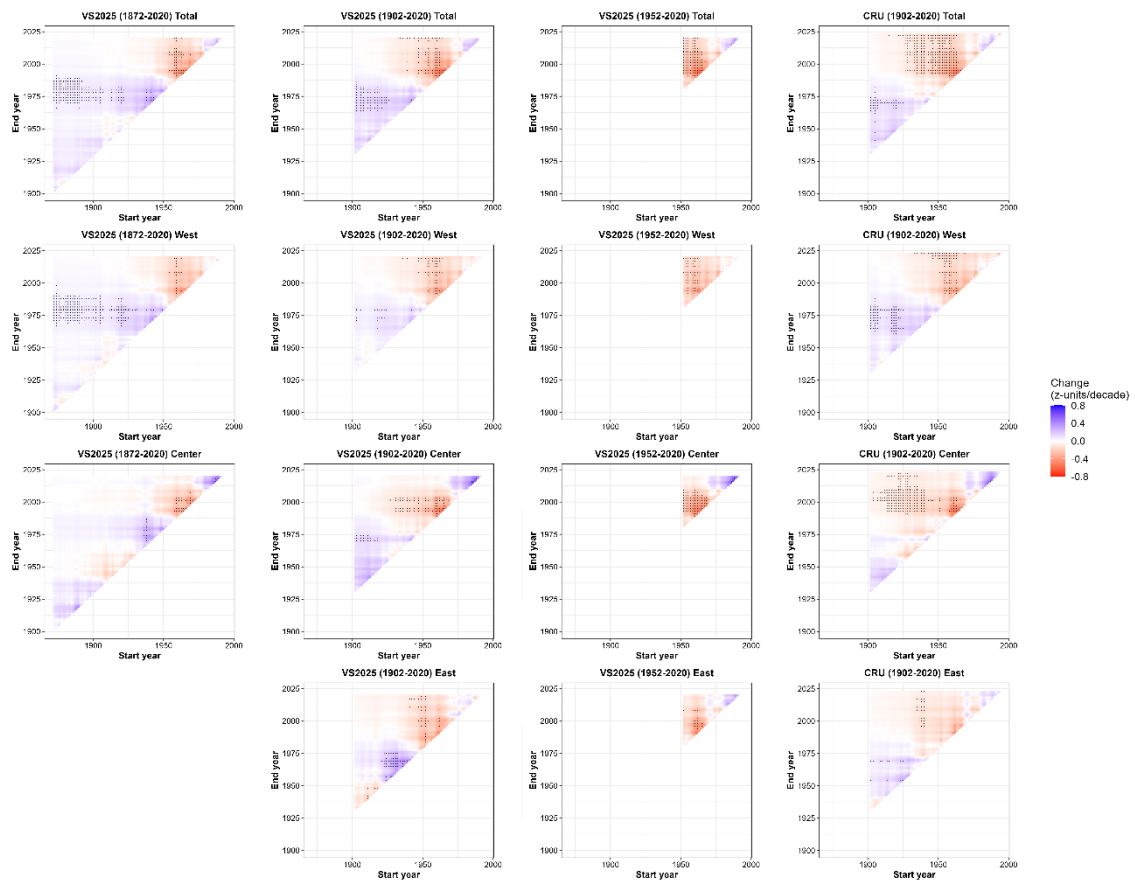


Figure 3. Trends in winter (DJF) precipitation based on the standardized regional and total Mediterranean mean series derived from the different datasets, computed for analysis periods with varying start and end years. Period lengths range from a minimum of 30 years to the full length of each record. Points in the panels indicate periods for which the trend is statistically significant (Mann–Kendall test, $p < 0.05$). Details on the construction of the regional series and the trend analysis methodology are provided in Figure 2.

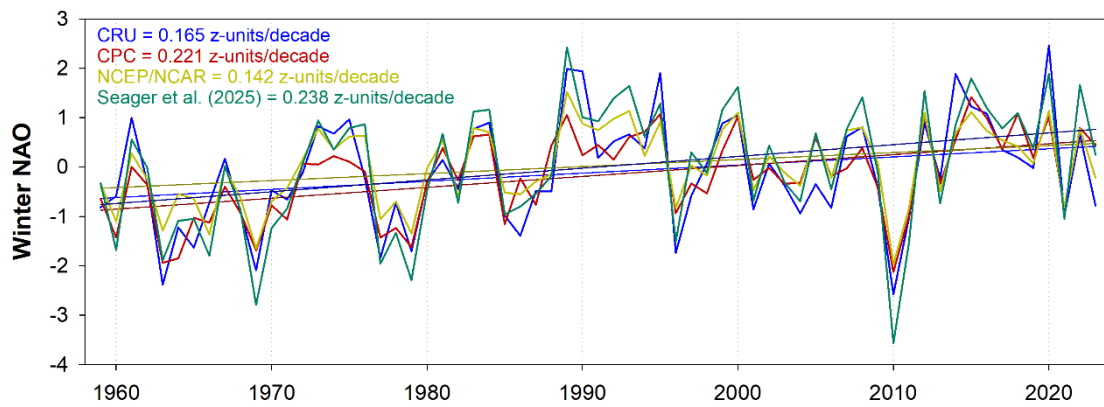


Figure 4: Evolution of the winter DJF NAO obtained from 700hPs geopotential fields as in Seager et al. (2026), CRU, CPC and NCEP/NCAR from 1959 to 2023. Linear regression lines and the magnitudes of change per decade are also shown.

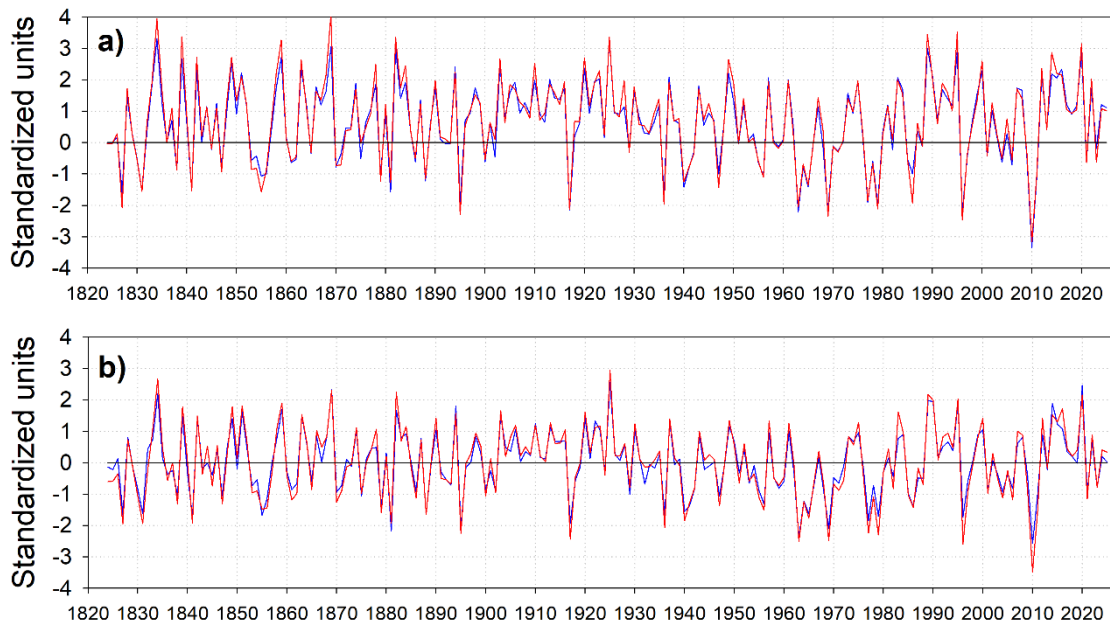
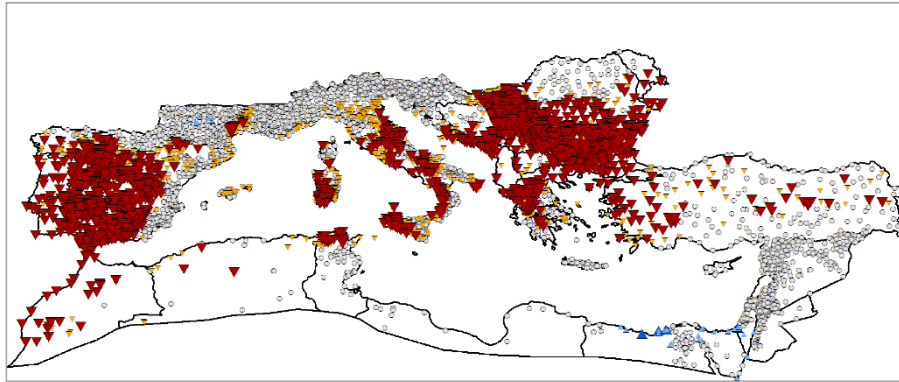


Figure 5. Time series of winter NAO indices. (a) Winter NAO index obtained by averaging monthly DJF NAO indices (blue), following CRU recommendations, and winter NAO index derived from seasonal mean pressure differences between Gibraltar and Iceland (red), standardized using the 1951–1980 reference period. (b) Standardized difference between DJF mean sea-level pressures at Gibraltar and Iceland using the full period of data availability as the reference (blue), and the average of monthly standardized DJF pressure differences between Gibraltar and Iceland, also standardized over the full period (red).



Statistical significance:

▲ Positive ($p < 0.01$) ● Positive ($p < 0.05$) ○ Non-significant ● Negative ($p < 0.05$) ▼ Negative ($p < 0.01$)

Statistical significance:

▲ Positive ($p < 0.01$) ● Positive ($p < 0.05$) ○ Non-significant ● Negative ($p < 0.05$) ▼ Negative ($p < 0.01$)

Figure 6: Spatial distribution of correlations between the DJF NAO from CRU and the DJF precipitation from 1952 to 2020 in the 5,441 meteorological stations available from the study of Vicente-Serrano et al. (2025a)

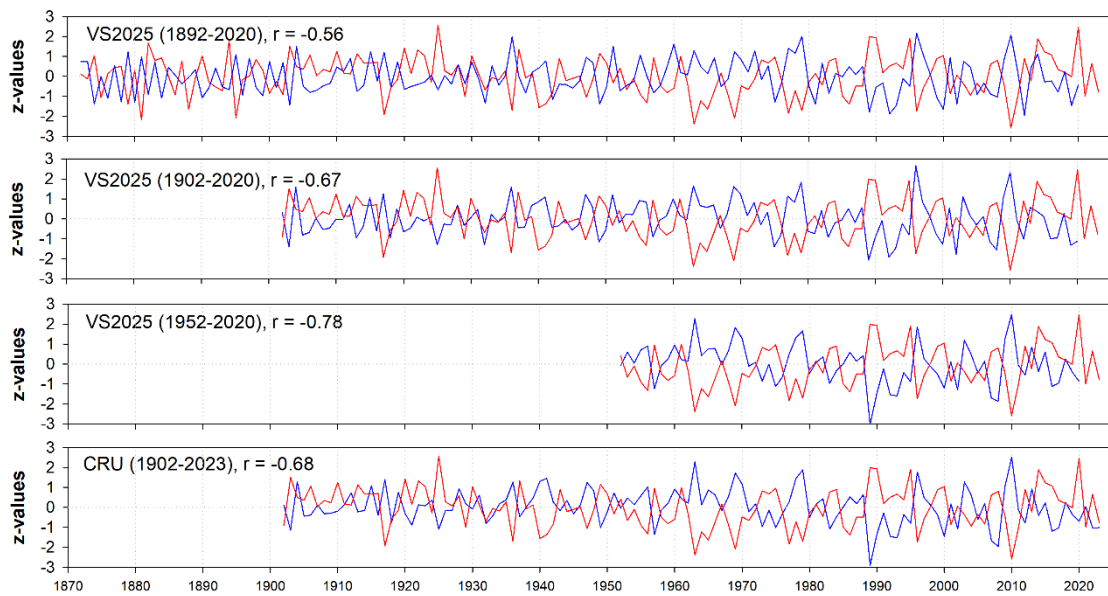


Figure 7: Temporal evolution of the Standardized DJF differences in pressures between Gibraltar and Iceland (red) and the average DJF precipitation over the whole Mediterranean region (blue) from the different databases used in this study. All correlations are statistically significant ($p < 0.05$).

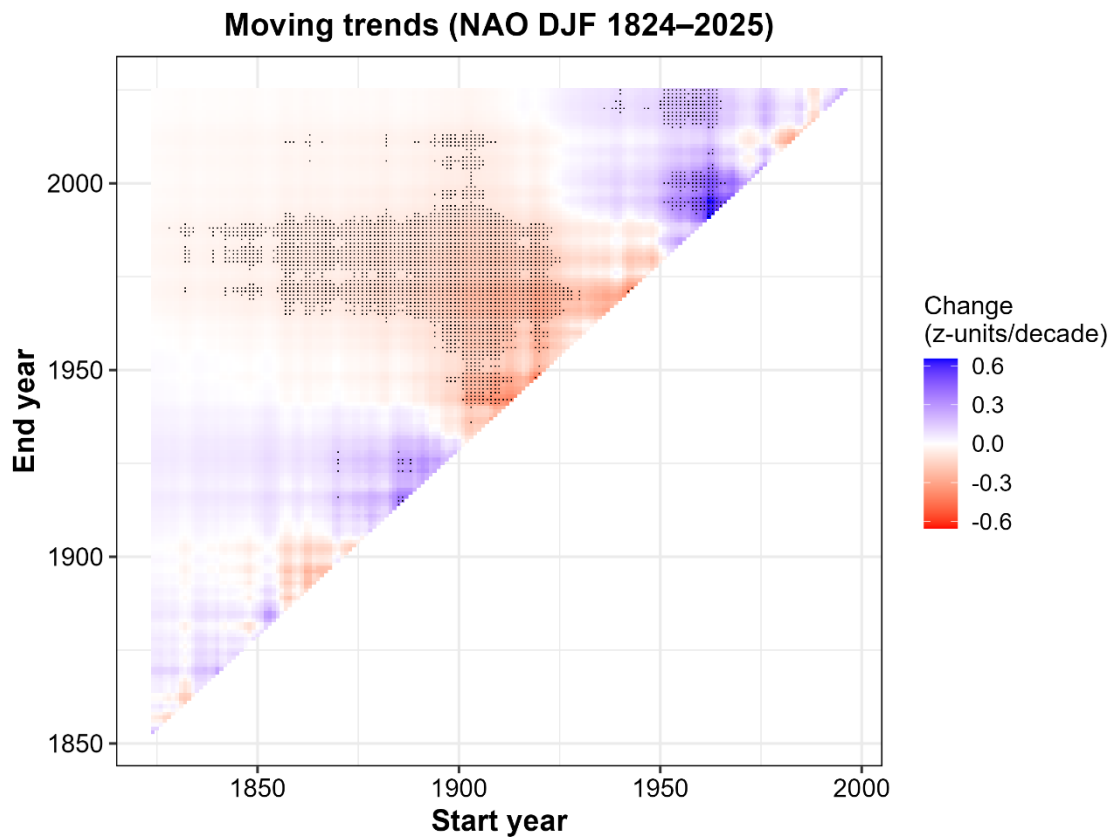


Figure 8: DJF trends considering the NAO index from Standardized DJF differences in pressures between Gibraltar and Iceland for periods with a different start and end, considering a minimum of 30 years and a maximum of the whole length of the series. Dots represent significant trends at $p < 0.05$.

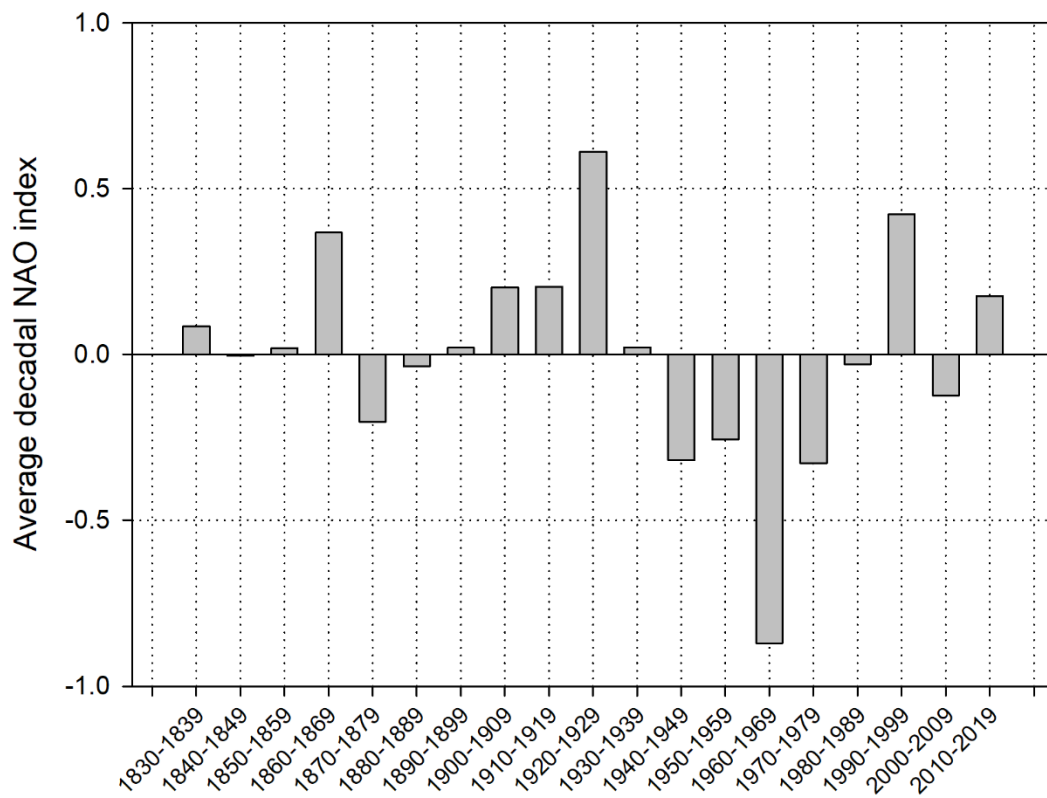


Figure 9: Average decadal NAO index from Standardized DJF differences in pressures between Gibraltar and Iceland.

844 Table 1. Number of experiments used in CMIP6 historical (609), hist-nat (214) and hist-GHG
845 (203) experiments.
846

Model	Reference	Historical	Hist-nat	Hist-GHG	piControl
ACCESS-CM2	Mackallah et al. (2022)	10	3	3	1
ACCESS-ESM1-5	Ziehn et al. (2020)	40	3		1
AWI-CM-1-1-MR	Semmler et al. (2020)	5			1
AWI-ESM-1-REcoM	Seifert et al. (2025)	1			1
BCC-CSM2-MR	Wu et al. (2019)	3	3	3	1
CanESM5	Swart et al. (2019)	65	50	50	2
CanESM5-1	Sigmond et al. (2023)	72			2
CanESM5-CanOE	Swart et al. (2019)	3			1
CAS-ESM2-0	Zhang et al. (2020)	4			1
CESM2	Danabasoglu et al. (2020)	11	3	3	1
CESM2-WACCM	Danabasoglu et al. (2020)	3			1
CIESM	Lin et al. (2020)	3			1
CMCC-CM2-SR5	Cherchi et al. (2019)	11		10	1
CMCC-ESM2	Lovato et al. (2022)	1			1
CNRM-CM6-1	Voldoire et al. (2019)	29	10	9	1
CNRM-CM6-1-HR	Voldoire et al. (2019)	1			1
CNRM-ESM2-1	Séférian et al. (2019)	11			1
EC-Earth3	Döscher et al. (2022)	23			1
EC-Earth3-Veg	Döscher et al. (2022)	4			1
E3SM-1-0	Golaz et al. (2019)			3	
E3SM-2-0	Golaz et al. (2022)		5	5	
FGOALS-f3-L	Bao et al. (2020)	3			1
FGOALS-g3	Pu et al. (2020)	6	3	3	1
GFDL-CM4	Held et al. (2019)		3		
GFDL-ESM4	Dunne et al. (2020)		3	1	
GISS-E2-1-G	Miller et al. (2021)	40	20	10	4
GISS-E2-1-H	Kelley et al. (2020)	10			3
GISS-E2-2-G	Rind et al. (2020)	11			1
HadGEM3-GC31-LL	Williams et al. (2018)	5	10	5	1
INM-CM4-8	Volodin et al. (2018)	1			1
INM-CM5-0	Volodin et al. (2017)	10			1
IPSL-CM6A-LR	Boucher et al. (2020)	33	10	10	2

KACE-1-0-G	Lee et al. (2020)	3			1
KIOST-ESM	Pak et al. (2021)	1			1
MIROC-ES2L	Hajima et al. (2020)	31			1
MIROC6	Tatebe et al. (2019)	50	50	50	1
MPI-ESM1-2-HR	Müller et al. (2018)	10			1
MPI-ESM1-2-LR	Mauritsen et al. (2019)	51	30	30	1
MRI-ESM2-0	Yukimoto et al. (2019)	11	5	5	2
NESM3	(Yang et al. 2020)	5		3	1
NorESM2-LM	Seland et al. (2020)	4	3		2
NorESM2-MM	Seland et al. (2020)	3			1
TaiESM1	Wang et al. (2021)	2			1
UKESM1-0-LL	Sellar et al. (2020)	19			1

Table 1. Number of experiments used in CMIP6 historical (609), hist-nat (214) and hist-GHG (203) experiments.

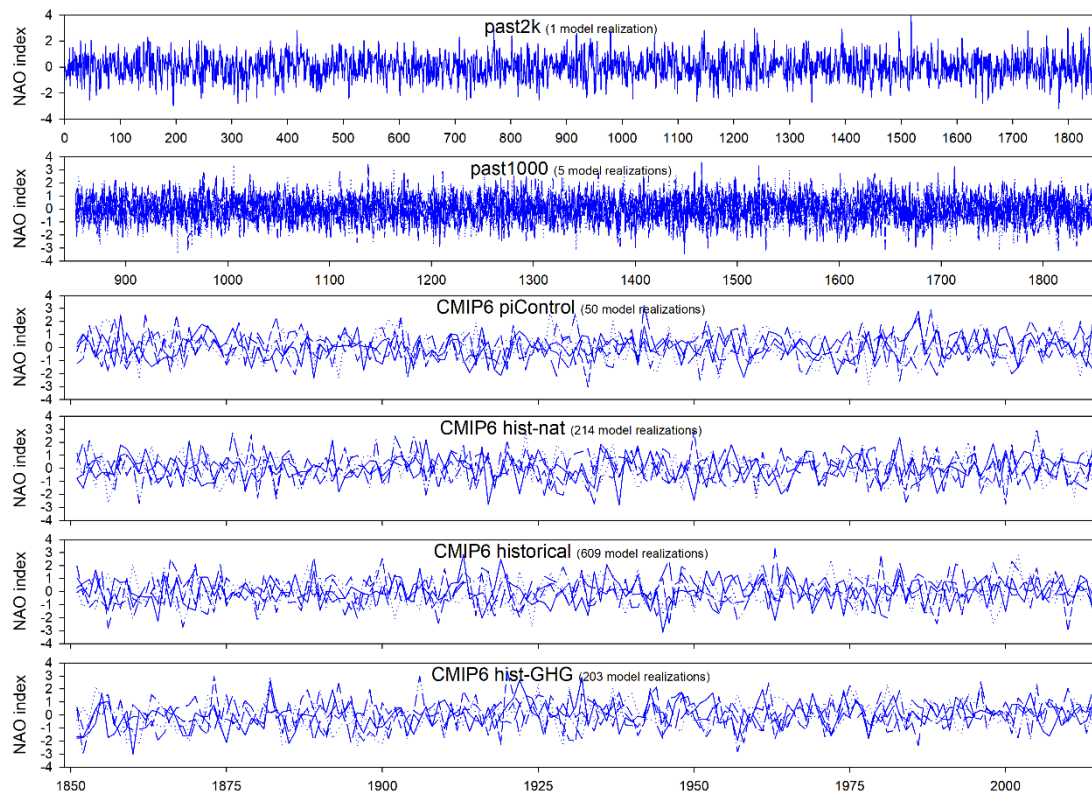


Figure 10: Time series of the NAO index from Standardized DJF differences in pressures between the coordinates of Gibraltar and Iceland in different modelling simulations. The number of realizations from different models is shown in each experiment. In the plots are shown a maximum of five series for experiment as example.

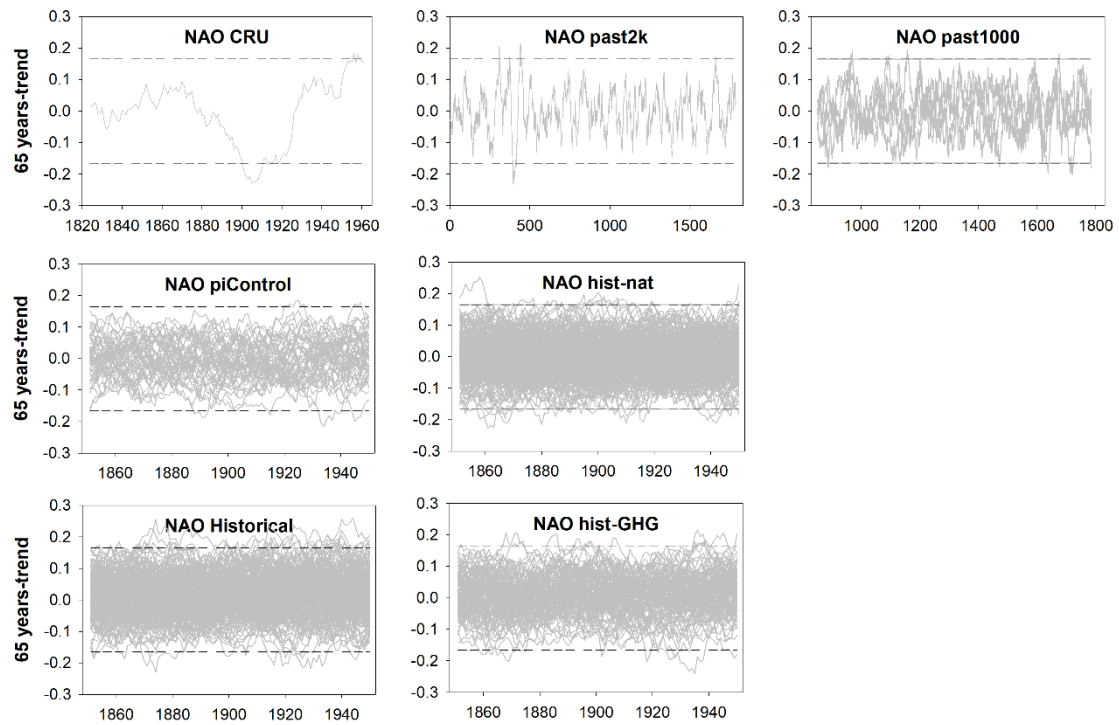


Figure 11: Evolution of the moving trends (in z-units/decade) for periods of 65 years starting in the first years of the available records to the end of the series in the different realizations from the different experiments. The upper horizontal black dotted lines show the 0.165 z-unit/decade that is the trends recorded from the NAO index from Standardized DJF differences in pressures between the coordinates of Gibraltar and Iceland between 1959 and 2023. The evolution of the moving trend for the CRU NAO series is also shown.

Experiment	% of cases
past2k	0.65
past1000	0.26
hist-nat	0.19
piControl	0.12
historical	0.56
Hist-GHG	0.23

Table 2: Percentage of cases from all the model experiments and realizations in which the trend over all possible 65-year periods available is equal or higher than 0.165 z-unit/decade.

	CRU	past2k	Past1000	piControl	Hist-nat	historical	Hist-GHG
<-0.85	5.26	0.54	0.61	0.40	0.34	0.25	0.16
>0.85	0	1.09	0.20	0.13	0.22	0.17	0.20

Table 3: Percentage of decades in all the available realizations for each one of the experiments in which the average NAO index is below -0.85 or above 0.85.

Reference	Period	Season	Proxies	Methods
(Cook et al. 1998)	1701-1980	DJFM	Tree-ring chronologies from Europe and North America	Regression between dendroclimatic proxies and instrumental NAO (1901-1980)
(Glueck and Stockton 2001)	1429-1983	DJF	Tree rings (Morocco and Finland) and Greenland ice-core	Multiple linear regression
(Luterbacher et al. 2001)	1500-2001	DJF	Early instrumental SLP data and documentary sources	Principal Component Regression Analysis
(Cook et al. 2002)	1400-1979	DJFM	Tree-ring chronologies (Europe, North America) and Greenland ice cores	Principal Component Regression calibrated against instrumental NAO indices (1826–1974)
(Goodkin et al. 2008)	1793-1988	DJF	Marine coral from Bermuda Sr/Ca	Spectral analysis and band-pass filtering
(Ortega et al. 2015)	1049-1969	DJF	Multiproxy network (tree rings, ice cores, lake sediments, speleothems)	Ensemble PCR constrained by climate model simulations
(Sjolte et al. 2018)	1241-1970	DJF	Greenland ice cores	Process-based data–model comparison using isotope-enabled climate model (ECHAM5/MPI-OM); pattern matching ensemble
(Cook et al. 2019)	910-2018	DJFM	tree-ring chronologies from Euro-Mediterranean region	Correlation-weighted PCR with ensemble approach and Maximum Entropy Bootstrap

Table 4: Main characteristics of NAO index reconstructions.

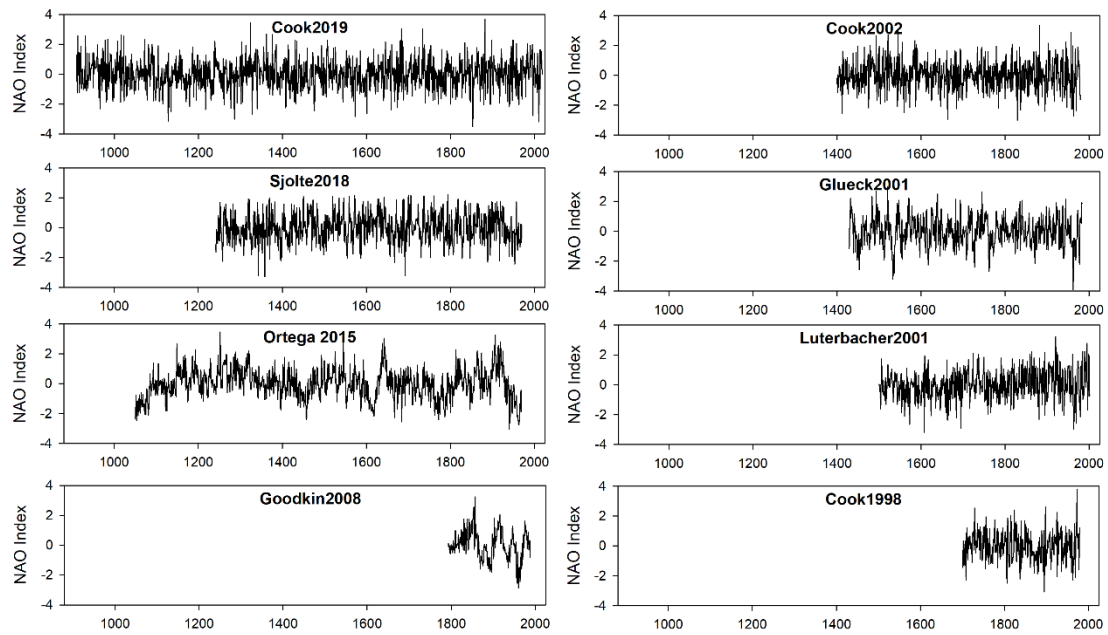


Figure 12: Evolution of the NAO index in the reconstructions used in this study.

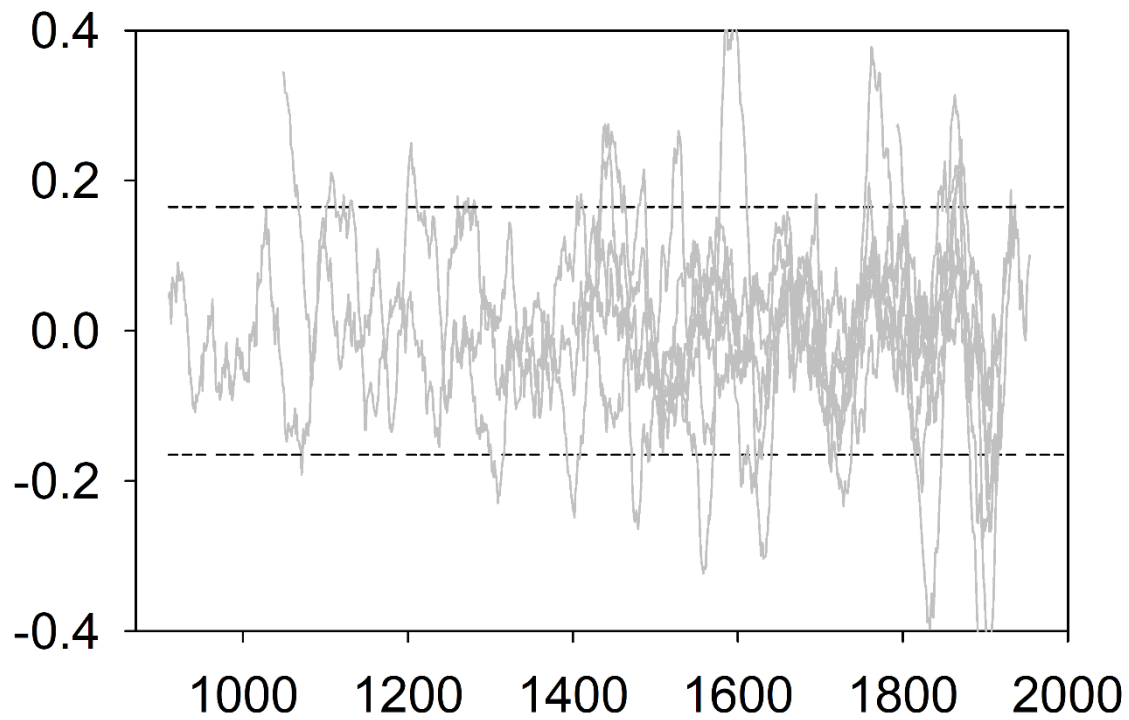


Figure 13: Evolution of the moving trends (in z-units/decade) for periods of 65 years starting in the first years of the available records to the end of the series in the different NAO reconstruction. The horizontal black dotted lines show the 0.165 z-unit/decade that is the trends recorded from the NAO index from Standardized DJF differences in pressures between the coordinates of Gibraltar and Iceland between 1959 and 2023.

Reconstruction	% of cases
Cook2019	0.86
Sjolte2018	2.25
Ortega2015	19.14
Goodkin2008	19.70
Cook2002	0.00
Glueck2001	6.72
Luterbacher2001	0.00
Cook1998	6.02

890

891 Table 5: Percentage of cases from all the NAO reconstructions in which the trend over the 65-
892 year periods available is equal to or higher than 0.165 z-unit/decade.

893

	Cook2019	Sjolte2018	Ortega2015	Goodkin2008	Cook2002	Glueck2001	Luterbacher2001	Cook1998
<-0.85	0.00	2.77	13.0	11.10	0.00	7.27	2.00	3.70
>0.85	0.00	1.38	10.87	11.10	0.00	1.81	2.00	0.00

894

895 Table 6: Percentage of decades in all the available NAO reconstructions in which the average
896 NAO index is below -0.85 or above 0.85.

897