Journal of Hydrology

Seasonal rainfall trends of a key Mediterranean area in relation to large-scale atmospheric circulation: how does current global change affect the rainfall regime?

--Manuscript Draft--

Manuscript Number:	HYDROL44505R1
Article Type:	Research paper
Keywords:	climatic patterns; Current Global Warming; East Atlantic; North Atlantic Oscillation; Western Mediterranean Oscillation; rainfall trend
Corresponding Author:	Marco Luppichini ITALY
First Author:	Marco Luppichini
Order of Authors:	Marco Luppichini
	Monica Bini
	Michele Barsanti
	Roberto Giannecchini
	Giovanni Zanchetta
Abstract:	Current global warming causes a change in atmospheric dynamics, with consequent variations in the rainfall regimes. Understanding the relationship between global climate patterns, global warming, and rainfall regimes is crucial for the creation of future scenarios and for the relative modification of water management. The aim of this study is to improve knowledge of the relationship between North Atlantic Oscillation (NAO), East Atlantic (EA), and Western Mediterranean Oscillation (WeMO) with the seasonal rainfalls in Tuscany, Italy. The study area occupies a strategic position since it lies in a transition zone between the wet area of northern Europe and the dry area of the northern coast of Africa. This research, based on a statistical correlation method and on linear models, is designed to understand the relationship between seasonal rainfalls and climate patterns. The results of this study demonstrate that the use of linear models can yield more information than traditional statistical correlations. The results show a decrease in rainfall in the warm period of the year, namely in the summer, when its expression is most visible. This phenomenon is ascribable to current global warming, which causes an increase in sea-surface temperatures. An increase in the Northern Atlantic Sea Surface Temperature and in the Mediterranean Sea Surface Temperature causes a reduction of the Iceland Low, with an extension of the Azores High. Moreover, an increase in the Genoa Gulf SST induces a weakening of the Genoa Gulf Low, one of the main cyclogenetic systems of the Mediterranean.
Suggested Reviewers:	Florian Börgel florian.boergel@io-warnemuende.de
	MATTHEW DEITCH mdeitch@ufl.edu
	Joan Albert LÓPEZ-BUSTINS jlopezbustins@ub.edu
	Raquel Lorente-Plazas raquel.lorente1@um.es
	Rebeca Izquierdo rebeca@creaf.uab.es
Response to Reviewers:	

Influence of large-scale atmospheric circulation on the rainfall of a key Mediterranean area: how does current global change affect the rainfall regime?

Marco Luppichini[1,2,*], Monica Bini[2,3,4], Michele Barsanti[5], Roberto Giannecchini[2,4,6], Giovanni Zanchetta[2,4,7]

[1] Department of Earth Sciences, University of Study of Florence, Via La Pira 4, Florence, Italy

[2] Department of Earth Sciences, University of Pisa, Via S. Maria, 52, 56126 Pisa, Italy

[3] Istituto Nazionale di Geofísica e Vulcanologia (INGV), Via Vigna Murata 605, 00143 Roma, Italy

[4] CIRSEC Centro Interdipartimentale di Ricerca per lo Studio degli Effetti del Cambiamento Climatico dell'Università di Pisa, Via del Borghetto 80, 56124 Pisa, Italy

[5] Department of Civil and Industrial Engineering, University of Pisa, Largo L. Lazzarino, 56122 Pisa, Italy

[6] Institute of Geosciences and Earth Resources, IGG-CNR, via Moruzzi 1, 56124 Pisa, Italy

[7] Istituto di Geologia Ambientale e Geoingegneria, IGAG-CNR, Rome, Italy

Abstract

Current global warming causes a change in atmospheric dynamics, with consequent variations in the rainfall regimes. Understanding the relationship between global climate patterns, global warming, and rainfall regimes is crucial for the creation of future scenarios and for the relative modification of water management. The aim of this study is to improve the knowledge of the relationship of North Atlantic Oscillation (NAO), East Atlantic (EA), and Western Mediterranean Oscillation (WeMO) with the seasonal rainfall in Tuscany, Italy. The study area occupies a strategic position since it lies in a transition zone between the wet area of northern Europe and the dry area of the northern coast of Africa. This research, based on a statistical correlation method and on linear models, is designed to understand the relationship between seasonal rainfalls and climate patterns. The method of linear models innovative in this thematic area, can yield more information than statistical correlations. The results show a possible decrease in rainfall in the warm period of the year, namely in the summer, when its expression is most visible. This phenomenon is ascribable to current global warming, which causes an increase in sea-surface temperatures. An increase in the Northern Atlantic Sea Surface Temperature (SST) and in the Mediterranean Sea Surface Temperature (SST) causes a reduction of the Iceland Low, with an extension of the Azores High. Moreover, an increase in the Genoa Gulf SST induces a weakening of the Genoa Gulf Low, one of the main cyclogenetic systems of the Mediterranean.

Keywords: Climatic Patterns, Current Global Warming, East Atlantic, North Atlantic Oscillation, Western Mediterranean Oscillation, rainfall trend, Tuscany.

Introduction and goals

Current global warming causes effects at different scale levels, including changes in the hydrological cycle (Allan, 2011; Bates et al., 2008). The effects are visible in air temperature trends and, more complexively, in rainfall, in the form of frequency and intensity of extreme events and changes in soil moisture (Blöschl et al., 2019; Stagl et al., 2014; Xu et al., 2011), with wide implications in terms of social-economic conditions and financial policy (European Environment Agency, 2019). The Mediterranean region is an ideal research testbed for current climatic changes both for its location and historico-cultural importance, and for having been considered a hot spot for future climatic changes (Giorgi, 2006). The Mediterranean, located between the European humid domain and the North African arid belt, provides alternating circulation regimes with large spatial and temporal variability (Dünkeloh and Jacobeit, 2003). Furthermore, the highly populated and industrialized Mediterranean region shows an increase in the demand of water supply. In this context, a correct characterization of rainfall regimes can improve the management of water resources (Tramblay et al., 2020) and extreme events (Cardoso Pereira et al., 2020; Myhre et al., 2019). Several studies have identified a general decrease (although with some exceptions) in the annual rainfall amount in the area of the Mediterranean basin (Bertola et al., 2019; Blöschl et al., 2019; Caloiero et al., 2018, 2011; Colantoni et al., 2015; Deitch et al., 2017; Dünkeloh and Jacobeit, 2003; Halifa-Marín et al., 2021; Longobardi and Villani, 2010; Martin-Vide and Lopez-Bustins, 2006; Philandras et al., 2011; Ríos-Cornejo et al., 2015); and atmospheric patterns related to mesoscale circulation (Brandimarte et al., 2011; Caloiero et al., 2011; Halifa-Marín et al., 2021; Lopez-Bustins et al., 2008; Luppichini et al., 2021; Martinez-Artigas et al., 2021; Ríos-Cornejo et al., 2015; Trigo et al., 2004). During the winter months, one of the main drivers of rainfall variability in southern Europe and in the Mediterranean is the presence of different pressure fields over the Northern Atlantic Ocean and their variability indicated as the North Atlantic Oscillation (NAO) (Hurrell, 1995). NAO is defined by an index measured as a north-southern dipole of pressure anomalies, with one pole located at higher latitude (Iceland Low 80°N) and the other at the central latitudes of the North Atlantic between 35°N and 40°N (Azores High).

The East Atlantic (EA) index is similar to that of NAO but is displaced south-eastward to the approximate nodal lines of the NAO pattern. The EA index is often interpreted as a downward-shifted NAO model, but its strong subtropical link entails a different peculiarity. The EA value is positive when a significant drop in pressure occurs in the Atlantic Ocean; at the same time, the subtropical oceanic anticyclone belt considerably rises in latitude and reinforces itself. In response, the African anticyclone gains energy and invasiveness over the Mediterranean, subjecting this area to frequent pulses of hot and dry Saharan air in all seasons (Climate Prediction Center, 2021; Mellado-Cano et al., 2019). The NAO and EA indexes present interannual and annual variabilities with positive and negative phases. The rainfall in the Mediterranean can be associated with a negative phase of NAO and/or EA, when we observe an expansion of the Iceland Low. Instead, during a positive phase of NAO and/or EA, Northern Europe is the rainiest area (Rousi et al., 2020).

The Western Mediterranean oscillation (WeMO) is an index often used to study variability in rainfall in alternative to NAO in the Mediterranean region. The WeMO index is the difference of atmospheric pressure in a dipole, with the first pole located in Padua (45.40◦N, 11.48◦E) in northern Italy and the second one located in San Fernando, Cádiz (36.28◦N, 6.12◦W) in southwestern Spain (Climatic Research Unit, 2021). Specifically, the former is located in the Po plain (an area with relatively high barometric variability due to the different influence of the central European anticyclone and the Genoa Gulf Low), while the latter pole is located in the Gulf of Cádiz in the southwest of the Iberian Peninsula, often subject to the influence of the Azores anticyclone and, episodically, to the cut-off of circumpolar lows or to its own cyclogenesis (Halifa-Marín et al., 2021; Lopez-Bustins et al., 2020; Martin-Vide and Lopez-Bustins, 2006). A positive phase of WeMO is associated with a low-pressure area in the Ligurian Sea and with an anticyclone in the Gulf of Cadiz. Instead, a negative phase of the index determines a low in the Gulf of Cadiz and an anticyclone in Central Europe. During the positive phase, in the Iberian Peninsula the winds are typically west and northwest coming from the North Atlantic area. These winds cross the continental areas of the peninsula, and become dry, causing rainfall on the north-western coasts and the inland. Conversely, a negative WeMO phase is associated with humid air masses travelling over the Mediterranean Sea. When these winds reach the eastern side of the Iberian Peninsula, they are laden with moisture, resulting in an increase in rainfall, sometimes torrential, in this area (Halifa-Marín et al., 2021; Martin-Vide and Lopez-Bustins, 2006).

Both NAO and EA are influenced by the Sea Surface Temperature (SST) of the Northern Atlantic Ocean (NASST) and of the Mediterranean (MSST). An increase in NASST and in MSST is correlated to an expansion of the Azores High and to a consecutive reduction of the Iceland Low, which cause a formation of the NAO and EA positive phases (Frankignoul et al., 2003; Robertson et al., 2000; Visbeck et al., 2001). More recently, NAO has been correlated to the Atlantic Multidecadal Oscillation (AMO), a representative index of the NASST trend (Knight et al., 2005). AMO changes the zonal position of the NAO center of action, moving the cyclonic area closer to Europe or North America. During a positive phase of AMO, the Icelandic Low moves further towards North America, while the Azores High moves further towards Europe (and viceversa) for the negative phase of AMO (Börgel et al., 2020). WeMO is also influenced by the NASST and MSST, but also by the Genoa Gulf Sea Surface Temperature (GGSST), with positive values correlating to low values of SST (Martín et al., 2012; Martin-Vide and Lopez-Bustins, 2006). Current global warming causes a progressive increase in NASST, MSST and GGSST (Pastor et al., 2020; Wang and Dong, 2010) so that NAO and EA are likely to be characterized by more positive phases, and WeMO by more negative phases.

The purpose of this study is to understand the rainfall seasonal trends of the last 70 years in Tuscany (central Italy), in relation to mesoscale circulation and to the indices defined above. The region has a strategic location: it is located in the northern sector of the Mediterranean, in the proximity of the Genoa Gulf, by far the most active cyclogenetic centre of the Mediterranean (Trigo et al., 2002). The rainfall dataset used came from several raingauges with high spatial density and temporal activity from 1950 to 2020. The large number of raingauges allowed us to investigate the rainfall trend in great detail and with direct measurements. The same dataset was used by Luppichini et al. (2020), who employed different types of elaboration to understand the variable influence of NAO on the Tuscany rainfall. The rainfall trends are compared with the NAO, EA and WeMO indices by means of mathematical and statistical methods to understand the climatic trends influencing the rainfall regime in the area. We investigated the link between the different indices by using traditional statistical methods (Spearman, 1904), but also by introducing in this field an innovative approach, which employs a linear model to understand the influence of each index on the rainfall prediction. The combination of these different methods helped us to comprehend the accuracy and the advantages of the new method proposed.

In our study, we compared these SSTs with the atmospheric indices to improve knowledge on the rainfall trend and to understand possible future scenarios.

Study area

As expected, the mean annual precipitation (MAP) in Tuscany is influenced by morphology (Figure 1a). The rainiest areas are located at the highest altitudes (Apuan Alps and Northern Apennines; Figure 1b). In particular, the Apuan Alps in north-western Tuscany show some of the highest rainfall amounts in Italy (Giannecchini and D'Amato Avanzi, 2012; Rapetti and Vittorini, 1994), often characterized by high intensity (D'Amato Avanzi et al., 2004; Giannecchini, 2006). In Tuscany, MAP is in a range of 400-3000 mm/year with a clear gradient from the northern to the southern and it is linked to the morphology (Figure 1a). The main rainy season is autumn, with a progressive decrease that generally starts in December. The mean rainfall in the DJF season is ca 300 mm, ca 250 mm in MAM, ca 130 mm in JJA, and ca 350 mm in SON.

FIGURE 1

Materials and Methods

Dataset

Rainfall dataset and processing

The raingauge dataset was provided by the Tuscany Region Hydrologic Service (SIR) network and includes 1103 raingauges (Figure 1c). The data were obtained by an automated download procedure through an HTTP request. The activity period of each raingauge is variable. The older stations have been monitoring since the beginning of the last century, even if a temporal continuity of the data is not always guaranteed for some stations. SIR provides the daily rainfall data for each raingauge in the operation period. To obtain longer and more complete time series from this dataset, we grouped the stations according to a stringent protocol. This procedure is necessary to reconstruct the time series of the stations that have experienced minor changes in position or that have undergone an administrative variation (e.g., a slight change in name or identification code). In many cases, stations have consecutive intermittent activity times due to the decommissioning of one and the subsequent installation of a new one. In these cases, we merged the stations by assigning the same, or part of the same name, with a difference in quote (less than 20%) of the measurement, and a maximum distance (less than 2 km). The geographic coordinates of the merged stations derived from a cartesian mean of the original coordinates of the origin stations.

By using the data available and following the procedure described above, a total of 117 time series were obtained from 1950 to 2020. The rainfall data can also be useful for comparison with the results of the models (see section Linear Models), which predict rainfall anomalies; instead, the absolute values are expressed as percentage anomalies of rainfall (PAR), and are calculated as follows:

$$PAR = \frac{x_i - \overline{x_i}}{\overline{x_i}} \cdot 100 \tag{1}$$

where, x_i is the rainfall amount, $\overline{x_i}$ is the rainfall amount mean of the period 1961-1990. The PAR is averaged with a ten-year mobile window.

Climatic Dataset

The NAO dataset is provided by the Climate Analysis Section of the US National Center for Atmospheric Research (NCAR). This dataset is based on the principal (PC)-based index component of the NAO, which are the time series of the leading Empirical Orthogonal Function (EOF) of SLP anomalies over the Atlantic sector, 20°-80°N, 90°W-40°E. This index is used to measure the yearly NAO, by tracking the seasonal movements of the Icelandic Low and Azores

High. The dataset has a monthly frequency from January 1889 to December 2020. PC-based indices are more optimal representations of the full spatial patterns of the NAO (National Center for Atmospheric Research Staff (Eds), 2021).

The EA dataset used in this study is provided by the National Weather Service of NOAA. The frequency of the dataset is on a monthly basis, from 1950 to 2020. The index is standardized by the 1981-2010 climatology (Climate Prediction Center, 2021).

The WeMO index is provided by the Climatic Research Unit (CRU) of the University of East Anglia (Climatic Research Unit, 2021). The time series starts in 1821 and has a monthly frequency.

The trends of NASS, MSST, and GGSST are calculated from the Extended Reconstructed Sea Surface Temperature (ERSST) dataset version 5 (NOAA, 2021), and they are expressed using a 10-year mobile window of anomalies. The anomalies are referred to the mean of the period 1961-1990. NASST is calculated in the area 0N-65N 80W-0E, MSST in the area 38N-49N 0E-28E, and GGSST in the area 42.8N-44.8N 7.6E-10.76E.

Statistical Correlation

We calculated the correlation coefficient in order to identify a possible relationship between atmospheric teleconnection and rainfall amount. Some authors (Caloiero et al., 2011; Izquierdo et al., 2014; Luppichini et al., 2021; Nalley et al., 2019; Vergni et al., 2016) use the Spearman's correlation coefficient (SCC) (Spearman, 1904) to understand the relationship between atmospheric index and rainfall amount. This relationship is suitable for monotonically-related variables, even when their relationship is not linear. The range of Spearman's coefficients is between -1 and 1; positive values indicate a tendency of one variable to increase or decrease together with another variable, whereas negative values indicate a trend in which the increase in the values of one variable is associated with the decrease in the values of the other variable, and viceversa. We calculated the SCC between the three atmospheric teleconnections and the rainfall for the four seasons: winter from December to February (DJF), spring from March to May (MAM), summer from June to August (JJA) and autumn from September to November (SON). SCC was calculated using a 10-year moving time-window from 1950 to 2020. The result of the correlation was assigned to the year halfway through each ten-year period.

Linear Models

The simplest mathematical model is the linear one. We can create linear models able to predict the rainfall amount by using the NAO, WeMO and EA time series. The equation of a linear model predicting the rainfall (R_p), by using the NAO, WeMO and EA time series, is the following:

$$R_p = \alpha NAO + \beta WeMO + \gamma EA + \delta \tag{2}$$

We can analyse the setting of the independent variable coefficients (α, β, γ) to understand the role of each input on the prediction of rainfall. The simplicity of the linear models does not allow to have the best prediction models, but it certainly allows to analyse the influence of the input clearly and to exclude synergy between the inputs. We created a linear model for each raingauge time series and for the four seasons. The different dimensionality of the three atmospheric teleconnections could influence the information expressed by the parameters of models α, β and δ. For this reason, we scaled the time series of NAO, WeMO and EA in the range between 0 and 1 for the studied period (1950-2020), applying the following equation:

$$Ts = \frac{Ts - Ts_m}{Ts_{\mathrm{M}} - Ts_m} \tag{3}$$

where Ts is the index time series in the range 0 and 1, Ts_{M} is the maximum value of the index, and Ts_m is the minimum value of the index. The fitting of the linear models is executed using the SciPy library in Python Language and, in more detail, the “curve_fit” method (Virtanen et al., 2020).

Results

Rainfall Trends

Figure 2 reports the values of PAR calculated for each time series used in this work. The graphs indicate a small variability of PAR between each time series, excluding the possibility of different influences on the linear model outcomes by the input stations. The rainfall trends expressed in PAR are shown in FiguresFigure **3**-6. These trends are very different in the four seasons. From 1950 to 1985, the DJF season was characterized by a slow rainfall reduction followed by a sudden decrease around the 90’s. The first years of the 1990’s presented a PAR reduction of about 30-40%. Starting from 2000, we can observe a progressive increase in winter rainfall with a return of the amount recorded before 1990 (Figure 3). Until the 1990s, the MAM rainfall trend was identified by an oscillation. From the 1990’s to the 2010’s, we observe PAR values between ca -10 and -20%. After 2008, there was an increase in precipitation (Figure 4). The JJA season was characterized by a progressive reduction of rainfall starting from 1965 with the minimum values of -30% around 2005. The last years were marked by a weakly increase in rainfall (Figure 5). Finally, rainfall in the SON season presented a certain variability over an approximate 20-year period. The maximum rainfall amount was recorded around 1965 and 1995, while the minimum values were referred to the period 1970-1990 (Figure 6).

FIGURE 2

Atmospheric Teleconnection Trends

From 1950 to 2020, NAO was characterized by an intensification of the positive phase in the DJF and MAM seasons (Figure 3 and 4). In the JJA season, NAO was characterized by a positive phase until 2005, whereas the index was characterized by a negative phase, except for some years. Finally, NAO was more variable in the SON season with periods characterized by negative alternated with positive phases (Figure 6).

From 1950 to 2020, the EA time series was characterized by an intensification of the positive phase starting from 1985 for the DJF period (Figure 3), and from 1995 for the MAM and JJA periods (Figure 4 and 5). The SON period presented a higher index fluctuation, with a negative phase until 1980, followed by a more positive ten-year phase and then by a negative phase until 2000. From 2000 to 2020, we can observe an increase in the positive phase except for some cases (Figure 6).

In DJF, WeMO was characterized by a positive phase with a decrease in the 1990-2010 period (Figure 3). Around 2005 we observed a drastic change in the WeMO index in the MAM, JJA and SON seasons with a negative persistence phase (Figures 4-6). Before 2005, the index in these seasons was characterized by positive phases except for some years in which the values of the index were negative (Figures 4-6).

Sea surface temperature trends

Figures 3-6 show the trends of NASST, MSST and GGSST display a clear increasing trend starting from the 1980's in all seasons. Such increase only started around the 2010's for DJF and GGSST, while it increased starting from 1980s in the other seasons. The increase in SST was higher in the summer than in the other seasons.

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

Statistical Correlation

Figure 7 reports the results obtained from the Spearman's correlation coefficient. In the DJF season, rainfall is correlated with WeMO and anticorrelated with NAO and EA. Rainfall increases during a negative phase of NAO or EA and a positive phase of WeMO. During this period, each atmospheric teleconnection has a similar effect on the rainfall amount. In the MAM season, the strongest correlation is with WeMO, and even in this case a positive phase of the index corresponds to a rainfall increase in the study area. NAO and EA are weakly anticorrelated with the rainfall amount. The strongest correlation is with EA in the JJA season, and a negative phase of this index indicates an increase in rainfall in the area. On other hand, a positive phase of EA corresponds to reduced precipitation in summer. NAO and WeMO are weakly correlated with the rainfall, but do not have a clear behaviour. Even in the SON season, the strongest correlation is with EA. The correlation in this season is positive, which indicates that a positive EA phase determines increased precipitation in the area. The spatial correlation distribution is homogenous with no clear spatial pattern, especially when the correlations are strong, providing a precise indication of the relationship (Figure 7).

FIGURE 7

Linear Models

In Figure 8a-d, we report four examples of the prediction of PAR by means of linear models referred to the DJF, MAM, JJA and SON seasons. The cases shown represent the results of the lineal models because they have Root Mean Square Error (RMSE) values similar to the error medians calculated on the whole dataset (Figure 8e). Figure 8e also reports the RMSE of the entire dataset. SON, followed by DJF, is the season with the highest average errors.

Figure 9 shows the mean values of coefficients α, β and γ for the linear models in each season (blue circles). We can observe a change in the values of the three coefficients from one season to another. The red circles in Figure 9 show the relative weights of each coefficient. In the DJF season, the coefficient with the greatest weight is α with a mean value of about 55%, followed by β and γ. The coefficients indicate that NAO has more influence on the rainfall trend than WeMO and EA in DJF. In this season, increased precipitation is linked to a negative phase of NAO (α is negative) and a positive phase of WeMO (β is positive). A positive γ is not to be understood as a positive link between rainfall and index, but it works as a compensation with respect to the α coefficient in the model. In the MAM season, β (WeMO) has the highest weight in the results of the models, followed by α and γ. In particular, the amount of precipitation is correlated with a positive phase of WeMO and with a negative phase of NAO. Again, EA has less influence on the model than the other two indices. In the JJA season EA is the most important index, with the greatest coefficient (γ). In particular, the summer rainfall seems to be linked to a negative phase of EA. Less important, the summer rainfall is linked to a negative phase of WeMO. In the SON season, NAO has the greatest weight and is followed by WeMO and EA, which have less influence on the rainfall trend. In this case, the coefficients are all negative, so that rainfall is correlated to a negative phase of these indices.

FIGURE 8

FIGURE 9

Discussion

Mathematical and statistical relationship between atmospheric teleconnections and rainfall

The statistical correlation calculated with Spearman's method represents a first indication of the influence of climate patterns on the local rainfall trend (Figure 7). In accordance with several studies (Caloiero et al., 2011; Deser et al., 2017; Ferrari et al., 2013; George et al., 2004; López-Moreno et al., 2011; Luppichini et al., 2021; Riaz et al., 2017; Vergni and Chiaudani, 2015; Vicente-Serrano and López-Moreno, 2008; West et al., 2019), NAO influence is predominant in winter, with an anticorrelation between index and rainfall amount. In agreement with the obtained SCC, an increase in the Azores High, and consequently a decrease in the Iceland Low, determine reduced winter rainfall in the study area. The correlation between NAO and rainfall decreases during the successive seasons with a minimum correlation in the summer. In winter and in spring, the correlation with WeMO is strong and it is characterized by a positive sign. This implies the formation of the Genoa Gulf Low and its reinforcement increases the amount of rainfall in the study area. This can be ascribed to the direction of the moist air masses coming from the Atlantic Ocean and directed to the north-western coast of Spain and to the Mediterranean (Degeai et al., 2020; Martín et al., 2012; Martin-Vide and Lopez-Bustins, 2006). In this dynamic state the moist air masses can reach Tuscany, enhancing local cyclogenesis and rainfall. The SCC values indicate that the influence of the Genoa Gulf Low decreases in summer and autumn (Figure 7). The correlation between rainfall and EA is strong in winter and summer; in summer, the main correlation with rainfall is particularly with EA. In winter, the link between EA and rainfall is the same for NAO. In summer, the greater representativeness of EA than of NAO on the Azores High allows a better understanding of the link between rainfall and global climate in this season. In detail, the formation of the Azores High and of the African High results in an increase in the EA index, and this means that there is reduced precipitation in the study area. In autumn, the statistical correlations do not allow to make a link between large-scale circulation and rainfall. Indeed, we can observe a weak anticorrelation with NAO, a weak correlation with EA, and no correlation with WeMO. This method seems unsuitable to represent the autumn season with its atmospheric dynamics.

The results of the linear models are conformant to the statistical correlation results for the DJF, MAM and JJA seasons, whereas we can observe some differences in SON. The strong correspondence between the two methods in DJF, MAM and JJA makes it possible to validate our linear model. In autumn, the analysis of the linear models identifies an important role of NAO, and therefore a link between the northern Atlantic atmospheric circulation and the rainfall in the study area. In autumn, the coefficients of NAO (α) are set negative and this means that an increase in the index is linked to a decrease in rainfall in the study area. This mathematical result is more plausible than that obtained from the analysis of correlations based on the notions of atmospheric physics that we introduced previously. The linear model-based method allowed us to refine our investigations and to improve our knowledge of the dynamics in the Mediterranean over the seasons.

The use of our linear models offers the advantage of clarifying the role and influence of large-scale atmospheric circulation on rainfall over the study region in different seasons, and this may appear controversial when using only the statistical correlation. These linear methods can also be useful for rainfall prediction, although it is not the intention of this paper to produce the best model for predictions. If we wanted to reduce the model errors, we should have chosen a more complex model able to better adapt to the variability of the inputs; however, it would have been difficult to understand the influence of each input parameter, which is the main scope of this paper.

Long-term rainfall trends and relationship with climate patterns

This study identified a confused trend for the DJF, MAM and SON rainfall, while JJA rainfall clearly tends to decrease (Figures 3-6). These results agree with those of other studies based on different rainfall datasets (Caloiero et al., 2018; Deitch et al., 2017; Philandras et al., 2011). More specifically, Deitch et al. (2017) studied the seasonal trend of rainfall in the Mediterranean area, demonstrating a negative trend for summer rainfall and no trend for winter/autumnal rainfall in Tuscany.

The DJF seasons are characterized by significantly decreased precipitation between 1984 and 2005 (Figure 3). This period is marked by a positive phase of NAO and EA and a negative phase of WeMO. Starting around 1984, the increase in NAO and EA is due to an increase in NASST (Figure 3). An increase in NASST is correlated to an expansion of the Azores High and a consecutive reduction of the Iceland Low, resulting in the formation of the NAO and EA positive phases (Börgel et al., 2020; Frankignoul et al., 2003; Robertson et al., 2000; Visbeck et al., 2001). The successive increase in rainfall from 2005 to 2020 seems to have been caused by an increase in the WeMO, and therefore by an increase in the Genoa Gulf Low persistence. This could indicate a change of the main climatic driver with respect to the previous period (Figure 3).

The MAM season presents a decrease in the amount of rainfall in the period between 1985 and 2008 (Figure 4). The WeMO constantly decreases with progressive intensification of the negative phase. This indicates a gradual reduced intensity of the Genoa Gulf Low. As a matter of fact, the GGSST has progressively increased since 1985. Furthermore, NAO and EA are in a persistent positive phase. Since 2008, there has been a weak increase in the precipitation trend.

The JJA rainfall trends have the highest correlation with EA, while NAO and WeMO have a lower influence (Figure 7 and 9). The increase in NASST, MSST and GGSST induces the NAO and EA indices to a positive phase, and WeMO to a negative phase. This process induces a progressive reduction of rainfall trends in this season.

SON is characterized by rainfall trend variability with two wet periods and two dry periods (Figure 6). Each dry period is marked by an increase in NAO, whereas the wet period results from an increase in WeMO linked to a weak decrease in GGSST (Figure 6).

The increase in sea surface temperature is greater in the warm periods of the year and it is caused by current global warming. From these observations, we can evince that the warm periods of the year are marked by a greater decrease in precipitation resulting in less water availability in the environmental system.

Conclusions

This study helps to gain a better knowledge of the rainfall trends of the last 70 years in Tuscany, a key area of the Mediterranean Basin, strongly influenced by the cyclogenetic activity related to the Genoa Gulf Low. These trends are analyzed on the basis of the trend of the main atmospheric drivers of the northern hemisphere. The location of the study area allows to understand the influences of Atlantic atmospheric circulation and of the Mediterranean atmospheric circulation on rainfall. Along with the Spearman’s traditional coefficient analysis, this study proposes a new mathematical method to investigate the relationship between climate pattern and rainfall. The method based on the use of linear models has resulted to be valid, with similar results derived from a statistical correlation. This new method has allowed a more detailed comprehension of the link between climate patterns and precipitation in the study area. In Tuscany, rainfall amount is influenced by Northern Atlantic atmospheric circulation and by the Genoa Gulf Low. The influences of the two atmospheric systems vary during the year: in winter, rainfall is strongly correlated to the three indices; in spring, the main influence is represented by WeMO, indicating an important role played by the Genoa Gulf Low; in summer, the main driver is EA, which represents better than NAO the influence of the Azores High in this season; in autumn, the strongest correlation is with NAO.

The amount of precipitation in the study area is influenced by the SSTs that induce a variation in the Northern Atlantic and Mediterranean atmospheric circulation (Börgel et al., 2020; Frankignoul et al., 2003; Robertson et al., 2000; Visbeck et al., 2001). Current global warming determines an increase in the SSTs and this increase is higher in the warm seasons of the year. The results of this study show that in these seasons there is the greatest reduction of water availability, on account of a direct decrease in precipitation.

In conclusion, current global warming can be responsible for less rainfall in this area, and this occurs mainly in the warm seasons when temperature increase is highest.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Acknowledgements: The authors are grateful to the Tuscany Region Hydrologic Service for providing the data used in this work.

Funding: This research was funded by project no. 249792 "Dalla Preistoria all'Antropocene: Nuove Tecnologie per la valorizzazione dell'eredità culturale della Versilia (PANTAREI)" Tuscany Region (call POR FSE 2014-2020, Resp. M. Bini); by the collaborative research agreement no. 579999-2019 "Autorità di Bacino Distrettuale Appennino Settentrionale" (Resp. Monica Bini and Roberto Giannecchini); and by the project: "Cambiamenti globali e impatti locali: conoscenza e consapevolezza per uno sviluppo sostenibile della pianura Apuo-versiliese" Fondazione Cassa Risparmio di Lucca, (Resp. M. Bini).

Reference

Allan, R.P., 2011. Human influence on rainfall. Nature 470, 344–345. https://doi.org/10.1038/470344a

Bates, B., Kundzewicz, Z.W., Wu, S., Burkett, V., Doell, P., Gwary, D., Hanson, C., Heij, B., Jiménez, B., Kaser, G., Kitoh, A., Kovats, S., Kumar, P., Magadza, C.H.D., Martino, D., Mata, L., Medany, M., Miller, K., Arnell, N., 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change.

Bertola, M., Viglione, A., Hall, J., Blöschl, G., 2019. Flood trends in Europe: are changes in small and big floods different? Hydrology and Earth System Sciences Discussions 1–23. https://doi.org/10.5194/hess-2019-523

Blöschl, G., Hall, J., Viglione, A., Perdigão, R.A.P., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G.T., Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G.B., Claps, P., Frolova, N., Ganora, D., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T.R., Kohnová, S., Koskela, J.J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Salinas, J.L., Sauquet, E., Šraj, M., Szolgay, J., Volpi, E., Wilson, D., Zaimi, K., Živković, N., 2019. Changing climate both increases and decreases European river floods. Nature 573, 108–111. https://doi.org/10.1038/s41586-019-1495-6

Börgel, F., Frauen, C., Neumann, T., Meier, H.E.M., 2020. The Atlantic Multidecadal Oscillation controls the impact of the North Atlantic Oscillation on North European climate. Environmental Research Letters 15. https://doi.org/10.1088/1748-9326/aba925

Brandimarte, L., di Baldassarre, G., Bruni, G., D’Odorico, P., Montanari, A., D’Odorico, P., Montanari, A., 2011. Relation Between the North-Atlantic Oscillation and Hydroclimatic Conditions in Mediterranean Areas. Water Resources Management 25, 1269–1279. https://doi.org/10.1007/s11269-010-9742-5

Caloiero, T., Caloiero, P., Frustaci, F., 2018. Long-term precipitation trend analysis in Europe and in the Mediterranean basin. Water and Environment Journal 32, 433–445. https://doi.org/https://doi.org/10.1111/wej.12346

Caloiero, T., Coscarelli, R., Ferrari, E., Mancini, M., 2011. Precipitation change in Southern Italy linked to global scale oscillation indexes. Nat. Hazards Earth Syst. Sci. 11, 1683–1694. https://doi.org/10.5194/nhess-11-1683-2011

Cardoso Pereira, S., Marta-Almeida, M., Carvalho, A.C., Rocha, A., 2020. Extreme precipitation events under climate change in the Iberian Peninsula. International Journal of Climatology 40, 1255–1278. https://doi.org/https://doi.org/10.1002/joc.6269

Climate Prediction Center, 2021. East Atlantic [WWW Document]. URL https://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml (accessed 9.22.21).

Climatic Research Unit, 2021. Mediterranean Oscillation Indices (MOI) [WWW Document]. URL https://crudata.uea.ac.uk/cru/data/moi/ (accessed 9.22.21).

Colantoni, A., Delfanti, L., Cossio, F., Baciotti, B., Salvati, L., Perini, L., Lord, R., 2015. Soil Aridity under Climate Change and Implications for Agriculture in Italy. Applied Mathematical Sciences 9, 2467–2475. https://doi.org/10.12988/ams.2015.52112

D’Amato Avanzi, G., Giannecchini, R., Puccinelli, A., 2004. The influence of the geological and geomorphological settings on shallow landslides. An example in a temperate climate environment: the June 19, 1996 event in northwestern Tuscany (Italy). Engineering Geology 73, 215–228. https://doi.org/https://doi.org/10.1016/j.enggeo.2004.01.005

Deitch, M.J., Sapundjieff, M.J., Feirer, S.T., 2017. Characterizing Precipitation Variability and Trends in the World’s Mediterranean-Climate Areas. Water 9. https://doi.org/10.3390/w9040259

Deser, C., Hurrell, J.W., Phillips, A.S., 2017. The role of the North Atlantic Oscillation in European climate projections. Climate Dynamics 49, 3141–3157. https://doi.org/10.1007/s00382-016-3502-z

Dünkeloh, A., Jacobeit, J., 2003. Circulation dynamics of Mediterranean precipitation variability 1948–98. International Journal of Climatology 23, 1843–1866. https://doi.org/https://doi.org/10.1002/joc.973

European Environment Agency, 2019. Economic losses from climate -related extremes in Europe. Indicator Assessment.

Ferrari, E., Caloiero, T., Coscarelli, R., 2013. Influence of the North Atlantic Oscillation on winter rainfall in Calabria (southern Italy). Theoretical and Applied Climatology 114, 479–494. https://doi.org/10.1007/s00704-013-0856-6

Frankignoul, C., Friederichs, P., Kestenare, E., 2003. Influence of Atlantic SST anomalies on the atmospheric circulation in the Atlantic-European sector, ANNALS OF GEOPHYSICS.

George, D.G., Järvinen, M., Arvola, L., 2004. The influence of the North Atlantic Oscillation on the winter characteristics of Windermere (UK) and Pääjärvi (Finland).

Giannecchini, R., 2006. Relationship between rainfall and shallow landslides in the southern Apuan Alps (Italy). Natural Hazards and Earth System Science 6, 357–364. https://doi.org/10.5194/nhess-6-357-2006

Giannecchini, R., D'Amato Avanzi, G., 2012. Historical research as a tool in estimating hydrogeological hazard in a typical small alpine-like area: The example of the Versilia River basin (Apuan Alps, Italy). Physics and Chemistry of the Earth, Parts A/B/C 49, 32–43. https://doi.org/10.1016/J.PCE.2011.12.005

Giorgi, F., 2006. Climate change hot-spots. Geophysical Research Letters 33. https://doi.org/https://doi.org/10.1029/2006GL025734

Halifa-Marín, A., Lorente-Plazas, R., Pravia-Sarabia, E., Montávez, J.P., Jiménez-Guerrero, P., 2021. Atlantic and Mediterranean influence promoting an abrupt change in winter precipitation over the southern Iberian Peninsula. Atmospheric Research 253. https://doi.org/10.1016/j.atmosres.2021.105485

Hurrell, J.W., 1995. Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. Science 269, 676 LP – 679. https://doi.org/10.1126/science.269.5224.676

Izquierdo, R., Alarcón, M., Aguillaume, L., Àvila, A., 2014. Effects of teleconnection patterns on the atmospheric routes, precipitation and deposition amounts in the north-eastern Iberian Peninsula. Atmospheric Environment 89, 482–490. https://doi.org/https://doi.org/10.1016/j.atmosenv.2014.02.057

Knight, J.R., Allan, R.J., Folland, C.K., Vellinga, M., Mann, M.E., 2005. A signature of persistent natural thermohaline circulation cycles in observed climate. Geophysical Research Letters 32. https://doi.org/10.1029/2005GL024233

Longobardi, A., Villani, P., 2010. Trend analysis of annual and seasonal rainfall time series in the Mediterranean area. International Journal of Climatology 30, 1538–1546. https://doi.org/https://doi.org/10.1002/joc.2001

Lopez-Bustins, J.A., Arbiol-Roca, L., Martin-Vide, J., Barrera-Escoda, A., Prohom, M., 2020. Intra-annual variability of the Western Mediterranean Oscillation (WeMO) and occurrence of extreme torrential precipitation in Catalonia (NE Iberia). Natural Hazards and Earth System Sciences 20, 2483–2501. https://doi.org/10.5194/nhess-20-2483-2020

Lopez-Bustins, J.-A., Martin-Vide, J., Sanchez-Lorenzo, A., 2008. Iberia winter rainfall trends based upon changes in teleconnection and circulation patterns. Global and Planetary Change 63, 171–176. https://doi.org/https://doi.org/10.1016/j.gloplacha.2007.09.002

López-Moreno, J.I., Vicente-Serrano, S.M., Morán-Tejeda, E., Lorenzo-Lacruz, J., Kenawy, A., Beniston, M., 2011. Effects of the North Atlantic Oscillation (NAO) on combined temperature and precipitation winter modes in the Mediterranean mountains: Observed relationships and projections for the 21st century. Global and Planetary Change 77, 62–76. https://doi.org/https://doi.org/10.1016/j.gloplacha.2011.03.003

Luppichini, M., Barsanti, M., Giannecchini, R., Bini, M., 2021. Statistical relationships between large-scale circulation patterns and local-scale effects: NAO and rainfall regime in a key area of the Mediterranean basin. Atmospheric Research 248, 105270.

Martín, P., Sabatés, A., Lloret, J., Martin-Vide, J., 2012. Climate modulation of fish populations: The role of the Western Mediterranean Oscillation (WeMO) in sardine (Sardina pilchardus) and anchovy (Engraulis encrasicolus) production in the north-western Mediterranean. Climatic Change 110, 925–939. https://doi.org/10.1007/s10584-011-0091-z

Martinez-Artigas, J., Lemus-Canovas, M., Lopez-Bustins, J.A., 2021. Precipitation in peninsular Spain: Influence of teleconnection indices and spatial regionalisation. International Journal of Climatology 41, E1320–E1335. https://doi.org/https://doi.org/10.1002/joc.6770

Martin-Vide, J., Lopez-Bustins, J.-A., 2006. The Western Mediterranean Oscillation and rainfall in the Iberian Peninsula. International Journal of Climatology 26, 1455–1475. https://doi.org/https://doi.org/10.1002/joc.1388

Mellado-Cano, J., Barriopedro, D., García-Herrera, R., Trigo, R.M., Hernández, A., 2019. Examining the North Atlantic Oscillation, East Atlantic Pattern, and Jet Variability since 1685. Journal of Climate 32, 6285–6298. https://doi.org/10.1175/JCLI-D-19-0135.1

Myhre, G., Alterskjær, K., Stjern, C.W., Hodnebrog, Ø., Marelle, L., Samset, B.H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M., Stohl, A., 2019. Frequency of extreme precipitation increases extensively with event rareness under global warming. Scientific Reports 9, 16063. https://doi.org/10.1038/s41598-019-52277-4

Nalley, D., Adamowski, J., Biswas, A., Gharabaghi, B., Hu, W., 2019. A multiscale and multivariate analysis of precipitation and streamflow variability in relation to ENSO, NAO and PDO. Journal of Hydrology 574, 288–307. https://doi.org/https://doi.org/10.1016/j.jhydrol.2019.04.024

National Center for Atmospheric Research Staff (Eds), 2021. The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (PC-based). [WWW Document]. https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based. URL https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based. (accessed 9.22.21).

NOAA, 2021. Extended Reconstructed SST [WWW Document]. URL https://www.ncei.noaa.gov/products/extended-reconstructed-sst (accessed 9.28.21).

Pastor, F., Valiente, J.A., Khodayar, S., 2020. A warming Mediterranean: 38 years of increasing sea surface temperature. Remote Sensing 12. https://doi.org/10.3390/RS12172687

Philandras, C., Nastos, P., Kapsomenakis, J., Douvis, K., Tselioudis, G., Zerefos, C., 2011. Long Term Precipitation Trends and Variability within the Mediterranean Region. Natural Hazards and Earth System Sciences 11, 3235–3250. https://doi.org/10.5194/nhess-11-3235-2011

Rapetti, F., Vittorini, S., 1994. Le precipitazioni in Toscana: osservazioni sui casi estremi. RIVISTA GEOGRAFICA ITALIANA 101, 47–76.

Riaz, S.M.F., Iqbal, M.J., Hameed, S., 2017. Impact of the North Atlantic Oscillation on winter climate of Germany. Tellus, Series A: Dynamic Meteorology and Oceanography 69. https://doi.org/10.1080/16000870.2017.1406263

Ríos-Cornejo, D., Penas, Á., Álvarez-Esteban, R., del Río, S., 2015. Links between teleconnection patterns and precipitation in Spain. Atmospheric Research 156, 14–28.

Robertson, A.W., Mechoso, C.R., Kim, Y.-J., 2000. The Influence of Atlantic Sea Surface Temperature Anomalies on the North Atlantic Oscillation. Journal of Climate 13, 122–138. https://doi.org/10.1175/1520-0442(2000)013<0122:TIOASS>2.0.CO;2

Rousi, E., Rust, H.W., Ulbrich, U., Anagnostopoulou, C., 2020. Implications of Winter NAO Flavors on Present and Future European Climate. Climate 8, 13. https://doi.org/10.3390/cli8010013

Spearman, C., 1904. The proof and measurement of association between two things. The American Journal of Psychology 15, 72–101. https://doi.org/10.2307/1412159

Stagl, J., Mayr, E., Koch, H., Hattermann, F.F., Huang, S., 2014. Effects of Climate Change on the Hydrological Cycle in Central and Eastern Europe BT - Managing Protected Areas in Central and Eastern Europe Under Climate Change, in: Rannow, S., Neubert, M. (Eds.), . Springer Netherlands, Dordrecht, pp. 31–43.

Tramblay, Y., Llasat, M.C., Randin, C., Coppola, E., 2020. Climate change impacts on water resources in the Mediterranean. Regional Environmental Change 20, 83. https://doi.org/10.1007/s10113-020-01665-y

Trigo, I.F., Bigg, G.R., Davies, T.D., 2002. Climatology of Cyclogenesis Mechanisms in the Mediterranean.

Trigo, R.M., Pozo- Vázquez, D., Osborn, T.J., Castro- Díez, Y., Gámiz- Fortis, S., Esteban- Parra, M.J., Pozo-Vázquez, D., Osborn, T.J., Castro-Díez, Y., Gámiz-Fortis, S., Esteban-Parra, M.J., 2004. North Atlantic

Oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. International Journal of Climatology: A Journal of the Royal Meteorological Society 24, 925–944. https://doi.org/10.1002/joc.1048

Vergni, L., Chiaudani, A., 2015. RELATIONSHIP BETWEEN THE NAO INDEX AND SOME INDICES OF EXTREME PRECIPITATION IN THE ABRUZZO REGION.

Vergni, L., di Lena, B., Chiaudani, A., 2016. Statistical characterisation of winter precipitation in the Abruzzo region (Italy) in relation to the North Atlantic Oscillation (NAO). Atmospheric Research 178–179, 279–290. https://doi.org/https://doi.org/10.1016/j.atmosres.2016.03.028

Vicente-Serrano, S.M., López-Moreno, J.I., 2008. Nonstationary influence of the North Atlantic Oscillation on European precipitation. Journal of Geophysical Research: Atmospheres 113. https://doi.org/10.1029/2008JD010382

Virtanen, P., Gommers, R., Oliphant, T.E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S.J., Brett, M., Wilson, J., Millman, K.J., Mayorov, N., Nelson, A.R.J., Jones, E., Kern, R., Larson, E., Carey, C.J., Polat, \.Ilhan, Feng, Y., Moore, E.W., VanderPlas, J., Laxalde, D., Perktold, J., Cimrman, R., Henriksen, I., Quintero, E.A., Harris, C.R., Archibald, A.M., Ribeiro, A.H., Pedregosa, F., van Mulbregt, P., SciPy 1.0 Contributors, 2020. SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. Nature Methods 17, 261–272. https://doi.org/10.1038/s41592-019-0686-2

Visbeck, M.H., Hurrell, J.W., Polvani, L., Cullen, H.M., 2001. The North Atlantic Oscillation: Past, present, and future. Proceedings of the National Academy of Sciences 98, 12876. https://doi.org/10.1073/pnas.231391598

Wang, C., Dong, S., 2010. Is the basin-wide warming in the North Atlantic Ocean related to atmospheric carbon dioxide and global warming? Geophysical Research Letters - GEOPHYS RES LETT 37. https://doi.org/10.1029/2010GL042743

West, H., Quinn, N., Horswell, M., 2019. Regional rainfall response to the North Atlantic Oscillation (NAO) across Great Britain. Hydrology Research 50, 1549–1563. https://doi.org/10.2166/nh.2019.015

Xu, H., Taylor, R.G., Xu, Y., 2011. Quantifying uncertainty in the impacts of climate change on river discharge in sub-catchments of the Yangtze and Yellow River Basins, China. Hydrol. Earth Syst. Sci. 15, 333–344. https://doi.org/10.5194/hess-15-333-2011

Figures

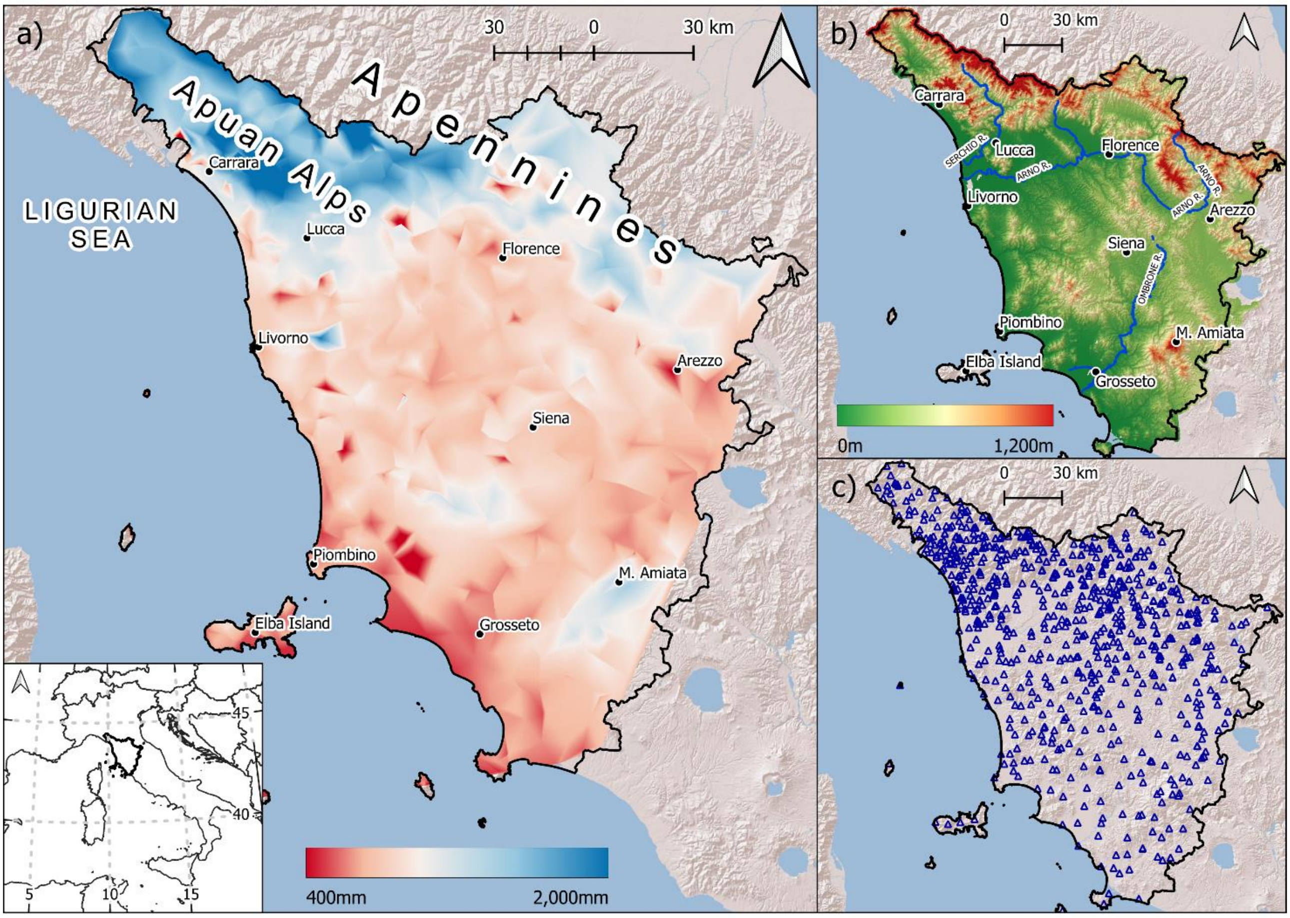


Figure 1. a) mean annual precipitation (MAP) of Tuscany linked to the morphology: the rainiest areas correspond to the mountainous areas; b) morphology of Tuscany; c) the 1103 raingauges of the Tuscany Region Hydrologic Service network used in this work.

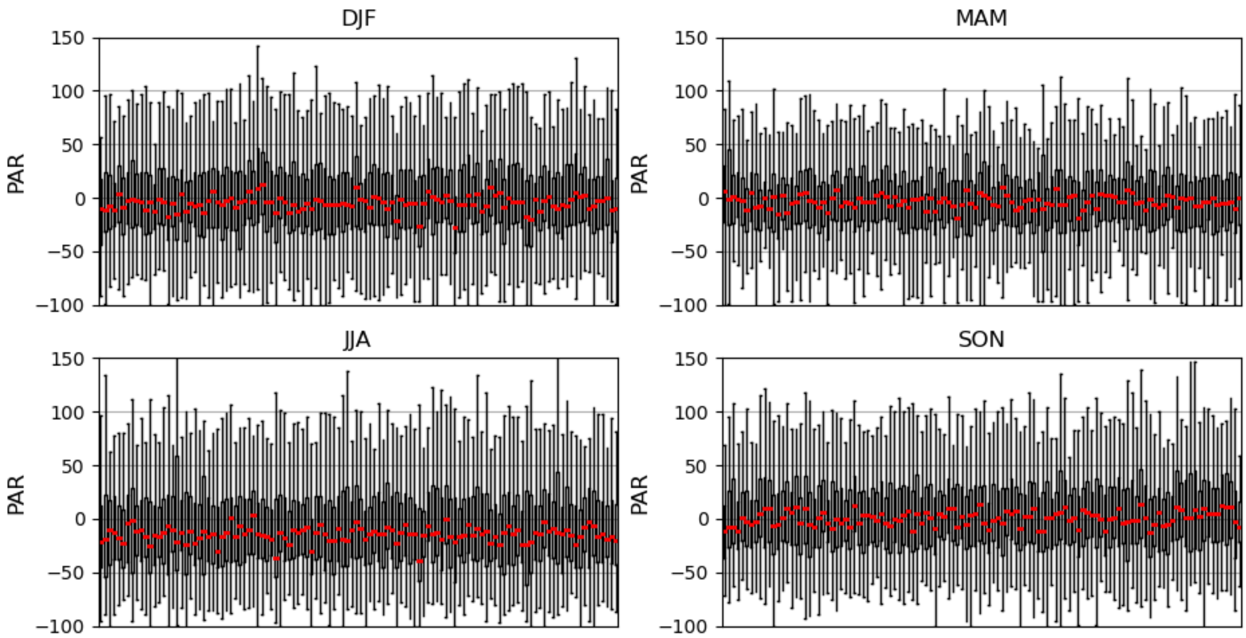


Figure 2. Percentage Anomaly of Rainfall (PAR) of the 117 rainfall time series used in this work, calculated for the four seasons. Each boxplot is referred to a rainfall time series. The boxes represent the interval between the 25th and 75th percentiles (Q1 and Q3). IQR is the interquartile range Q3-Q1. The upper whisker will extend to the last datum lower than Q3 + 1.5×IQR. Similarly, the lower whisker will reach the first datum higher than Q1 – 1.5×IQR. The red lines represent the medians (DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November).

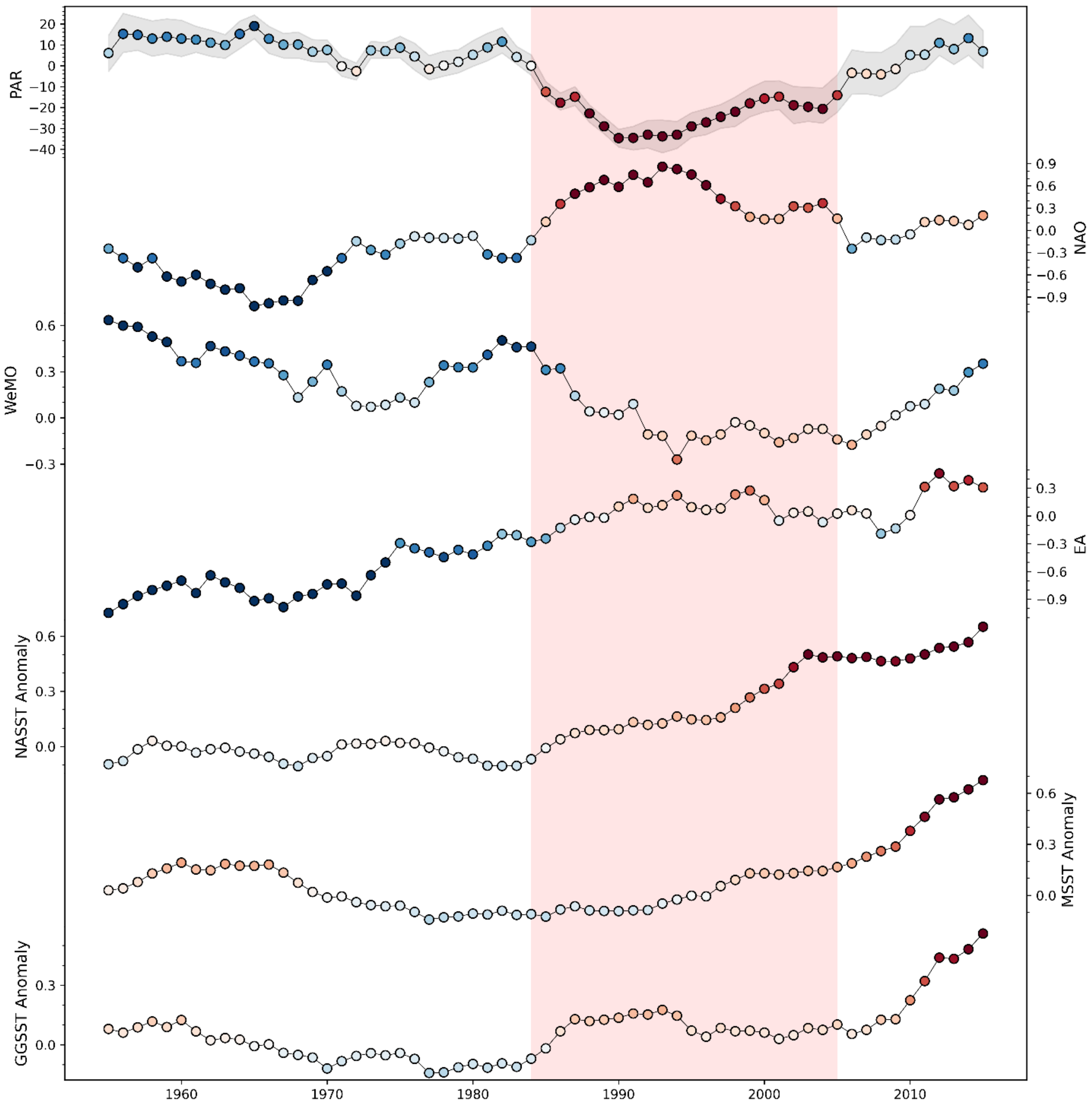


Figure 3. Trends of Percentage Anomaly Rainfall (PAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature

(GGSST) for the DJF season. The trends are smoothed by a 10-year mobile window and the colour of the points varies between blue and red: blue is linked to wet periods, red to dry periods. The grey band on PAR represents the 25th and 75th percentile. The pink band is referred to the main dry period of the time series.

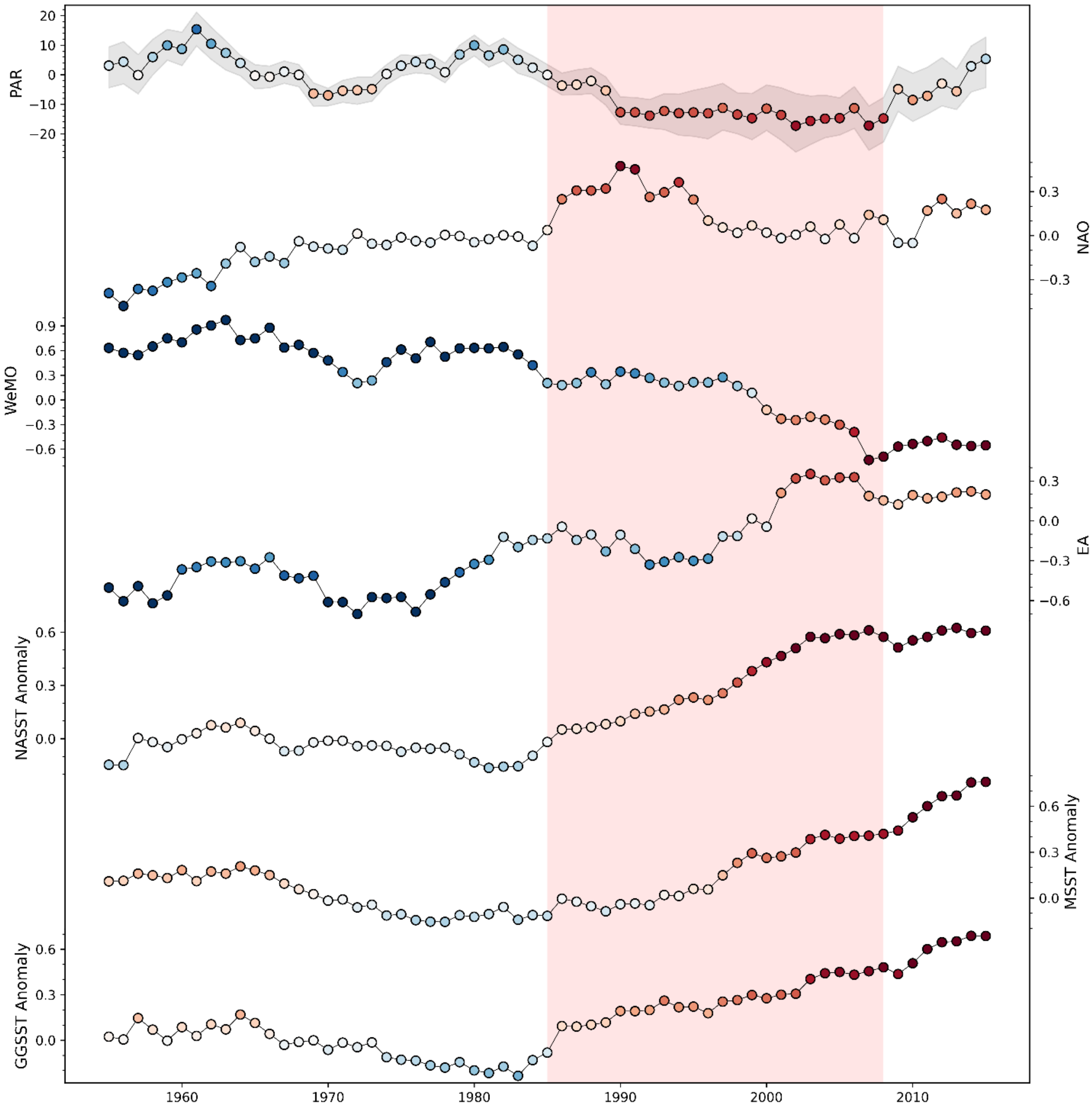


Figure 4. Trends of Percentage Anomaly Rainfall (PAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature (GGSST) for the MAM season. The trends are smoothed by a 10-year mobile window and the colour of the points goes from blue to red: blue is linked to wet periods, red to dry periods. The grey band on PAR represents the 25th and 75th percentiles. The pink band refers to the main dry period of the time series.

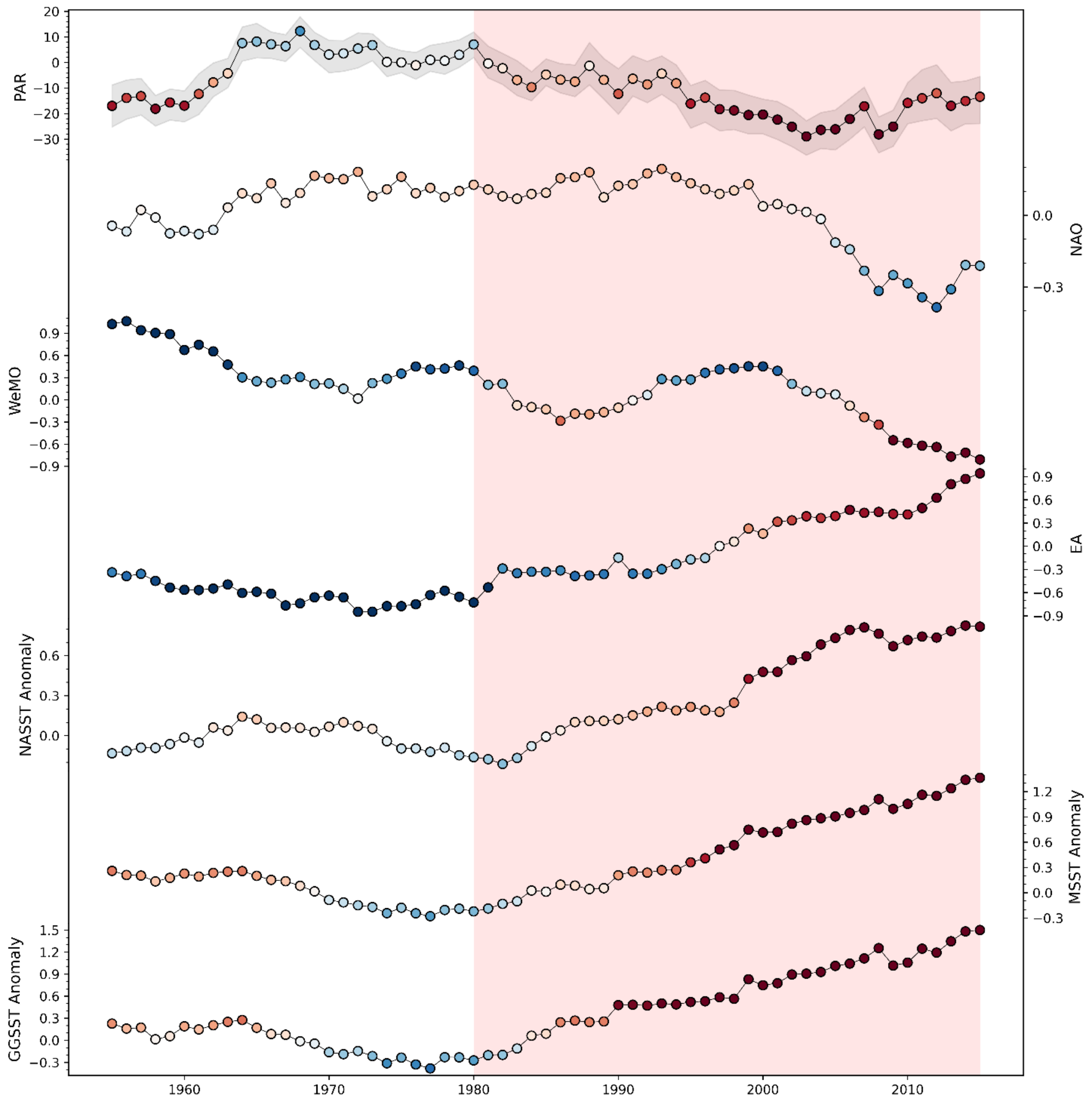


Figure 5. Trends of Percentage Anomaly Rainfall (PAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature (GGSST) for the JJA season. The trends are smoothed with a 10-year mobile window and the colour of the points varies between blue to red: blue is linked to wet periods, while red is linked to dry periods. The grey band on PAR represents the 25th and 75th percentile. The pink band refers to the main dry period of the time series.

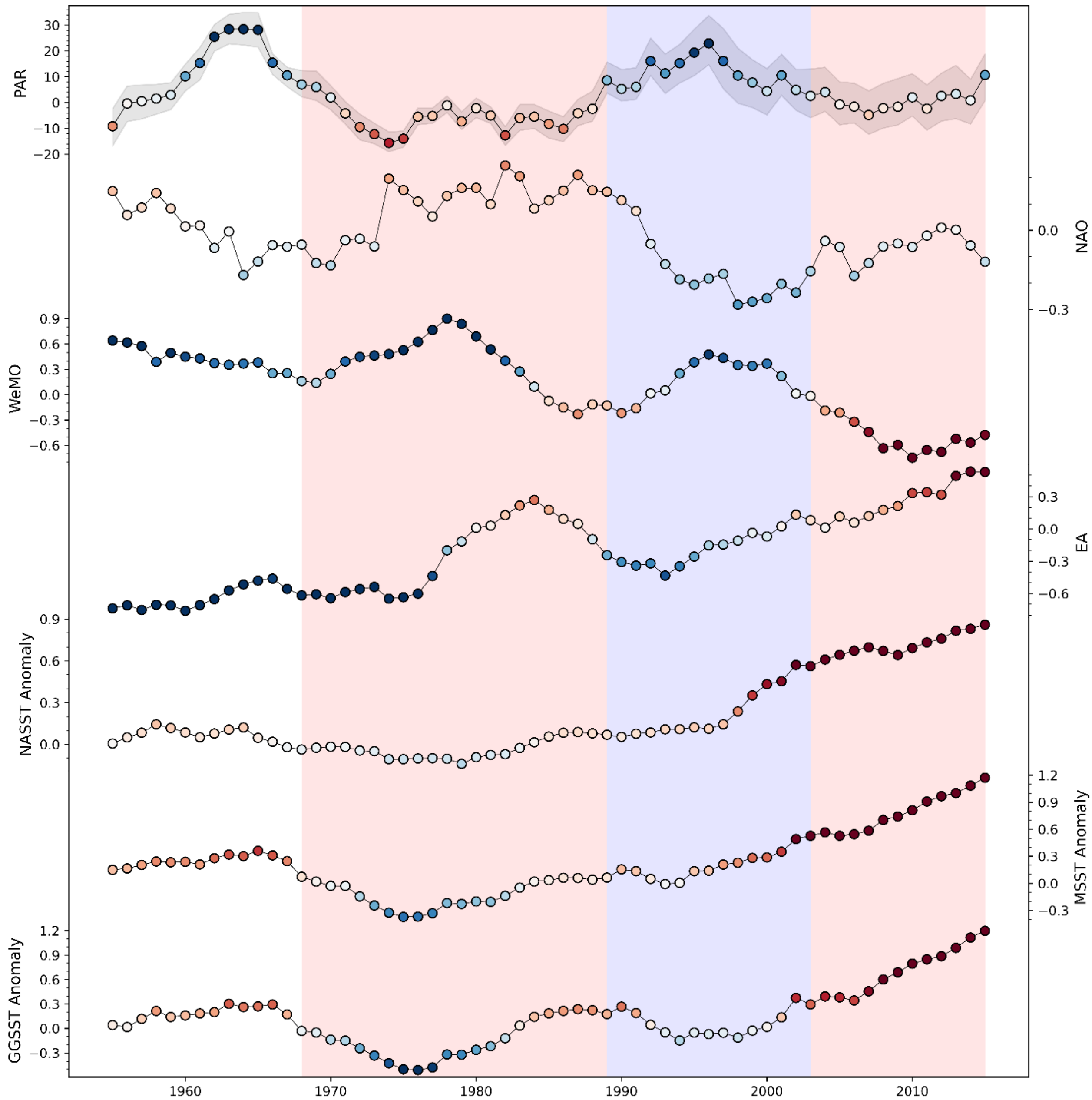


Figure 6 Trends of Percentage Anomaly Rainfall (PAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature (GGSST) for the SON season. The trends are smoothed with a 10-year mobile window and the colour of the points varies between blue to red: blue indicates wet periods, red indicates dry periods. The grey band on PAR represents the 25th and 75th percentile. The pink band is referred to the main dry period of the time series, while the blue band is referred to the main wet period of the time series.

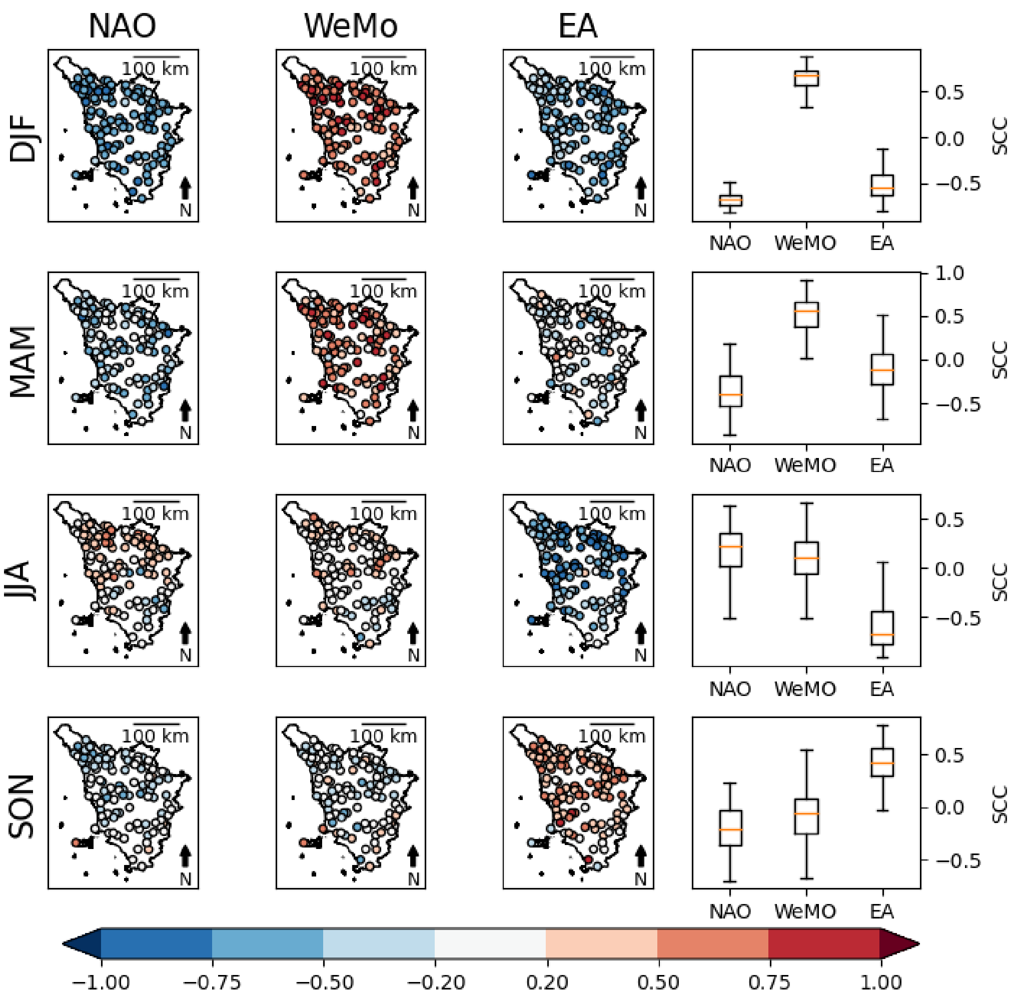


Figure 7. Spearman's correlation coefficients (SCC) between season rainfall and climatic patterns. For each season, we report the correlation with NAO, EA and WeMO and the relative boxplots. The boxes represent the interval between the 25th and 75th percentiles (Q1 and Q3). IQR is the interquartile range Q3-Q1. The upper whisker will extend to the last datum lower than Q3 + 1.5×IQR. Similarly, the lower whisker will reach the first datum higher than Q1 – 1.5×IQR. The orange lines represent the medians (DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November).

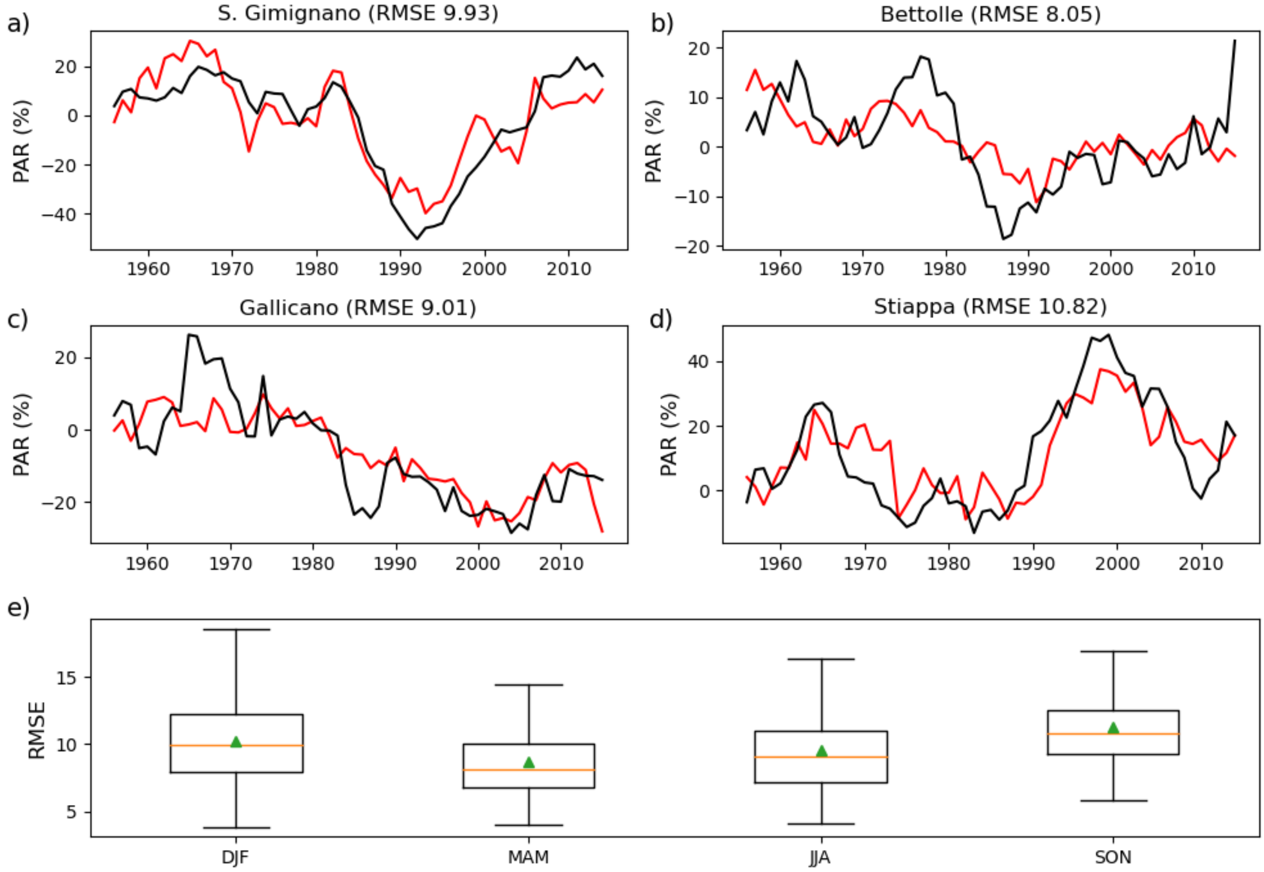


Figure 8. a-d) Four examples of observed PAR (black line) and predicted PAR (red line) respectively for the seasons DJF, MAM, JJA and SON. We selected these examples because they have Root Mean Square Error (RMSE) values similar to the error medians calculated on the whole dataset; e) the boxplots represent the RMSE of the linear models for the four seasons. The boxes represent the interval between the 25th and 75th percentiles (Q1 and Q3). IQR is the interquartile range Q3-Q1. The upper whisker will extend to the last datum lower than Q3 + 1.5×IQR. Similarly, the lower whisker will reach the first datum higher than Q1 – 1.5×IQR. The orange lines represent the medians, while the green triangles represent the means (DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November).

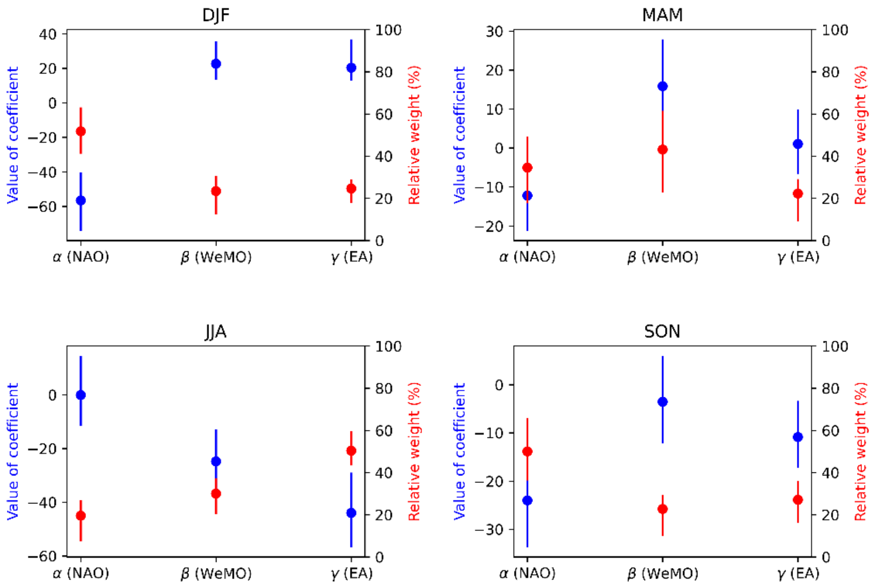


Figure 9. Setting of the linear model coefficients used to understand the relationship between climate patterns and rainfall. The blue circle is the mean absolute value of the coefficient, whereas the red circle represents the mean relative weight of the coefficient on the prediction. The results are reported for each season. The blue and red lines represent the interval between the 25th and 75th percentiles of the coefficient distributions (DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November).

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Conflicts of Interest
The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Cover letter

Dear Editor of Journal of Hydrology,

I am submitting a manuscript for consideration of publication in Journal of Hydrology. The manuscript is entitled “Influence of large-scale atmospheric circulation on the rainfall of a key Mediterranean area: how does current global change affect the rainfall regime?”.

It has not been published elsewhere and that it has not been submitted simultaneously for publication elsewhere.

The work aim is to understand the variation of the rainfall trend in the last 70 years in an important area of the Mediterranean. The study area is influenced by the most important cyclonic and anticyclonic dynamics of the Northern Hemisphere, which are represented by North Atlantic Oscillation, East Atlantic, and Western Mediterranean Oscillations. The study of the influences of these climatic patterns is very important in the contest of the current climate change. The study demonstrated a clear reduction of rainfall during the warm period of the year. This is in accordance with several studies, and the rainfall trend is explained with the pattern trends.

We think that the article may be of interest to your journal as it belongs to the category of hydrometeorology.

Thank you very much for your consideration.

Yours Sincerely,

Dr. Marco Luppichini

University of Pisa

Via Santa Maria 53, 56126 Pisa, Italy

E-mail: marco.luppichini@unifi.it

Seasonal rainfall trends ~~Influence of large-scale atmospheric circulation on~~ of ~~the rainfall of~~ a key Mediterranean area in relation~~ship~~ to~~with the~~ large-scale atmospheric circulation: how does current global change affect the rainfall regime?

Marco Luppichini[1,2,*], Monica Bini[2,3,4], Michele Barsanti[5], Roberto Giannecchini[2,4,6], Giovanni Zanchetta[2,4,7]

[1] Department of Earth Sciences, University of Study of Florence, Via La Pira 4, Florence, Italy

[2] Department of Earth Sciences, University of Pisa, Via S. Maria, 52, 56126 Pisa, Italy

[3] Istituto Nazionale di Geofísica e Vulcanologia (INGV), Via Vigna Murata 605, 00143 Roma, Italy

[4] CIRSEC Centro Interdipartimentale di Ricerca per lo Studio degli Effetti del Cambiamento Climatico dell'Università di Pisa, Via del Borghetto 80, 56124 Pisa, Italy

[5] Department of Civil and Industrial Engineering, University of Pisa, Largo L. Lazzarino, 56122 Pisa, Italy

[6] Institute of Geosciences and Earth Resources, IGG-CNR, via Moruzzi 1, 56124 Pisa, Italy

[7] Istituto di Geologia Ambientale e Geoingegneria, IGAG-CNR, Rome, Italy

Abstract

Current global warming causes a change in atmospheric dynamics, with consequent variations in the rainfall regimes. Understanding the relationship between global climate patterns, global warming, and rainfall regimes is crucial for the creation of future scenarios and for the relative modification of water management. The aim of this study is to improve ~~the~~ knowledge of the relationship ~~of~~ between North Atlantic Oscillation (NAO), East Atlantic (EA), and Western Mediterranean Oscillation (WeMO) with the seasonal rainfalls in Tuscany, Italy. The study area occupies a strategic position since it lies in a transition zone between the wet area of northern Europe and the dry area of the northern coast of Africa. This research, based on a statistical correlation method and on linear models, is designed to understand the relationship between seasonal rainfalls and climate patterns. The results of this study demonstrate that ~~The method ofof~~ the use of linear models ~~innovative in this thematic area,~~ can yield more information than traditional statistical correlations. The results show a ~~possible~~ decrease in rainfall in the warm period of the year, namely in the summer, when its expression is most visible. This phenomenon is ascribable to current global warming, which causes an increase in sea-surface temperatures. An increase in the Northern Atlantic Sea Surface Temperature ~~(SST)~~ and in the Mediterranean Sea Surface Temperature ~~(SST)~~ causes a reduction of the Iceland Low, with an extension of the Azores

High. Moreover, an increase in the Genoa Gulf SST induces a weakening of the Genoa Gulf Low, one of the main cyclogenetic systems of the Mediterranean.

Keywords: Climatic Patterns, Current Global Warming, East Atlantic, North Atlantic Oscillation, Western Mediterranean Oscillation, rainfall trend, Tuscany.

Introduction~~ and goals~~

Current global warming causes effects at different scale levels, including changes in the hydrological cycle (Allan, 2011; Bates et al., 2008). The effects are visible in air temperature trends and, more ~~complexively~~generally, in rainfall, in the form of frequency and intensity of extreme events and changes in soil moisture (Blöschl et al., 2019; Stagl et al., 2014; Xu et al., 2011), with wide implications in terms of socio~~al-~~economic conditions and financial policy (European Environment Agency, 2019). The Mediterranean region is an ideal research testbed for current climatic changes both for its location ~~and ~~for its historico-cultural importance, and for having been considered a hot spot for future climatic changes (Giorgi, 2006). The Mediterranean, located between the European humid domain and the North African arid belt, provides alternating circulation regimes with large spatial and temporal variability (Dünkeloh and Jacobeit, 2003). ~~Furthermore, the highly populated and industrialized Mediterranean region shows an increase in the demand of water supply. ~~In this context, a correct characterization of rainfall regimes can improve the management of water resources (Tramblay et al., 2020) and of extreme events (Cardoso Pereira et al., 2020; Myhre et al., 2019). Several studies have identified a general decrease (although with some exceptions) in the annual rainfall amount in the area of the Mediterranean basin (Bertola et al., 2019; Blöschl et al., 2019; Caloiero et al., 2018, 2011; Colantoni et al., 2015; Deitch et al., 2017; Dünkeloh and Jacobeit, 2003; Halifa-Marín et al., 2021; Longobardi and Villani, 2010; Martin-Vide and Lopez-Bustins, 2006; Philandras et al., 2011; Ríos-Cornejo et al., 2015); and atmospheric patterns related to mesoscale circulation (Brandimarte et al., 2011; Caloiero et al., 2011; Halifa-Marín et al., 2021; Lopez-Bustins et al., 2008; Luppichini et al., 2021; Martinez-Artigas et al., 2021; Ríos-Cornejo et al., 2015; Trigo et al., 2004).

During the winter months, one of the main drivers of rainfall variability in southern Europe and in the Mediterranean is the presence of different pressure fields over the Northern Atlantic Ocean and their variability indicated as the North Atlantic Oscillation (NAO) (Hurrell, 1995). NAO is defined by an index measured as a north-southern dipole of pressure anomalies, with one pole located at higher latitudes (Iceland Low 80°N) and the other at the central latitudes of the North Atlantic between 35°N and 40°N (Azores High).

The East Atlantic (EA) index is similar to that of NAO but is displaced south-eastward to the approximate nodal lines of the NAO pattern. The EA index is often interpreted as a downward-shifted NAO model, but its strong subtropical link entails a different peculiarity. The EA value is positive when a significant drop in pressure occurs in the

Atlantic Ocean; at the same time, the subtropical oceanic anticyclone belt considerably rises in latitude and ~~reinforces~~ strengthens~~itself~~. In response, the African anticyclone gains energy and invasiveness over the Mediterranean, subjecting this area to frequent pulses of hot and dry Saharan air in all seasons (Climate Prediction Center, 2021; Mellado-Cano et al., 2019). The NAO and EA indexes present interannual and annual variabilities with positive and negative phases. The rainfall in the Mediterranean can be associated with a negative phase of NAO and/or EA, when we observe an expansion of the Iceland Low. Instead, during a positive phase of NAO and/or EA, Northern Europe is the rainiest area (Rousi et al., 2020). Both NAO and EA are influenced by the Sea Surface Temperature (SST) of the Northern Atlantic Ocean (NASST) and of the Mediterranean (MSST). An increase in NASST and in MSST is correlated to an expansion of the Azores High and to a consecutive reduction of the Iceland Low, which cause a formation of the NAO and EA positive phases (Frankignoul et al., 2003; Robertson et al., 2000; Visbeck et al., 2001). More recently, NAO has been correlated to the Atlantic Multidecadal Oscillation (AMO), a representative index of the NASST trend (Knight et al., 2005). AMO changes the zonal position of the NAO centre of action, moving the cyclonic area closer to Europe or to North America. During a positive phase of AMO, the Icelandic Low moves further towards North America, while the Azores High moves further towards Europe (and vice versa) for the negative phase of AMO (Börgel et al., 2020). The statistical correlation between the NAO and the winter rainfalls in Europe varies over time (Vicente-Serrano and López-Moreno, 2008) and it is a function of NAO and AMO with a different role of the indices from northern Europe to the Mediterranean (Luppichini et al., 2021).

Formatted: Font color: Auto

The Western Mediterranean oscillation (WeMO) is an index often used to study variability in rainfall in alternative to NAO in the Mediterranean region. The WeMO index is the difference of atmospheric pressure in a dipole, with the first pole located in Padua (45.40◦N, 11.48◦E) in northern Italy and the second one located in San Fernando, Cádiz (36.28◦N, 6.12◦W) in southwestern Spain (Climatic Research Unit, 2021). Specifically, the former is located in the Po plain (an area with relatively high barometric variability due to the different influence of the central European anticyclone and of the Genoa Gulf Low), while the latter pole is located in the Gulf of Cádiz in the southwest of the Iberian Peninsula, often subject to the influence of the Azores anticyclone and, episodically, to the cut-off of circumpolar lows or to its own cyclogenesis (Halifa-Marín et al., 2021; Lopez-Bustins et al., 2020; Martin-Vide and Lopez-Bustins, 2006). A positive phase of WeMO is associated with a low-pressure area in the Ligurian Sea and with an anticyclone in the Gulf of Cadiz. Instead, a negative phase of the index determines a low in the Gulf of Cadiz and an anticyclone in Central Europe. ~~During the positive phase, in the Iberian Peninsula the winds are typically west and northwest coming from the North Atlantic area. These winds cross the continental areas of the peninsula, and become dry, causing rainfall on the north-western coasts and the inland. Conversely, a negative WeMO phase is associated with humid air masses travelling over the Mediterranean Sea. When these winds reach the eastern side of the Iberian~~

~~Peninsula, they are laden with moisture, resulting in an increase in rainfall, sometimes torrential, in this~~WeMO is influenced by NASST and MSST, but also by the Genoa Gulf Sea Surface Temperature (GGSST), with positive values correlating to low values of SST (Martín et al., 2012; Martin-Vide and Lopez-Bustins, 2006).

~~Both NAO and EA are influenced by the Sea Surface Temperature (SST) of the Northern Atlantic Ocean (NASST) and of the Mediterranean (MSST). An increase in NASST and in MSST is correlated to an expansion of the Azores High and to a consecutive reduction of the Iceland Low, which cause a formation of the NAO and EA positive phases. More recently, NAO has been correlated to the Atlantic Multidecadal Oscillation (AMO), a representative index of the NASST trend. AMO changes the zonal position of the NAO center of action, moving the cyclonic area closer to Europe or North America. During a positive phase of AMO, the Icelandic Low moves further towards North America, while the Azores High moves further towards Europe (and viceversa) for the negative phase of AMO. WeMO is also influenced by the NASST and MSST, but also by the Genoa Gulf Sea Surface Temperature (GGSST), with positive values correlating to low values of SST. C~~Current global warming causes a progressive increase in NASST, MSST and GGSST (Pastor et al., 2020; Wang and Dong, 2010) so that NAO and EA are likely to be characterized by more positive phases, and WeMO by more negative phases.

The purpose of this study is to understand the rainfall seasonal trends of the last 70 years in Tuscany (central Italy), in relation to mesoscale circulation and to the indices defined above. ~~The region has a strategic location: it is located in the northern sector of the Mediterranean, in the proximity of the Genoa Gulf, by far the most .~~The rainfall dataset ~~used~~ employed ~~came~~ derives from several raingauges with high spatial density and temporal activity ~~from 1950 to 2020. The large number of raingauges allowed us to~~ which allow us to investigate the rainfall trend in great detail and with direct measurements. ~~The same dataset was used by Luppichini et al. (2020), who employed different types of elaboration to understand the variable influence of NAO on the Tuscany rainfall.~~ The rainfall trends are compared with the NAO, EA and WeMO indices by means of mathematical and statistical methods, so as ~~-~~to understand the climatic trends influencing the rainfall regime in the area. ~~.~~We investigated the link between the different indices by using traditional statistical methods ~~. We investigated the link between the different indices by using traditional statistical methods~~ (Spearman, 1904)~~, but also by introducing in this field an innovative approach, which employs a linear model to understand the influence of each index on the rainfall prediction. The combination of these different methods helped us to comprehend the accuracy and the advantages of the new method proposed.~~

~~In our study, we compared these SSTs with the atmospheric indices to improve knowledge on the rainfall trend and to understand possible future scenarios.~~

Many land dynamics (e.g., drought, floods, solid transport, coastal erosion) are linked to the rainfall regime which can create management criticalities (e.g., Billi and Fazzini, 2017; Bini et al., 2021; Piccarreta et al., 2004). The study of variations in the amount of rainfall related to climatic indices allows to lay the foundations for future studies and land management. The observations put forward in this work and the methods adopted could be extended to other Mediterranean areas by increasing knowledge about these issues.

~~**In our study, we compared these SSTs with the atmospheric indices to improve knowledge on the rainfall trend and to understand possible future scenarios.**~~

~~**Study area**~~~~**The region has a strategic location: it is located in the northern sector of the Mediterranean, in the proximity of the Genoa Gulf, by far the most active cyclogenetic centre of the Mediterranean.**~~

~~**As expected, the mean annual precipitation (MAP) in Tuscany is influenced by morphology (Figure 1a). The rainiest areas are located at the highest altitudes (Apuan Alps and Northern Apennines; Figure 1b). In particular, the Apuan Alps in north-western Tuscany show some of the highest rainfall amounts in Italy, often characterized by high intensity. In Tuscany, MAP is in a range of 400-3000 mm/year with a clear gradient from the northern to the southern and it is linked to the morphology (Figure 1a). The main rainy season is autumn, with a progressive decrease that generally starts in December. The mean rainfall in the DJF season is ca 300 mm, ca 250 mm in MAM, ca 130 mm in JJA, and ca 350 mm in SON.**~~

~~**FIGURE 1**~~

Formatted: Heading 1

Formatted: Heading 1

Formatted: English (United States)

Field Code Changed

Formatted: English (United States)

Formatted: English (United States)

~~Materials and~~ Methods

~~The same dataset was used by Luppichini et al. (2020), who employed different types of elaboration to understand the variable influence of NAO on the Tuscany rainfall.~~

Formatted: Heading 1

Study area

Tuscany has a strategic location because it is located in the northern sector of the Mediterranean, in the proximity of the Genoa Gulf, by far the most active cyclogenetic centre of the Mediterranean (Trigo et al., 2002).

As expected, the mean annual precipitation (MAP) in Tuscany is influenced by morphology (Figure 1a). The rainiest areas are located at the highest altitudes (Apuan Alps and Northern Apennines; Figure 1b). In particular, the Apuan Alps in north-western Tuscany show some of the highest rainfall amounts in Italy (Giannecchini and D'Amato Avanzi, 2012; Rapetti and Vittorini, 1994), often characterized by high intensity (D'Amato Avanzi et al., 2004; Giannecchini, 2006). In Tuscany, MAP is in a range of 400-3000 mm/year with a clear gradient from the northern to the southern and it is linked to the morphology (Figure 1a). The main rainy season is autumn, with a progressive decrease that generally starts in December. The mean rainfall in the DJF season is ca 300 mm, ca 250 mm in MAM, ca 130 mm in JJA, and ca 350 mm in SON.

FIGURE 1

Formatted: English (United Kingdom)

Dataset

Rainfall dataset and processing

The raingauge dataset was provided by the Tuscany Region Hydrologic Service (SIR) network and includes 1103 raingauges (Figure 1c). The daily data were obtained by an automated download procedure through an HTTP request in March 2021. The dataset is the best one available in this area and it is managed by the SIR which validates and checks the data. The dataset is used in several research works because it is referenced and managed by a public body. In particular, Luppichini et al. 2021 used this dataset to understand the relationship between NAO and winter rainfall in this area. The activity period of each raingauge is variable. The older stations have been monitoring since the beginning of the last century, even if a temporal continuity of the data is not always guaranteed for some stations. SIR provides the daily rainfall data for each raingauge in the operation period. To obtain longer and more complete time series from this dataset, we grouped the stations according to a stringent protocol. This procedure is necessary to reconstruct the time series of the stations that have experienced minor changes in position or that have undergone an administrative variation (e.g., a slight change in name or identification code). ~~In many cases, s~~The stations have consecutive intermittent activity times due to the decommissioning of one and the subsequent installation of a new one. In these cases, we merged the stations by assigning the same, or part of the same name, with a difference in ~~quote~~ altimetry (less than 20%) of the measurement, and a maximum distance (less than 2 km). The geographic coordinates of the merged stations derived from a cartesian mean of the original coordinates of the origin stations.

By using the data available and following the procedure described above, a total of 117 time series were obtained from 1950 to 2020. The rainfall data can also be useful for comparison with the results of the linear models ~~(see section Linear Models),~~ which predict rainfall anomalies~~;~~. ~~instead, t~~The ~~absolute values~~ rainfall values are expressed as percentage anomalies of rainfall (PAR), and are calculated as follows:

$$PAR_{s,i} = \frac{x_{s,i} - \bar{x}_i}{\bar{x}_i} \cdot 100 \qquad (1)$$

Formatted: Centered

where, $x_{s,i}$ is the annual seasonal rainfall amount of the i-th year and s-th season, $\bar{x}_i$ is the annual rainfall amount mean of the period 1961-1990.

-The values of *PAR* are calculated for the four seasons: winter (DJF: December, January and February); spring (MAM: March, April and May –); summer (JJA: June, July and August); autumn (SON: September, October and November). ~~The *PA*~~ Mean Average PAR (MAPAR) is ~~the averaged with a~~ a ten-year mobile ~~window~~average of PAR calculated for each season, and the values are associated with the central year~~.~~. We chose to use a ten-year mobile average because this time range is within the standard 10–30 year time scale considered to be decadal variability (Meehl et al., 2009).

Formatted: Indent: First line: 0"

Climatic Dataset

The NAO dataset is provided by the Climate Analysis Section of the US National Center for Atmospheric Research (NCAR). This dataset is based on the principal (PC)-based index component of the NAO, which are the time series of the leading Empirical Orthogonal Function (EOF) of SLP anomalies over the Atlantic sector, 20°-80°N, 90°W-40°E. This index is used to measure the yearly NAO, by tracking the seasonal movements of the Icelandic Low and Azores High. The dataset has a monthly frequency from January 1889 to December 2020. PC-based indices are more optimal representations of the full spatial patterns of the NAO (National Center for Atmospheric Research Staff (Eds), 2021).

The EA dataset used in this study is provided by the National Weather Service of NOAA. The frequency of the dataset is on a monthly basis, from 1950 to 2020. The index is standardized by ~~the~~ 1981-2010 climatology (Climate Prediction Center, 2021).

The WeMO index is provided by the Climatic Research Unit (CRU) of the University of East Anglia (Climatic Research Unit, 2021). The time series start~~s~~ed in 1821 and has a monthly frequency.

The trends of NASST, MSST, and GGSST are calculated from the Extended Reconstructed Sea Surface Temperature (ERSST) dataset version 5 (NOAA, 2021), and they are expressed using a 10-year mobile window of anomalies. The anomalies are referred to the mean of the ~~period~~ 1961-1990 period. NASST is calculated in the area 0N-65N 80W-0E;~~,~~ MSST in the area 38N-49N 0E-28E;~~,~~ and GGSST in the area 42.8N-44.8N 7.6E-10.76E.

Statistical Correlation and Linear Models

. We investigated the link between the different indices by using traditional statistical methods (Spearman, 1904), but also by introducing in this field an innovative approach, which employs a linear model to understand the influence of each index on the rainfall prediction. The combination of these different methods helped us to comprehend the accuracy and the advantages of the new method proposed.

Formatted: English (United States)

We calculated the correlation coefficient ~~in order~~ to identify a possible relationship between atmospheric teleconnection and rainfall amount. Several authors use a statistical method of correlation to quantify the relationship between atmospheric indices and rainfalls (Brandimarte et al., 2011; Faust et al., 2016; Kalimeris et al., 2017; Kotsias et al., 2020; Koyama and Stroeve, 2019; López-Moreno et al., 2011; Vicente-Serrano and López-Moreno, 2008). In particular, ~~S~~some authors (Caloiero et al., 2011; Izquierdo et al., 2014; Luppichini et al., 2021; Nalley et al., 2019; Vergni et al., 2016) use ~~the~~ Spearman's correlation coefficient (SCC) (Spearman, 1904) to understand the relationship between atmospheric index and rainfall amount. This relationship is suitable for monotonically-related variables, even when their relationship is not linear. The range of Spearman's coefficients is between -1 and 1; positive values indicate a tendency of one variable to increase or decrease together with another variable, whereas negative values indicate a trend in which the increase in the values of one variable is associated with the decrease in the values of the other variable, and vice versa. We have divided the time series into four seasons~~We calculated the SCC between the three atmospheric teleconnections and the rainfall for the four seasons~~: winter from December to February (DJF), spring from March to May (MAM), summer from June to August (JJA) and autumn from September to November (SON). We calculated the SCC among the three atmospheric teleconnections and the rainfall for the four seasons using a 10-year moving time window from 1950 to 2020. We assigned the correlation result to the year halfway through each ten-years. ~~SCC was calculated using a 10-year moving time-window from 1950 to 2020. The result of the correlation was assigned to the year halfway through each ten-year period.~~

However, the trends in the time series can influence the SCC (Arianos and Carbone, 2009; Boris et al., 2009; Iqbal et al., 2020; Podobnik and Stanley, 2008). To exclude the influence of the trends on the results of this study, we investigated further using the detrended cross-correlation analysis (DCCA) proposed by ~~(~~Kristoufek, (2014) in the framework developed by ~~(~~Ide et al.~~,~~ (2017). The DCCA results are in perfect agreement with the SCC results. Therefore, we could exclude an influence of the trends on the use of SCC in this study. More information can be found in the supplementary material.

~~Linear Models~~

~~The simplest mathematical model is the linear one.~~ We can create linear models capable ~~to~~ of predicting the rainfall amount by using the NAO, WeMO and EA time series. The equation of a linear model predicting the rainfall (R_p), ~~by using the NAO, WeMO and EA time series,~~ is the following:

$$R_p = \alpha NAO + \beta WeMO + \gamma EA + \delta \qquad (\cancel{1}2)$$

We can analyse the best estimates ~~setting of the independent variable coefficients~~of the model parameters (α, β, γ) to understand the role of each input ~~on~~ in the prediction of rainfall. If we want to obtain the best prediction models, we should use models that are more complex than a simple linear model. However, ~~T~~the simplicity of the linear models ~~does not allow to have the best prediction models, but it certainly~~ allows to analyse the influence of the inputs~~.~~, since one of the tasks of this work is to show that more complex models (for instance with the inclusion of synergies between the input data) are not necessary to explain the rainfall observed. ~~input clearly and to exclude synergy between the inputs, and this is the main of this work.~~ We therefore created a linear model for each raingauge time series for each season. ~~We created a linear model for each raingauge time series and for the four seasons.~~ The different ~~dimensionality~~ range of the three atmospheric teleconnections could influence the information expressed by the parameters of models α, β and δ. For this reason, we scaled the time series of NAO, WeMO and EA in the range between 0 and 1 for the studied period (1950-2020), by applying the following equation:

$$T\cancel{s} = \frac{Ts - Ts_m}{Ts_M - Ts_m} \qquad (\cancel{3}3)$$

where $T\cancel{s}$ is the index time series in the ~~range~~ 0~~- and~~ 1 range, Ts_M is the maximum value of the index, and Ts_m is the minimum value of the index.~~-~~ We fitted a linear model for each time series,~~The fitting of the linear models is executed~~ using the SciPy library in Python Language and, in more detail, the "curve_fit" method (Virtanen et al., 2020). We validated the fits calculating the Root Mean Square Error (*RMSE*) and the Correlation Coefficient (*r*) as follows~~The quality valuation of the models is done calculating Root Mean Square Error (RMSE) and Correlation Coefficient (r) as following:~~

Formatted: English (United States)

Formatted: English (United States)

Formatted: English (United States)

Formatted: Not Highlight

Formatted: Not Highlight

Formatted: Not Highlight

Formatted: Not Highlight

Formatted: Not Highlight

Formatted: Not Highlight

$$RMSE = \left(\frac{1}{N}\sum_{i=0}^{N}(F_i - V_i)^2\right)^{0.5} \quad (4)$$

$$r = \frac{\left(\frac{1}{N}\sum_{i=0}^{N}(F_i * V_i)\right)}{\left(\frac{1}{N}\sum_{i=0}^{N}F_i^2\right)^{0.5} \cdot \left(\frac{1}{N}\sum_{i=0}^{N}V_i^2\right)^{0.5}} \quad (5)$$

where F_i are the forecast values, V_i are the observed values and N the number of years.

Results

Rainfall Trends

Figure 2 reports the values of PAR calculated for each time series used in this work, and obtained from equation 1. The graphs indicate a small variability of PAR between each time series, excluding the possibility of different influences on the linear model outcomes by the input stations and a significant variability in the study area. The MAPAR of the study area is shown in Figures 3-6 for the four seasons. ~~The rainfall trends expressed in PAR are shown in Figures 3-6.~~ These ~~trends~~ variations of MAPAR over time are~~are very~~ different in the four seasons. From 1950 to 1985, the DJF season was characterized by a slow rainfall reduction followed by a sudden decrease around the 90's. The first years of the 1990's presented a MAPAR reduction of ~~about 30~~ -40%. Starting from 2000, the DJF MAPAR increased ~~we can observe a~~ progressively ~~progressive increase in winter rainfall with~~ until reaching~~a return of~~ the amount recorded before 1990 (Figure 3). Until the 1990s, the MAM ~~rainfall trend~~MAPAR was ~~identified~~ characterized by an oscillation, ~~. F~~from the 1990's to the 2010's, ~~we observe~~ MAM MAPAR ~~values~~ has the minimum values which are in the range between ~~ca~~ -10 and -20%. ~~After 2008,~~ MAM MAPAR ~~there was an~~ increased after 2008 ~~in precipitation~~ (Figure 4). The JJA MAPAR started to ~~season was characterized by a progressive reduction~~ decrease ~~of rainfall starting from~~ in 1965 with ~~the~~ minimum values of -30% around 2005. The last years were marked by a weakly increase of JJA MAPAR ~~in rainfall~~ (Figure 5). ~~Finally, rainfall in the SON season presented~~ SON MAPAR had a ~~a~~ certain variability over an approximate 20-year period. The maximum ~~rainfall~~ SON MAPAR amount was recorded around 1965 and 1995, while the minimum values were ~~referred~~ those of~~to~~ the period 1970-1990 (Figure 6).

FIGURE 2

Atmospheric Teleconnection Trends

In DJF, NAO was characterized by an intensification of the positive phase, the EA time series was characterized by an intensification of the positive phase starting from 1985 (Figure 3), and WeMO was characterized by a positive phase with a decrease in the 1990-2010 period.

In MAM, NAO and EA time series were characterized by a progressive increase with an intensification of the positive phase; WeMO has experienced a progressive decrease from a positive phase to a negative persistence phase since 2005 (Figure 4).

In JJA, NAO was characterized by a positive phase until 2005, whereas the index was characterized by a negative phase, except for some years. In this season, EA started to increase progressively in 1995, while WeMO had a progressive decrease with a persistence positive phase since 2005 (Figure 5).

In SON, NAO is variable with periods characterized by negative alternated with positive phases. In this season, EA had a higher index fluctuation, with a negative phase until 1980, followed by a more positive ten-year phase and then by a negative phase until 2000. From 2000 to 2020, EA increased reaching its maximum values. WeMO was characterized by two distinct positive phases around 1975 and 1995, but the overall trend has decreased with a negative phase since 2005 (Figure 6).

Formatted: English (United States)

~~From 1950 to 2020, NAO was characterized by an intensification of the positive phase in the DJF and MAM seasons (Figures 3 and 4). In the JJA season, NAO was characterized by a positive phase until 2005, whereas the index was characterized by a negative phase, except for some years. Finally, NAO was more variable in the SON season with periods characterized by negative alternated with positive phases (Figure 6).~~

Formatted: Heading 2

~~From 1950 to 2020, the EA time series was characterized by an intensification of the positive phase starting from 1985 for the DJF period (Figure 3), and from 1995 for the MAM and JJA periods (Figures 4 and 5). The SON period presented a higher index fluctuation, with a negative phase until 1980, followed by a more positive ten-year phase and then by a negative phase until 2000. From 2000 to 2020, we can observe an increase in the positive phase except for some cases (Figure 6).~~

~~In DJF, WeMO was characterized by a positive phase with a decrease in the 1990-2010 period (Figure 3). Around 2005 we observed a drastic change in the WeMO index in the MAM, JJA and SON seasons with a negative persistence phase (Figures 4-6). Before 2005, the index in these seasons was characterized by positive phases except for some years in which the values of the index were negative (Figures 4-6).~~

Sea surface temperature trends

~~Figures 3-6 show t~~The ~~trends~~ variations of NASST, MSST and GGSST ~~display~~ started to display a clear increasing trend ~~starting~~ in ~~from~~ the 1980's in all seasons. Such increase only started around the 2010's for DJF and GGSST, while it started to increase~~d~~ ~~st~~in the~~arting~~ ~~from~~ 1980s in the other seasons. The increase in SST was ~~higher~~ greater in the summer than in the other seasons (Figures 3-6).

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

Statistical Correlation

Figure 7 reports the results obtained from ~~the Spearman's correlation coefficient~~SCC~~.~~ and Figure 8 shows the spatial distribution of the p-values obtained. In the DJF season, rainfall is correlated with WeMO and anticorrelated with NAO and EA. Rainfall increases during a negative phase of NAO or EA and a positive phase of WeMO. During this period, each atmospheric teleconnection has a similar effect on the rainfall amount. In the MAM season, the strongest correlation is with WeMO, and even in this case a positive phase of the index corresponds to a rainfall increase in the study area. NAO and EA are weakly anticorrelated with the rainfall amount. The strongest correlation is with EA in the JJA season, and a negative phase of this index indicates an increase in rainfall in the area~~.~~ ~~On other hand,~~, while a positive phase of EA corresponds to reduced precipitation in summer. NAO and WeMO are weakly correlated with ~~the~~ rainfall, but do not ~~have~~ show a clear behaviour. Even in the SON season, the strongest correlation is with EA. The correlation in this season is positive, which indicates that a positive EA phase determines increased precipitation in the area. The spatial correlation distribution is homogenous with no clear spatial pattern, especially when the correlations are strong, providing a precise indication of the relationship (Figure 7).

FIGURE 7

FIGURE 8

Formatted: Highlight

Linear Models

In Figure 9a-d, we report four examples of the MAPAR prediction ~~of PAR~~ by means of linear models referred to the DJF, MAM, JJA and SON seasons. The cases shown represent the results of the lineal models because they have ~~Root Mean Square Error (~~RMSE~~)~~ values similar to the error medians calculated on the ~~whole~~ entire dataset (Figure 9e). For the case shown in Figure 9a, α, β and γ are respectively -96.56, 42.53, and 4.85; for the case reported in Figure 9b they are -21.39, -15.54 and -15.76, for the case reported in Figure 9c they are -30.71, -56.10 and -1.34; for the case reported in Figure 9c they are -48.05, 7.54 and 6.71. Figure 9e and 9d also report~~s~~ the RMSE and r o~~o~~f the entire dataset. SON, followed by MAM, which is the season with the highest average errors.

Figure 10 shows the mean values of coefficients α, β and γ for the linear models in each season (blue circles). We can observe a change in the values of the three coefficients from one season to another. In Figure 10, ~~T~~the red circles ~~in Figure 9~~ show the relative weights of each coefficient. In the DJF season, the coefficient with the greatest weight is α with a mean value of about 55%, followed by β and γ. The coefficients indicate that NAO has more influence on the rainfall trend than WeMO and EA ~~in~~ on DJF. In this season, the coefficient values indicate that an increase in rainfall~~increased precipitation~~ is linked to a negative phase of NAO (α is negative) and a positive phase of WeMO (β is

Formatted: English (United States)

positive). ~~A positive γ is not to be understood as a positive link between rainfall and index, but it works as a compensation with respect to the α coefficient in the model.~~ In the MAM season, β (WeMO) has the highest weight in the results of the models, followed by α (NAO) and γ (EA). Therefore, ~~In particular,~~ the coefficients denote that the amount of ~~precipitation~~ rainfall is correlated with a positive phase of WeMO and with a negative phase of NAO. ~~Again~~Also in this season, EA has less influence on the model than the other two indices. In the JJA season EA is the index with ~~the most important index, with~~ the greatest coefficient (γ). In particular, the coefficients suggest that the summer rainfall is ~~seems to be~~ linked to a negative phase of EA. Less important, the coefficients indicate that the summer rainfall is linked to a negative phase of WeMO. In the SON season, NAO has the greatest weight and is followed by WeMO and EA, which have less influence on the rainfall trend. In this case, the coefficients are all negative, so that rainfall is correlated to a negative phase of these indices.

FIGURE 9~~8~~

FIGURE ~~9~~10

Formatted: Highlight

Discussion

Mathematical and statistical relationship between atmospheric teleconnections and rainfall

The statistical correlation calculated with Spearman's method represents a first indication of the influence of climate patterns on the local rainfall trend ~~(Figure 7)~~. In accordance with several studies (Caloiero et al., 2011; Deser et al., 2017; Ferrari et al., 2013; George et al., 2004; López-Moreno et al., 2011; Luppichini et al., 2021; Riaz et al., 2017; Vergni and Chiaudani, 2015; Vicente-Serrano and López-Moreno, 2008; West et al., 2019), NAO influence is predominant in winter, with an anticorrelation between index and rainfall amount. In agreement with the obtained SCC, an increase in the Azores High, and consequently a decrease in the Iceland Low, determine reduced winter rainfall in the study area. The correlation between NAO and rainfall decreases during the successive seasons with a minimum correlation in ~~the~~ summer. In winter and in spring, the correlation with WeMO is strong and it is characterized by a positive sign. This implies the formation of the Genoa Gulf Low and its reinforcement increases the amount of rainfall in the study area. This can be ascribed to the direction of the moist air masses coming from the Atlantic Ocean and directed to the north-western coast of Spain and to the Mediterranean (Degeai et al., 2020; Martín et al., 2012; Martin-Vide and Lopez-Bustins, 2006). In this dynamic state the moist air masses can reach Tuscany, enhancing local cyclogenesis and rainfall. The SCC values indicate that the influence of the Genoa Gulf Low decreases in summer and autumn ~~(Figure 7)~~. The correlation between rainfall and EA is strong in winter and summer; in summer, the ~~main~~ correlation with rainfall is ~~particularly~~ mainly with EA. In winter, the link between EA and rainfall is the same for

NAO. In summer, the greater representativeness of EA than of NAO on the Azores High allows a better understanding of the link between rainfall and global climate in this season. In detail, the formation of the Azores High and of the African High results in an increase in the EA index, and this means that there is reduced precipitation in the study area. In autumn, the statistical correlations do not allow to ~~make~~ create a link between large-scale circulation and rainfall. Indeed, we can observe a weak anticorrelation with NAO, a weak correlation with EA, and no correlation with WeMO. This method seems unsuitable to represent the autumn season with its atmospheric dynamics.

The results of the linear models are conformant to the statistical correlation results for the DJF, MAM and JJA seasons, ~~whereas~~ while we ~~can~~ observe some differences in SON. The strong correspondence between the two methods in DJF, MAM and JJA makes it possible to validate our linear model. In autumn, the analysis of the linear models identifies an important role of NAO, and therefore a link between ~~the~~ northern Atlantic atmospheric circulation and ~~the~~ rainfall in the study area. In autumn, the coefficients of NAO (α) are set negative and this means that an increase in the index is linked to a decrease in rainfall in the study area. This mathematical result is more plausible than that obtained from the analysis of correlations based on the notions of atmospheric physics ~~that we~~ introduced previously. The linear model-based method has allowed us to refine our investigations and to improve our knowledge of the dynamics in the Mediterranean over the seasons.

The use of our linear models offers the advantage of clarifying the role and influence of large-scale atmospheric circulation on rainfall over the study region in different seasons, and this may appear controversial when using only the statistical correlation. These linear methods can also be useful for rainfall prediction, although it is not the ~~intention~~ aim of this paper to produce the best model for predictions. A more complex model may be better suited to reduce the overall model; ~~If we wanted to reduce the model errors, we should have chosen a more complex model able to better adapt to the variability of the inputs;~~ however, it would have been difficult to understand the influence of each input parameter, which is the main scope of this paper.

Long-term rainfall trends and relation~~ship~~ with climate patterns

This study has identified a confused trend for the DJF, MAM and SON rainfall, while the JJA rainfall clearly tends to decrease ~~(Figures 3-6)~~. These results agree with those of other studies based on different rainfall datasets (Caloiero et al., 2018; Deitch et al., 2017; Philandras et al., 2011). More specifically, Deitch et al. (2017) studied the seasonal trend of rainfall in the Mediterranean area, demonstrating a negative trend for summer rainfall and no trend for winter/autumnal rainfall in Tuscany.

The DJF seasons are characterized by significantly decreased precipitation between 1984 and 2005 (Figure 3). This period is marked by a positive phase of NAO and EA and a negative phase of WeMO. Starting around 1984, the increase in NAO and EA is due to an increase in NASST (Figure 3). An increase in NASST is correlated to an expansion of the Azores High and a consecutive reduction of the Iceland Low, resulting in the formation of the NAO and EA positive phases (Börgel et al., 2020; Frankignoul et al., 2003; Robertson et al., 2000; Visbeck et al., 2001). The successive increase in rainfall from 2005 to 2020 seems to have been caused by an increase in the WeMO, and therefore by an increase in the Genoa Gulf Low persistence. This could indicate a change of the main climatic driver with respect to the previous period (Figure 3).

The MAM season presents a decrease in the amount of rainfall in the period between 1985 and 2008 (Figure 4). The WeMO constantly decreases with progressive intensification of the negative phase. This indicates a gradual reduced intensity of the Genoa Gulf Low. ~~As a matter of fact, t~~The GGSST has progressively increased since 1985. Furthermore, NAO and EA are in a persistent positive phase. Since 2008, there has been a weak increase in the precipitation trend.

The JJA rainfall trends have the highest correlation with EA, while NAO and WeMO have a lower influence (Figure 7 and ~~9~~10). The increase in NASST, MSST and GGSST induces the NAO and EA indices to a positive phase, and WeMO to a negative phase. This process induces a progressive reduction of rainfall trends in this season.

SON is characterized by rainfall trend variability with two wet periods and two dry periods (Figure 6). Each dry period is marked by an increase in NAO, whereas the wet period results from an increase in WeMO linked to a weak decrease in GGSST (Figure 6).

The increase in sea surface temperature is greater in the warm periods of the year and it is caused by current global warming. From these observations, we can evince that the warm periods of the year are marked by a greater decrease in precipitation resulting in less water availability in the environmental system.

Conclusions

This study helps to gain a better knowledge of the rainfall trends of the last 70 years in Tuscany, a key area of the Mediterranean Basin, strongly influenced by the cyclogenetic activity related to the Genoa Gulf Low. These trends are analyzed on the basis of the trend of the main atmospheric drivers of the northern hemisphere. The location of the study area allows to understand the influences of Atlantic atmospheric circulation and of the Mediterranean atmospheric circulation on rainfall. Along with ~~the~~ Spearman's traditional coefficient analysis, this study proposes a new mathematical method to investigate the relationship between climate pattern and rainfall. The method based on the use of linear models has resulted to be valid, with similar results derived from a statistical correlation. This new method has allowed for a more detailed comprehension of the link between climate patterns and precipitation in the study area. In Tuscany, the rainfall amount is influenced by Northern Atlantic atmospheric circulation and by the Genoa Gulf Low.

The influences of the two atmospheric systems vary during the year: in winter, rainfall is strongly correlated to the three indices; in spring, the main influence is represented by WeMO, indicating an important role played by the Genoa Gulf Low; in summer, the main driver is EA, which represents better than NAO the influence of the Azores High in this season; in autumn, the strongest correlation is with NAO.

The amount of ~~precipitation~~ rainfall in the study area is influenced by the SSTs ~~that~~ which induce a variation in the Northern Atlantic and Mediterranean atmospheric circulations (Börgel et al., 2020; Frankignoul et al., 2003; Robertson et al., 2000; Visbeck et al., 2001). Current global warming determines an increase in the SSTs and this increase is higher in the warm seasons of the year (James et al., 2006). The results of this study show that in these seasons there is the greatest reduction of water availability, on account of a direct decrease in precipitation. For this reason,

~~In conclusion,~~ current global warming ~~can~~ could be responsible for less rainfall in this area, and this occurs mainly in the warm seasons when temperature increase is highest. These aspects can be deepened by future studies that can strengthen the relationships found and the considerations made in this work.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Acknowledgements: The authors are grateful to the Tuscany Region Hydrologic Service for providing the data used in this work.

Funding: This research was funded by project no. 249792 "Dalla Preistoria all'Antropocene: Nuove Tecnologie per la valorizzazione dell'eredità culturale della Versilia (PANTAREI)" Tuscany Region (call POR FSE 2014-2020, Resp. M. Bini); by the collaborative research agreement no. 579999-2019 "Autorità di Bacino Distrettuale Appennino Settentrionale" (Resp. Monica Bini and Roberto Giannecchini); and by the project: "Cambiamenti globali e impatti locali: conoscenza e consapevolezza per uno sviluppo sostenibile della pianura Apuo-versiliese" Fondazione Cassa Risparmio di Lucca, (Resp. M. Bini).

Reference

Allan, R.P., 2011. Human influence on rainfall. Nature 470, 344–345. https://doi.org/10.1038/470344a

Arianos, S., Carbone, A., 2009. Cross-correlation of long-range correlated series. Journal of Statistical Mechanics: Theory and Experiment 2009, P03037.

Bates, B., Kundzewicz, Z.W., Wu, S., Burkett, V., Doell, P., Gwary, D., Hanson, C., Heij, B., Jiménez, B., Kaser, G., Kitoh, A., Kovats, S., Kumar, P., Magadza, C.H.D., Martino, D., Mata, L., Medany, M., Miller, K., Arnell, N., 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change.

Bertola, M., Viglione, A., Hall, J., Blöschl, G., 2019. Flood trends in Europe: are changes in small and big floods different? Hydrology and Earth System Sciences Discussions 1–23. https://doi.org/10.5194/hess-2019-523

Billi, P., Fazzini, M., 2017. Global change and river flow in Italy. Global and Planetary Change 155, 234–246. https://doi.org/https://doi.org/10.1016/j.gloplacha.2017.07.008

Bini, M., Casarosa, N., Luppichini, M., 2021. Exploring the relationship between river discharge and coastal erosion: An integrated approach applied to the pisa coastal plain (italy). Remote Sensing 13. https://doi.org/10.3390/rs13020226

Blöschl, G., Hall, J., Viglione, A., Perdigão, R.A.P., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G.T., Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G.B., Claps, P., Frolova, N., Ganora, D., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T.R., Kohnová, S., Koskela, J.J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Salinas, J.L., Sauquet, E., Šraj, M., Szolgay, J., Volpi, E., Wilson, D., Zaimi, K., Živković, N., 2019. Changing climate both increases and decreases European river floods. Nature 573, 108–111. https://doi.org/10.1038/s41586-019-1495-6

Börgel, F., Frauen, C., Neumann, T., Meier, H.E.M., 2020. The Atlantic Multidecadal Oscillation controls the impact of the North Atlantic Oscillation on North European climate. Environmental Research Letters 15.

Boris, P., Davor, H., M, P.A., Eugene, S.H., 2009. Cross-correlations between volume change and price change. Proceedings of the National Academy of Sciences 106, 22079–22084. https://doi.org/10.1073/pnas.0911983106

Brandimarte, L., di Baldassarre, G., Bruni, G., D'Odorico, P., Montanari, A., D'Odorico, P., Montanari, A., 2011. Relation Between the North-Atlantic Oscillation and Hydroclimatic Conditions in Mediterranean Areas. Water Resources Management 25, 1269–1279. https://doi.org/10.1007/s11269-010-9742-5

Caloiero, T., Caloiero, P., Frustaci, F., 2018. Long-term precipitation trend analysis in Europe and in the Mediterranean basin. Water and Environment Journal 32, 433–445. https://doi.org/https://doi.org/10.1111/wej.12346

Caloiero, T., Coscarelli, R., Ferrari, E., Mancini, M., 2011. Precipitation change in Southern Italy linked to global scale oscillation indexes. Nat. Hazards Earth Syst. Sci. 11, 1683–1694. https://doi.org/10.5194/nhess-11-1683-2011

Cardoso Pereira, S., Marta-Almeida, M., Carvalho, A.C., Rocha, A., 2020. Extreme precipitation events under climate change in the Iberian Peninsula. International Journal of Climatology 40, 1255–1278. https://doi.org/https://doi.org/10.1002/joc.6269

Climate Prediction Center, 2021. East Atlantic [WWW Document]. URL https://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml (accessed 9.22.21).

Climatic Research Unit, 2021. Mediterranean Oscillation Indices (MOI) [WWW Document]. URL https://crudata.uea.ac.uk/cru/data/moi/ (accessed 9.22.21).

Colantoni, A., Delfanti, L., Cossio, F., Baciotti, B., Salvati, L., Perini, L., Lord, R., 2015. Soil Aridity under Climate Change and Implications for Agriculture in Italy. Applied Mathematical Sciences 9, 2467–2475. https://doi.org/10.12988/ams.2015.52112

D'Amato Avanzi, G., Giannecchini, R., Puccinelli, A., 2004. The influence of the geological and geomorphological settings on shallow landslides. An example in a temperate climate environment: the June 19, 1996 event in northwestern Tuscany (Italy). Engineering Geology 73, 215–228. https://doi.org/https://doi.org/10.1016/j.enggeo.2004.01.005

Deitch, M.J., Sapundjieff, M.J., Feirer, S.T., 2017. Characterizing Precipitation Variability and Trends in the World's Mediterranean-Climate Areas. Water (Basel) 9. https://doi.org/10.3390/w9040259

Deser, C., Hurrell, J.W., Phillips, A.S., 2017. The role of the North Atlantic Oscillation in European climate projections. Climate Dynamics 49, 3141–3157. https://doi.org/10.1007/s00382-016-3502-z

Dünkeloh, A., Jacobeit, J., 2003. Circulation dynamics of Mediterranean precipitation variability 1948–98. International Journal of Climatology 23, 1843–1866. https://doi.org/https://doi.org/10.1002/joc.973

European Environment Agency, 2019. Economic losses from climate -related extremes in Europe. Indicator Assessment.

Faust, J.C., Fabian, K., Milzer, G., Giraudeau, J., Knies, J., 2016. Norwegian fjord sediments reveal NAO related winter temperature and precipitation changes of the past 2800 years. Earth and Planetary Science Letters 435, 84–93. https://doi.org/https://doi.org/10.1016/j.epsl.2015.12.003

Ferrari, E., Caloiero, T., Coscarelli, R., 2013. Influence of the North Atlantic Oscillation on winter rainfall in Calabria (southern Italy). Theoretical and Applied Climatology 114, 479–494. https://doi.org/10.1007/s00704-013-0856-6

Frankignoul, C., Friederichs, P., Kestenare, E., 2003. Influence of Atlantic SST anomalies on the atmospheric circulation in the Atlantic-European sector. Annals of Geophysics 46.

Formatted: English (United States)

Formatted: English (United States)

George, D.G., Järvinen, M., Arvola, L., 2004. The influence of the North Atlantic Oscillation on the winter characteristics of Windermere (UK) and Pääjärvi (Finland).

Giannecchini, R., 2006. Relationship between rainfall and shallow landslides in the southern Apuan Alps (Italy). Natural Hazards and Earth System Science 6, 357–364. https://doi.org/10.5194/nhess-6-357-2006

Giannecchini, R., D'Amato Avanzi, G., 2012. Historical research as a tool in estimating hydrogeological hazard in a typical small alpine-like area: The example of the Versilia River basin (Apuan Alps, Italy). Physics and Chemistry of the Earth, Parts A/B/C 49, 32–43. https://doi.org/10.1016/J.PCE.2011.12.005

Giorgi, F., 2006. Climate change hot-spots. Geophysical Research Letters 33. https://doi.org/https://doi.org/10.1029/2006GL025734

Halifa-Marín, A., Lorente-Plazas, R., Pravia-Sarabia, E., Montávez, J.P., Jiménez-Guerrero, P., 2021. Atlantic and Mediterranean influence promoting an abrupt change in winter precipitation over the southern Iberian Peninsula. Atmospheric Research 253. https://doi.org/10.1016/j.atmosres.2021.105485

Hurrell, J.W., 1995. Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. Science (1979) 269, 676 LP – 679. https://doi.org/10.1126/science.269.5224.676

Ide, J.S., Cappabianco, F.A., Faria, F.A., Li, C.-S.R., 2017. Detrended Partial Cross Correlation for Brain Connectivity Analysis.

Iqbal, J., Lone, K.J., Hussain, L., Rafique, M., 2020. Detrended cross correlation analysis (DCCA) of radon, thoron, temperature and pressure time series data. Physica Scripta 95, 085213. https://doi.org/10.1088/1402-4896/ab9fb1

Izquierdo, R., Alarcón, M., Aguillaume, L., Àvila, A., 2014. Effects of teleconnection patterns on the atmospheric routes, precipitation and deposition amounts in the north-eastern Iberian Peninsula. Atmospheric Environment 89, 482–490. https://doi.org/https://doi.org/10.1016/j.atmosenv.2014.02.057

James, H., Makiko, S., Reto, R., Ken, L., W, L.D., Martin, M.-E., 2006. Global temperature change. Proceedings of the National Academy of Sciences 103, 14288–14293. https://doi.org/10.1073/pnas.0606291103

Kalimeris, A., Ranieri, E., Founda, D., Norrant, C., 2017. Variability modes of precipitation along a Central Mediterranean area and their relations with ENSO, NAO, and other climatic patterns. Atmospheric Research 198, 56–80. https://doi.org/https://doi.org/10.1016/j.atmosres.2017.07.031

Knight, J.R., Allan, R.J., Folland, C.K., Vellinga, M., Mann, M.E., 2005. A signature of persistent natural thermohaline circulation cycles in observed climate. Geophysical Research Letters 32. https://doi.org/10.1029/2005GL024233

Formatted: English (United States)

Formatted: English (United States)

Formatted: English (United States)

Formatted: English (United States)

Formatted: English (United States)

Kotsias, G., Lolis, C.J., Hatzianastassiou, N., Levizzani, V., Bartzokas, A., 2020. On the connection between large-scale atmospheric circulation and winter GPCP precipitation over the Mediterranean region for the period 1980-2017. Atmospheric Research 233, 104714. https://doi.org/https://doi.org/10.1016/j.atmosres.2019.104714

Koyama, T., Stroeve, J., 2019. Greenland monthly precipitation analysis from the Arctic System Reanalysis (ASR): 2000–2012. Polar Science 19, 1–12. https://doi.org/https://doi.org/10.1016/j.polar.2018.09.001

Kristoufek, L., 2014. Measuring correlations between non-stationary series with DCCA coefficient. Physica A: Statistical Mechanics and its Applications 402, 291–298. https://doi.org/https://doi.org/10.1016/j.physa.2014.01.058

Longobardi, A., Villani, P., 2010. Trend analysis of annual and seasonal rainfall time series in the Mediterranean area. International Journal of Climatology 30, 1538–1546. https://doi.org/https://doi.org/10.1002/joc.2001

Lopez-Bustins, J.A., Arbiol-Roca, L., Martin-Vide, J., Barrera-Escoda, A., Prohom, M., 2020. Intra-annual variability of the Western Mediterranean Oscillation (WeMO) and occurrence of extreme torrential precipitation in Catalonia (NE Iberia). Natural Hazards and Earth System Sciences 20, 2483–2501. https://doi.org/10.5194/nhess-20-2483-2020

Lopez-Bustins, J.-A., Martin-Vide, J., Sanchez-Lorenzo, A., 2008. Iberia winter rainfall trends based upon changes in teleconnection and circulation patterns. Global and Planetary Change 63, 171–176. https://doi.org/https://doi.org/10.1016/j.gloplacha.2007.09.002

López-Moreno, J.I., Vicente-Serrano, S.M., Morán-Tejeda, E., Lorenzo-Lacruz, J., Kenawy, A., Beniston, M., 2011. Effects of the North Atlantic Oscillation (NAO) on combined temperature and precipitation winter modes in the Mediterranean mountains: Observed relationships and projections for the 21st century. Global and Planetary Change 77, 62–76. https://doi.org/https://doi.org/10.1016/j.gloplacha.2011.03.003

Luppichini, M., Barsanti, M., Giannecchini, R., Bini, M., 2021. Statistical relationships between large-scale circulation patterns and local-scale effects: NAO and rainfall regime in a key area of the Mediterranean basin. Atmospheric Research 248, 105270.

Martín, P., Sabatés, A., Lloret, J., Martin-Vide, J., 2012. Climate modulation of fish populations: The role of the Western Mediterranean Oscillation (WeMO) in sardine (Sardina pilchardus) and anchovy (Engraulis encrasicolus) production in the north-western Mediterranean. Climatic Change 110, 925–939. https://doi.org/10.1007/s10584-011-0091-z

Formatted: English (United States)

Formatted: English (United States)

Formatted: English (United States)

Martinez-Artigas, J., Lemus-Canovas, M., Lopez-Bustins, J.A., 2021. Precipitation in peninsular Spain: Influence of teleconnection indices and spatial regionalisation. International Journal of Climatology 41, E1320–E1335. https://doi.org/https://doi.org/10.1002/joc.6770

Martin-Vide, J., Lopez-Bustins, J.-A., 2006. The Western Mediterranean Oscillation and rainfall in the Iberian Peninsula. International Journal of Climatology 26, 1455–1475. https://doi.org/https://doi.org/10.1002/joc.1388

Meehl, G., Goddard, L., Murphy, J., Boer, G., Danabasoglu, G., Dixon, K., Giorgetta, M., Greene, A., Hawkins, E., Hegerl, G., Karoly, D., Kimoto, M., 2009. Decadal Prediction: Can It Be Skillful? Bull Am Meteorol Soc 90, 1467–1485. https://doi.org/10.1175/2009BAMS2778.1

Mellado-Cano, J., Barriopedro, D., García-Herrera, R., Trigo, R.M., Hernández, A., 2019. Examining the North Atlantic Oscillation, East Atlantic Pattern, and Jet Variability since 1685. Journal of Climate 32, 6285–6298. https://doi.org/10.1175/JCLI-D-19-0135.1

Myhre, G., Alterskjær, K., Stjern, C.W., Hodnebrog, Ø., Marelle, L., Samset, B.H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M., Stohl, A., 2019. Frequency of extreme precipitation increases extensively with event rareness under global warming. Scientific Reports 9, 16063. https://doi.org/10.1038/s41598-019-52277-4

Nalley, D., Adamowski, J., Biswas, A., Gharabaghi, B., Hu, W., 2019. A multiscale and multivariate analysis of precipitation and streamflow variability in relation to ENSO, NAO and PDO. Journal of Hydrology 574, 288–307. https://doi.org/https://doi.org/10.1016/j.jhydrol.2019.04.024

National Center for Atmospheric Research Staff (Eds), 2021. The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (PC-based). [WWW Document]. https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based.

NOAA, 2021. Extended Reconstructed SST [WWW Document]. URL https://www.ncei.noaa.gov/products/extended-reconstructed-sst (accessed 9.28.21).

Pastor, F., Valiente, J.A., Khodayar, S., 2020. A warming Mediterranean: 38 years of increasing sea surface temperature. Remote Sensing 12. https://doi.org/10.3390/RS12172687

Philandras, C., Nastos, P., Kapsomenakis, J., Douvis, K., Tselioudis, G., Zerefos, C., 2011. Long Term Precipitation Trends and Variability within the Mediterranean Region. Natural Hazards and Earth System Sciences 11, 3235–3250. https://doi.org/10.5194/nhess-11-3235-2011

Piccarreta, M., Capolongo, D., Boenzi, F., 2004. Trend analysis of precipitation and drought in Basilicata from 1923 to 2000 within a southern Italy context. International Journal of Climatology 24, 907–922. https://doi.org/https://doi.org/10.1002/joc.1038

Podobnik, B., Stanley, H.E., 2008. Detrended Cross-Correlation Analysis: A New Method for Analyzing Two Nonstationary Time Series. Physical Review Letters 100, 84102. https://doi.org/10.1103/PhysRevLett.100.084102

Rapetti, F., Vittorini, S., 1994. Le precipitazioni in Toscana: osservazioni sui casi estremi. RIVISTA GEOGRAFICA ITALIANA 101, 47–76.

Riaz, S.M.F., Iqbal, M.J., Hameed, S., 2017. Impact of the North Atlantic Oscillation on winter climate of Germany. Tellus, Series A: Dynamic Meteorology and Oceanography 69. https://doi.org/10.1080/16000870.2017.1406263

Ríos-Cornejo, D., Penas, Á., Álvarez-Esteban, R., del Río, S., 2015. Links between teleconnection patterns and precipitation in Spain. Atmospheric Research 156, 14–28.

Robertson, A.W., Mechoso, C.R., Kim, Y.-J., 2000. The Influence of Atlantic Sea Surface Temperature Anomalies on the North Atlantic Oscillation. Journal of Climate 13, 122–138. https://doi.org/10.1175/1520-0442(2000)013<0122:TIOASS>2.0.CO;2

Rousi, E., Rust, H.W., Ulbrich, U., Anagnostopoulou, C., 2020. Implications of Winter NAO Flavors on Present and Future European Climate. Climate 8, 13. https://doi.org/10.3390/cli8010013

Spearman, C., 1904. The proof and measurement of association between two things. The American Journal of Psychology 15, 72–101. https://doi.org/10.2307/1412159

Stagl, J., Mayr, E., Koch, H., Hattermann, F.F., Huang, S., 2014. Effects of Climate Change on the Hydrological Cycle in Central and Eastern Europe BT - Managing Protected Areas in Central and Eastern Europe Under Climate Change, in: Rannow, S., Neubert, M. (Eds.), . Springer Netherlands, Dordrecht, pp. 31–43.

Tramblay, Y., Llasat, M.C., Randin, C., Coppola, E., 2020. Climate change impacts on water resources in the Mediterranean. Regional Environmental Change 20, 83. https://doi.org/10.1007/s10113-020-01665-y

Trigo, I.F., Bigg, G.R., Davies, T.D., 2002. Climatology of Cyclogenesis Mechanisms in the Mediterranean.

Trigo, R.M., Pozo- Vázquez, D., Osborn, T.J., Castro- Díez, Y., Gámiz- Fortis, S., Esteban- Parra, M.J., Pozo-Vázquez, D., Osborn, T.J., Castro-Díez, Y., Gámiz-Fortis, S., Esteban-Parra, M.J., 2004. North Atlantic Oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. International Journal of Climatology: A Journal of the Royal Meteorological Society 24, 925–944. https://doi.org/10.1002/joc.1048

Vergni, L., Chiaudani, A., 2015. RELATIONSHIP BETWEEN THE NAO INDEX AND SOME INDICES OF EXTREME PRECIPITATION IN THE ABRUZZO REGION.

Formatted: English (United States)

Formatted: English (United States)

Vergni, L., di Lena, B., Chiaudani, A., 2016. Statistical characterisation of winter precipitation in the Abruzzo region (Italy) in relation to the North Atlantic Oscillation (NAO). Atmospheric Research 178–179, 279–290. https://doi.org/https://doi.org/10.1016/j.atmosres.2016.03.028

Vicente-Serrano, S.M., López-Moreno, J.I., 2008. Nonstationary influence of the North Atlantic Oscillation on European precipitation. Journal of Geophysical Research: Atmospheres 113. https://doi.org/10.1029/2008JD010382

Virtanen, P., Gommers, R., Oliphant, T.E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S.J., Brett, M., Wilson, J., Millman, K.J., Mayorov, N., Nelson, A.R.J., Jones, E., Kern, R., Larson, E., Carey, C.J., Polat, \.Ilhan, Feng, Y., Moore, E.W., VanderPlas, J., Laxalde, D., Perktold, J., Cimrman, R., Henriksen, I., Quintero, E.A., Harris, C.R., Archibald, A.M., Ribeiro, A.H., Pedregosa, F., van Mulbregt, P., SciPy 1.0 Contributors, 2020. SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. Nature Methods 17, 261–272. https://doi.org/10.1038/s41592-019-0686-2

Visbeck, M.H., Hurrell, J.W., Polvani, L., Cullen, H.M., 2001. The North Atlantic Oscillation: Past, present, and future. Proceedings of the National Academy of Sciences 98, 12876. https://doi.org/10.1073/pnas.231391598

Wang, C., Dong, S., 2010. Is the basin-wide warming in the North Atlantic Ocean related to atmospheric carbon dioxide and global warming? Geophysical Research Letters - GEOPHYS RES LETT 37. https://doi.org/10.1029/2010GL042743

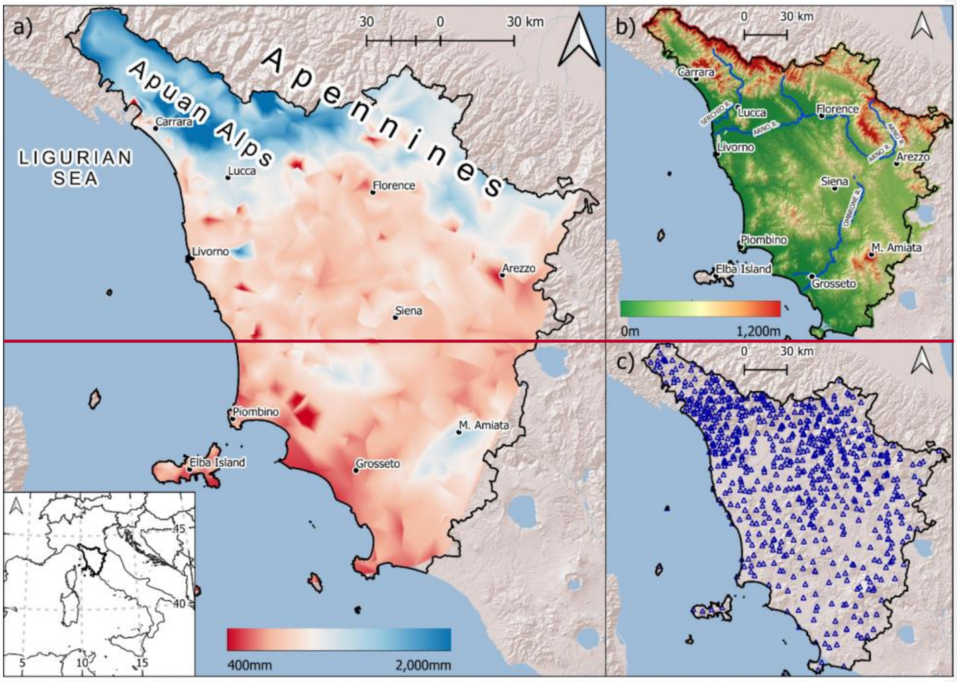
West, H., Quinn, N., Horswell, M., 2019. Regional rainfall response to the North Atlantic Oscillation (NAO) across Great Britain. Hydrology Research 50, 1549–1563. https://doi.org/10.2166/nh.2019.015

Xu, H., Taylor, R.G., Xu, Y., 2011. Quantifying uncertainty in the impacts of climate change on river discharge in sub-catchments of the Yangtze and Yellow River Basins, China. Hydrol. Earth Syst. Sci. 15, 333–344. https://doi.org/10.5194/hess-15-333-2011

Formatted: English (United States)

Formatted: English (United States)

652 **Figures**


a)
30
0
30 km
Apennines
Apuan Alps
LIGURIAN SEA
Carrara
Lucca
Florence
Livorno
Arezzo
Siena
Piombino
M. Amiata
Elba Island
Grosseto
45
40
5
10
15
400mm
2,000mm
b)
0
30 km
SERCHIO R.
ARNO R.
OMBRONE R.
0m
1,200m
c)
0
30 km

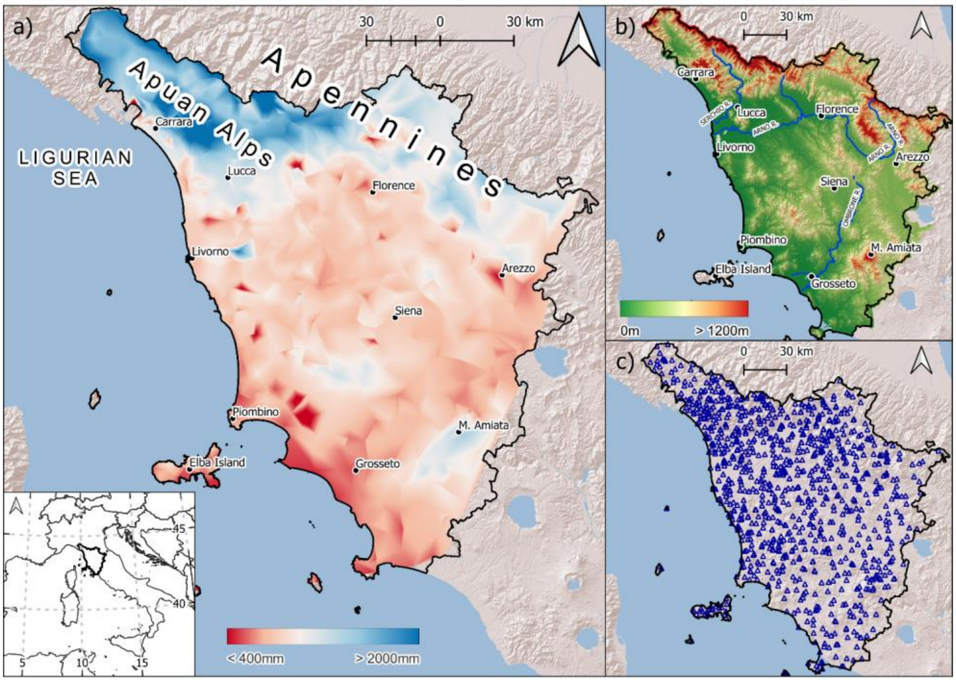
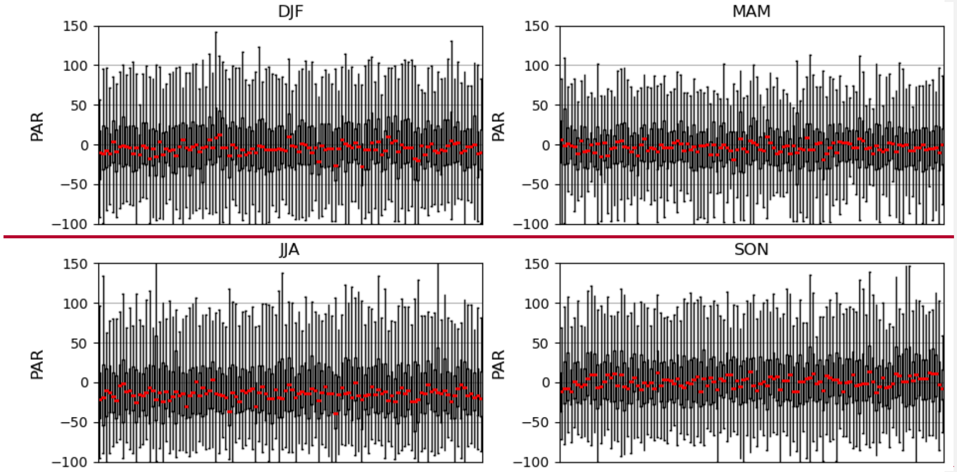

a)
30
0
30 km
Apennines
Apuan Alps
LIGURIAN SEA
Carrara
Lucca
Florence
Livorno
Arezzo
Siena
Piombino
M. Amiata
Elba Island
Grosseto
45
40
5
10
15
< 400mm
> 2000mm
b)
0
30 km
SERCHIO R.
ARNO R.
OMBRONE R.
0m
> 1200m
c)
0
30 km

Figure 1. a) mean annual precipitation (MAP) of Tuscany linked to the morphology: the rainiest areas correspond to the mountainous areas; b) morphology of Tuscany; c) the 1103 raingauges of the Tuscany Region Hydrologic Service network used in this work.



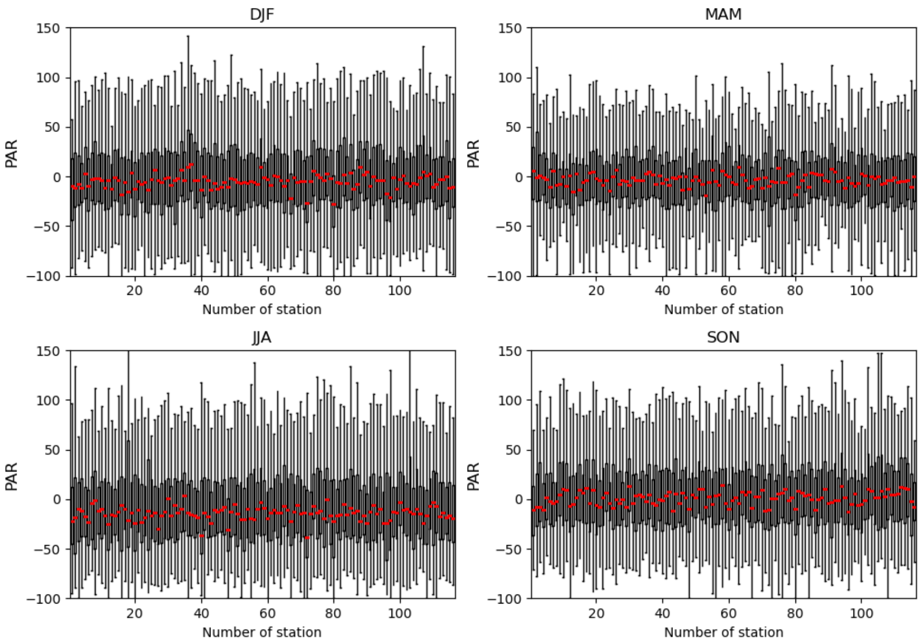
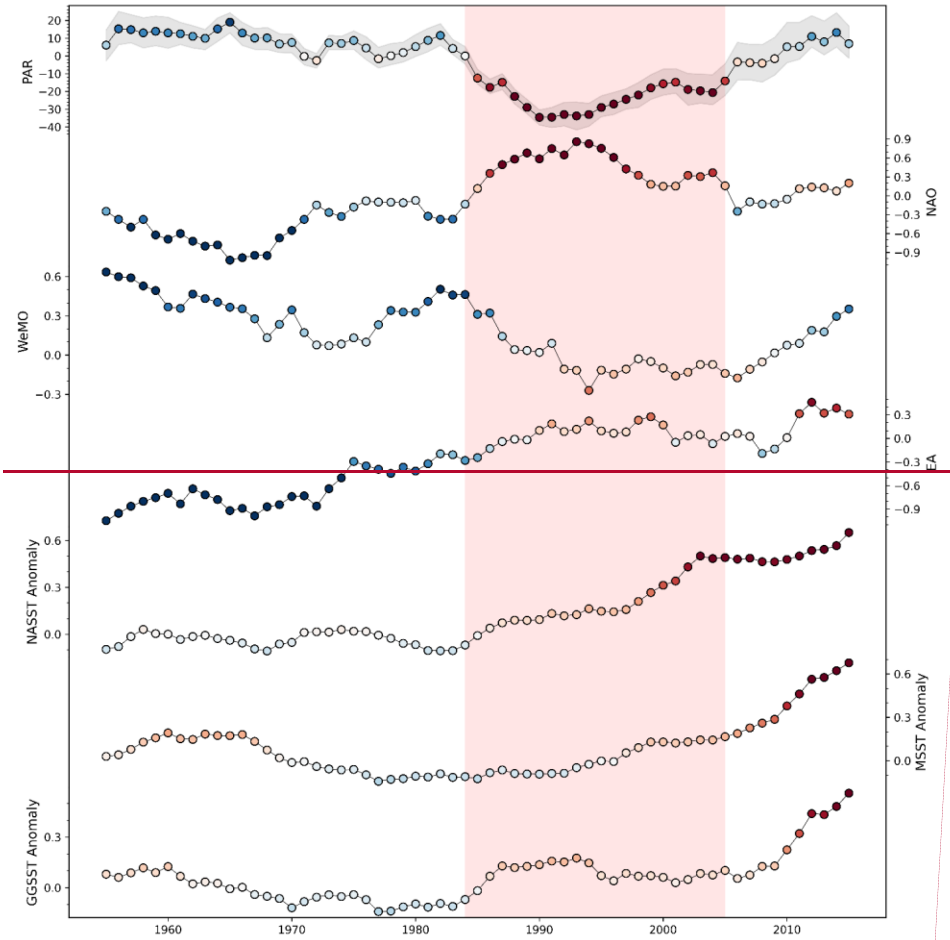


Figure 2. For the four seasons, Percentage Anomaly of Rainfall (PAR) of the 117 rainfall time series used in this work~~, calculated for the four seasons~~. Each boxplot is referred to a rainfall time series and represents the distribution of

rainfall anomaly values with respect to the annual rainfall amount of the 1961-1990 period, in agreement with the equation 1 in the text. The boxes represent the interval between the 25th and 75th percentiles (Q1 and Q3). IQR is the interquartile range Q3-Q1. The upper whisker will extend to the last datum lower than Q3 + 1.5×IQR. Similarly, the lower whisker will reach the first datum higher than Q1 – 1.5×IQR. The red lines represent the medians (DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November).

668 

Commented [ml1]: Cambiare fig MAPAR

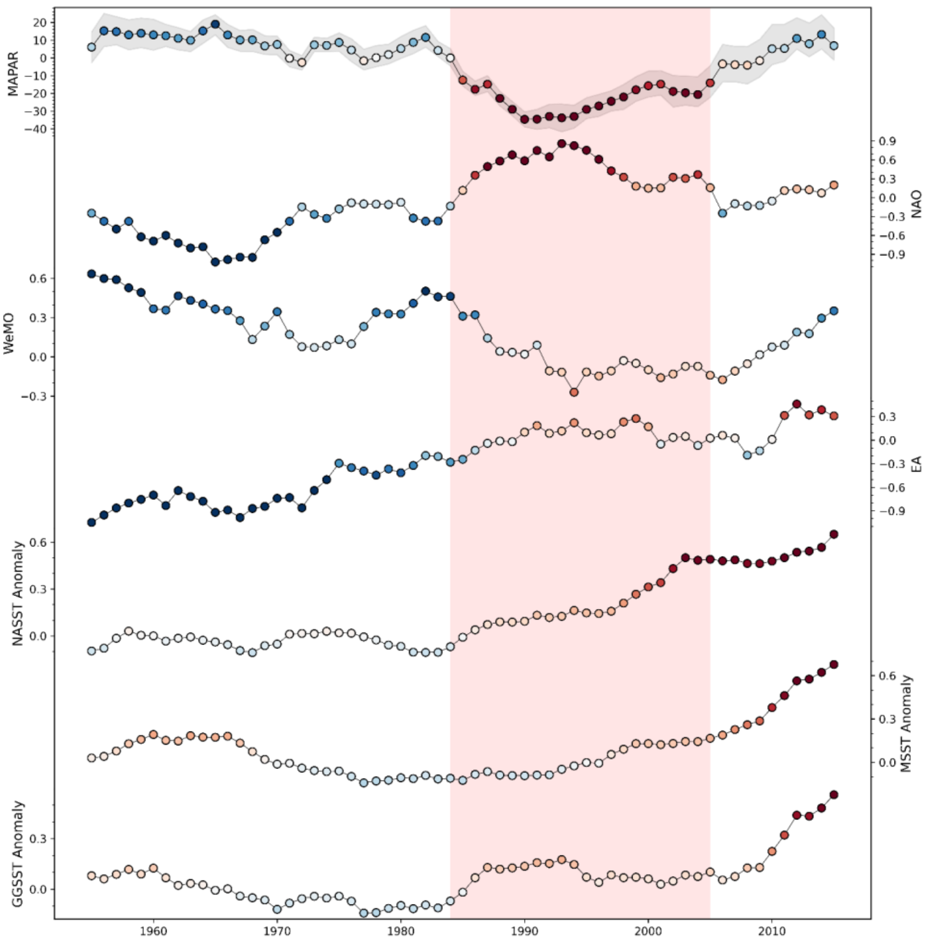
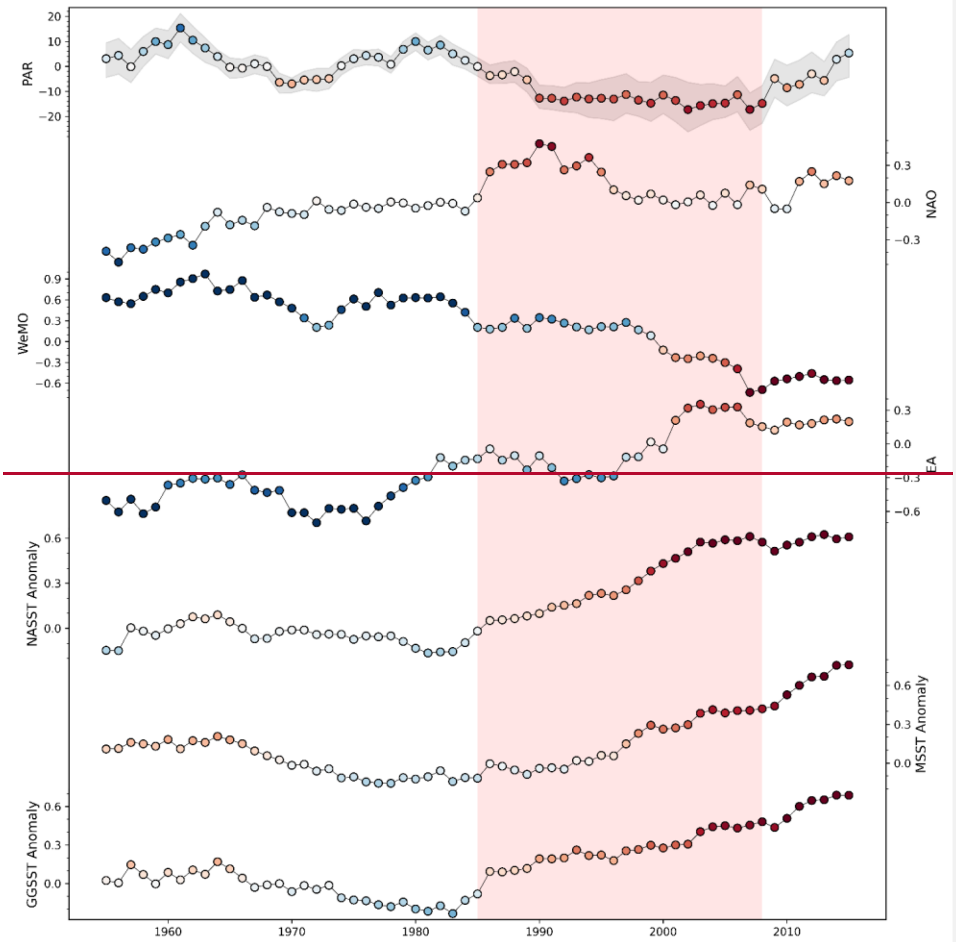


Figure 3. DJF season, t~~T~~rends of Mobile Average Percentage Anomaly Rainfall (MAPAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature (GGSST) ~~for the DJF season~~. The trends are smoothed by a 10-year mobile window and the colour of the points varies between blue and red: blue is linked to wet periods, red to dry periods. The grey band on MAPAR represents the 25th and 75th percentile, the dots represent the mean value. The pink band is referred to the main dry period of the time series.

Formatted: Font: Not Bold

676



PAR
NAO
WeMO
EA
NASST Anomaly
MSST Anomaly
GGSST Anomaly
1960
1970
1980
1990
2000
2010

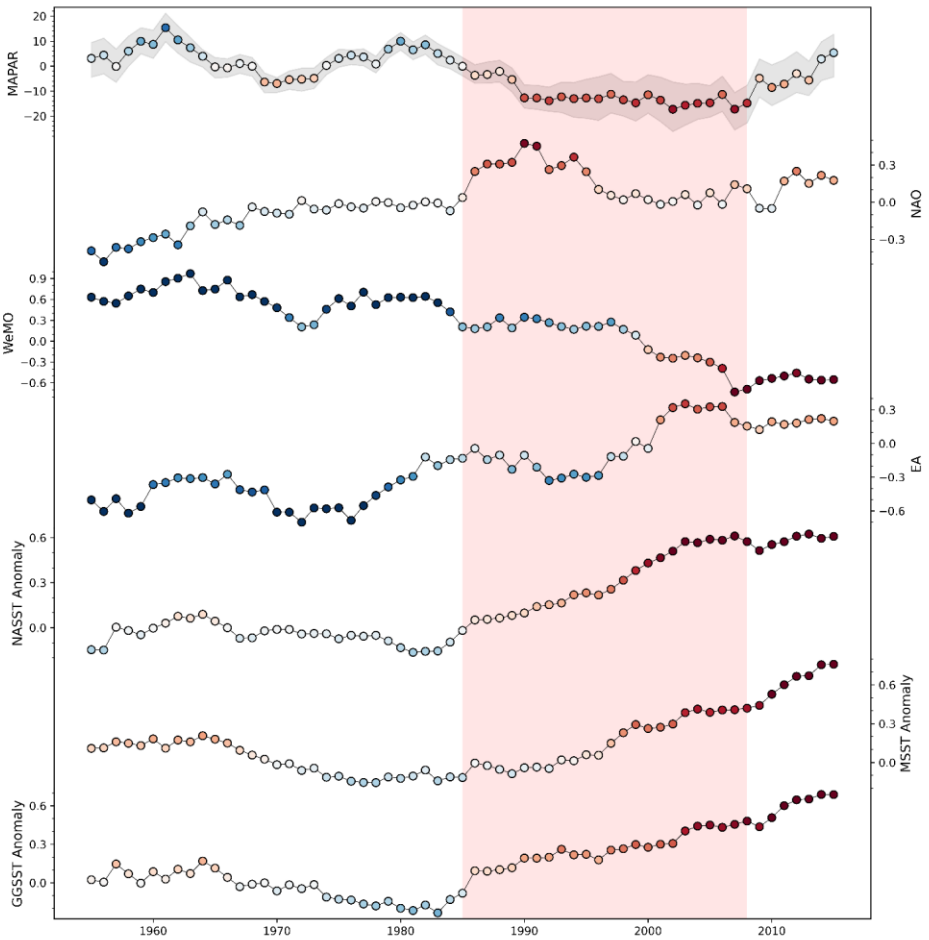
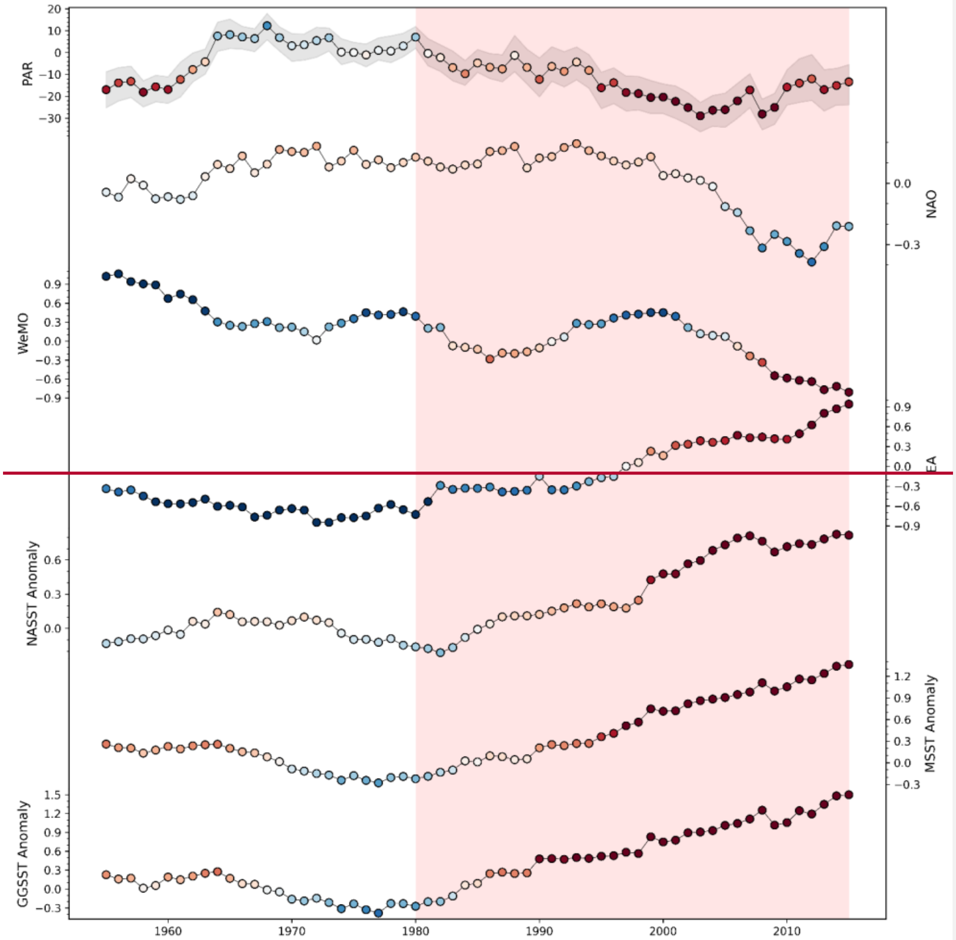


Figure 4. MAM season, ~~T~~trends of Mobile Average Percentage Anomaly Rainfall (MAPAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature (GGSST) for the MAM season. The trends are smoothed by a 10-year mobile window and the colour of the points goes from blue to red: blue is linked to wet periods, red to dry periods. The grey band on MAPAR represents the 25th and 75th percentiles, the dots represent the mean value. The pink band refers to the main dry period of the time series.

Formatted: Font: Not Bold

684


PAR
NAO
WeMO
EA
NASST Anomaly
MSST Anomaly
GGSST Anomaly
1960
1970
1980
1990
2000
2010

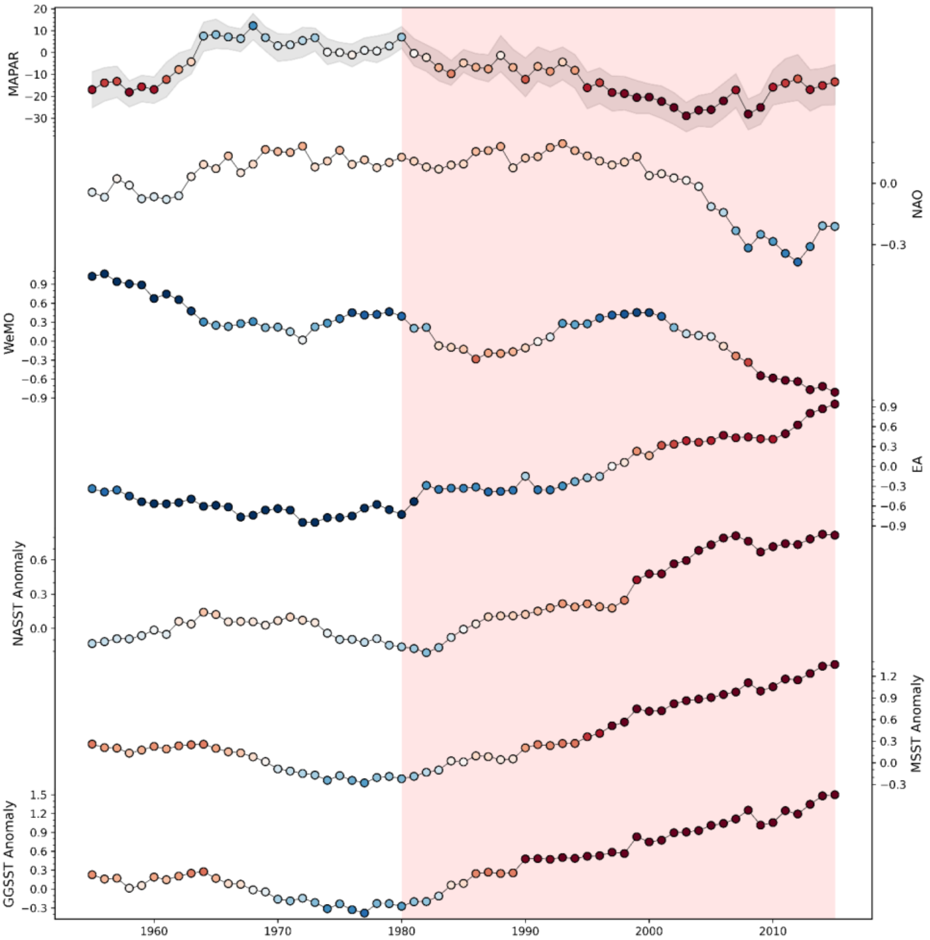
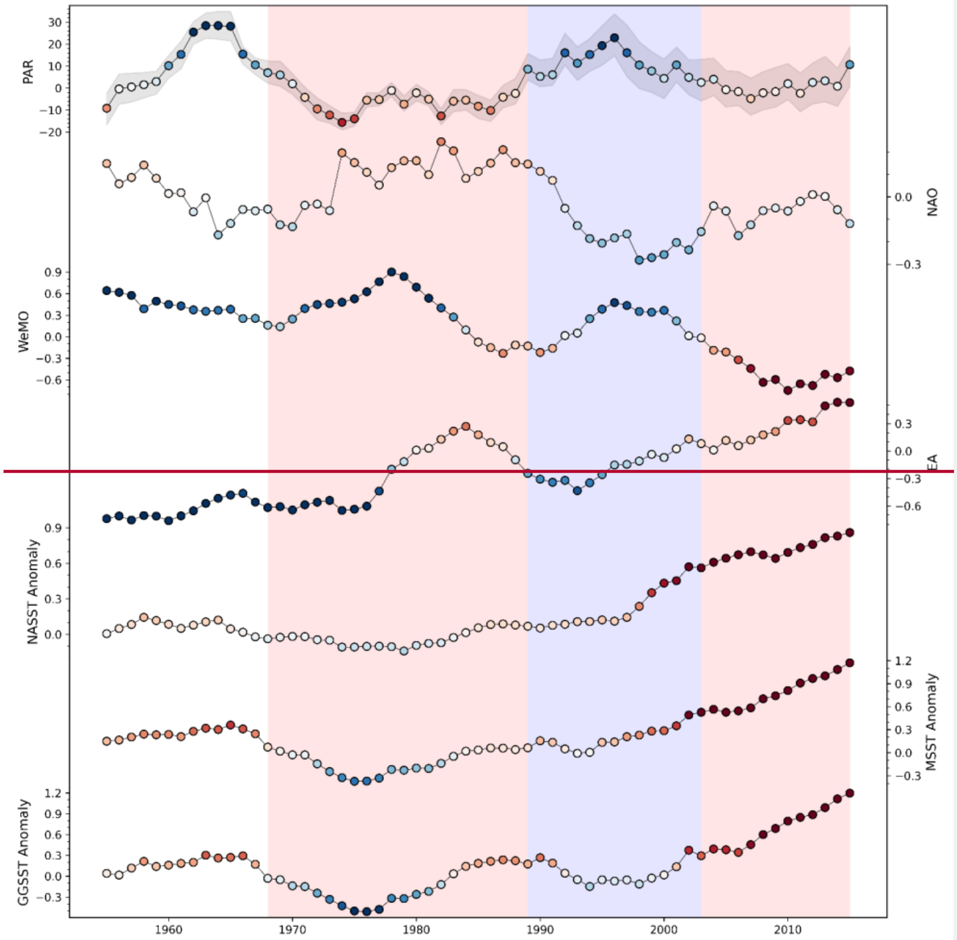


Figure 5. JJA, t~~T~~rends of Mobile Average Percentage Anomaly Rainfall (MAPAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature (GGSST)~~ for the JJA season~~. The trends are smoothed with a 10-year mobile window and the colour of the points varies between blue to red: blue is linked to wet periods, while red is linked to dry periods. The grey band on MAPAR represents the 25th and 75th percentile, the dots represent the mean value. The pink band refers to the main dry period of the time series.

Formatted: Font: Not Bold



PAR
NAO
WeMO
EA
NASST Anomaly
MSST Anomaly
GGSST Anomaly
1960
1970
1980
1990
2000
2010

692

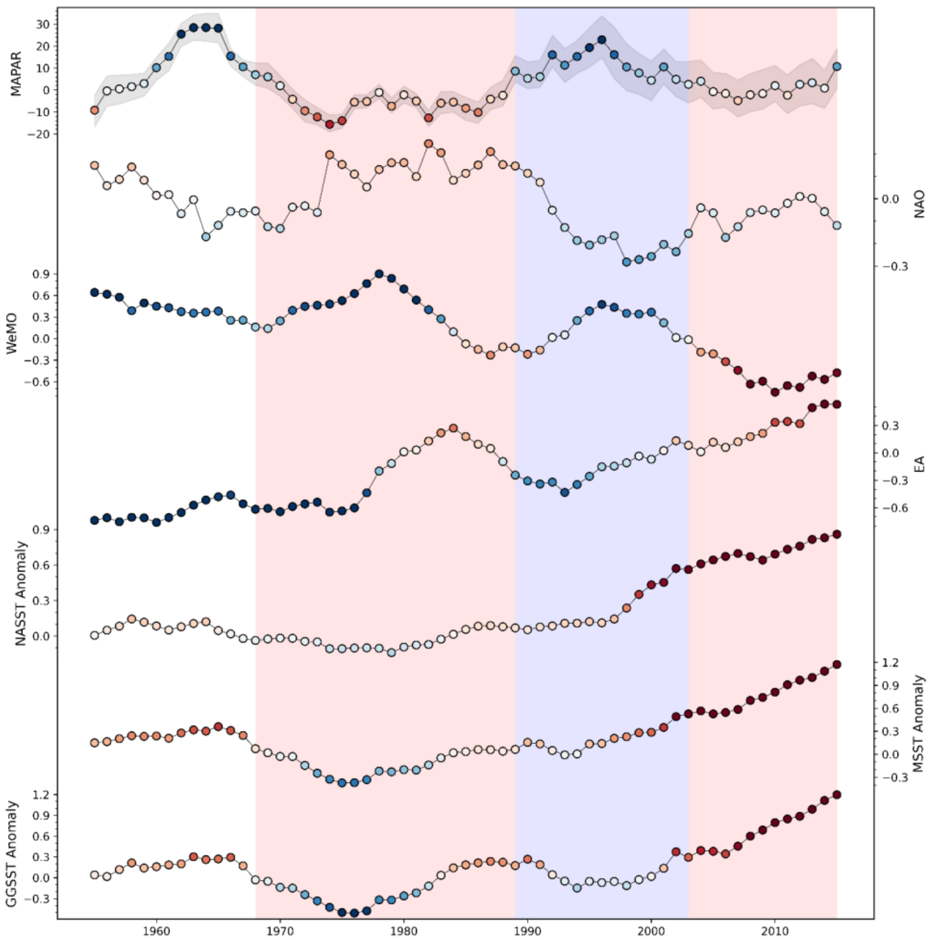


Figure 6 SON season, ~~T~~trends of Mobile Average Percentage Anomaly Rainfall (MAPAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature (GGSST)~~ for the SON season~~. The trends are smoothed with a 10-year mobile window and the colour of the points varies between blue to red: blue indicates wet periods,~~;~~ red indicates dry periods. The grey band on MAPAR represents the 25th and 75th percentile, the dots represent the mean value. The pink band is referred to the main dry period of the time series, while the blue band is referred to the main wet period of the time series.

Formatted: Font: Not Bold

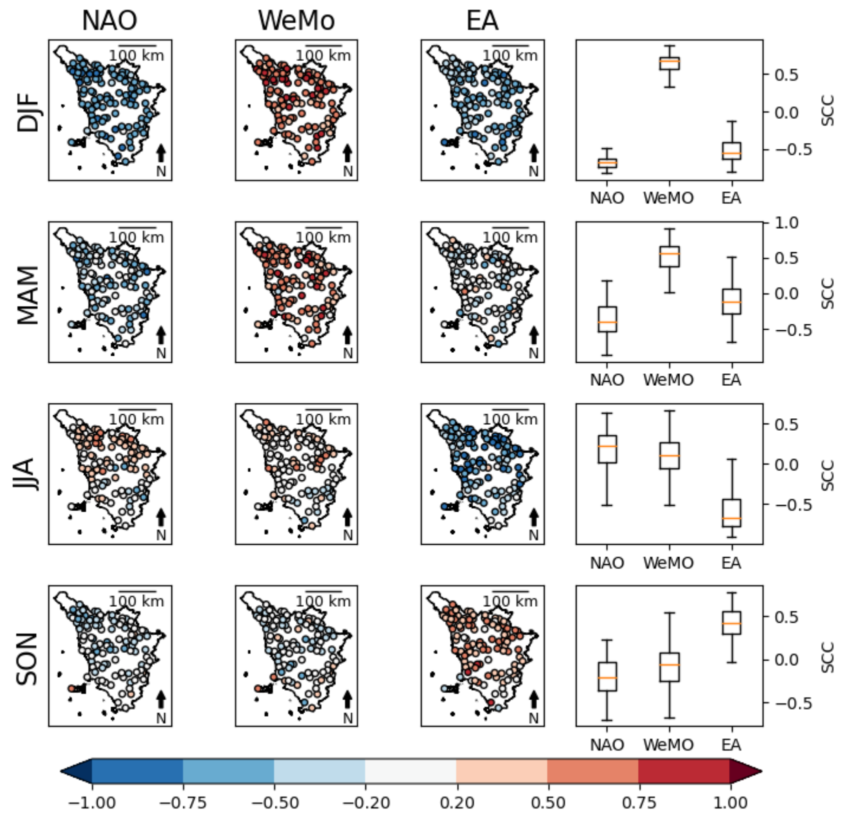
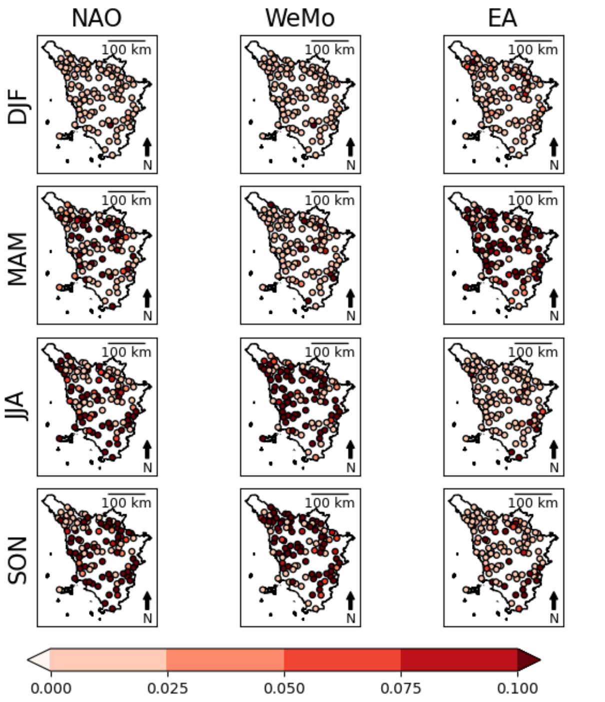


Figure 7. Spearman's correlation coefficients (SCC) between season rainfall and climatic patterns. For each season, we report the correlation with NAO, EA and WeMO and the relative boxplots. The boxes represent the interval between the 25th and 75th percentiles (Q1 and Q3). IQR is the interquartile range Q3-Q1. The upper whisker will extend to the last datum lower than Q3 + 1.5×IQR. Similarly, the lower whisker will reach the first datum higher than Q1 – 1.5×IQR. The orange lines represent the medians. ~~(DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November).~~



707

708

709 **Figure 8.** P-values of Spearman's correlation coefficients (SCC).

710

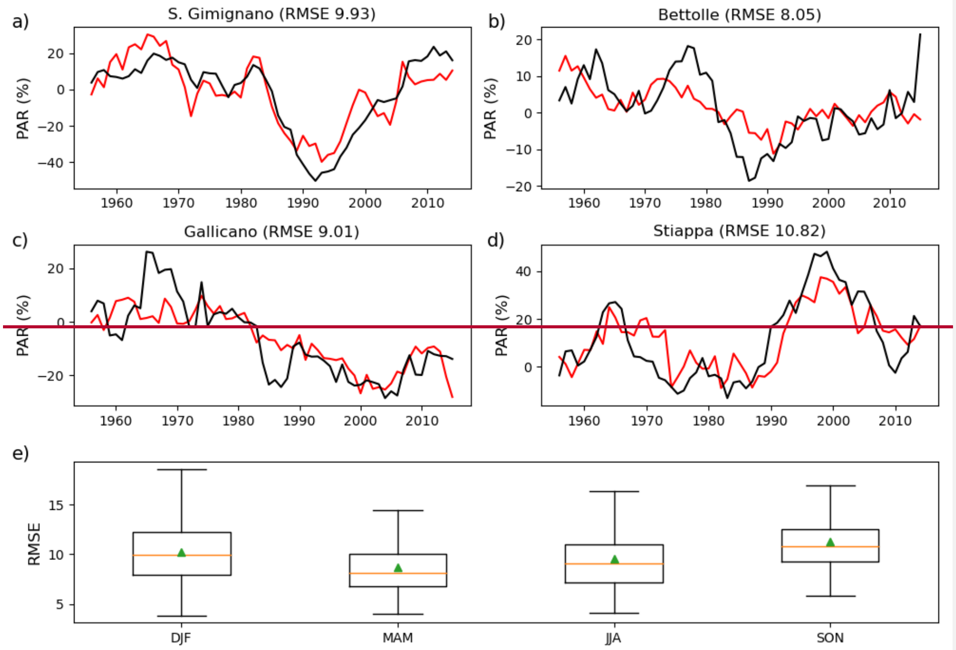
Formatted: Centered

Formatted: Font: Bold, English (United Kingdom)

Formatted: Font: Not Bold

Formatted: English (United States)

Formatted: Normal


a)
S. Gimignano (RMSE 9.93)
b)
Bettolle (RMSE 8.05)
c)
Gallicano (RMSE 9.01)
d)
Stiappa (RMSE 10.82)
PAR (%)
e)
RMSE
DJF
MAM
JJA
SON

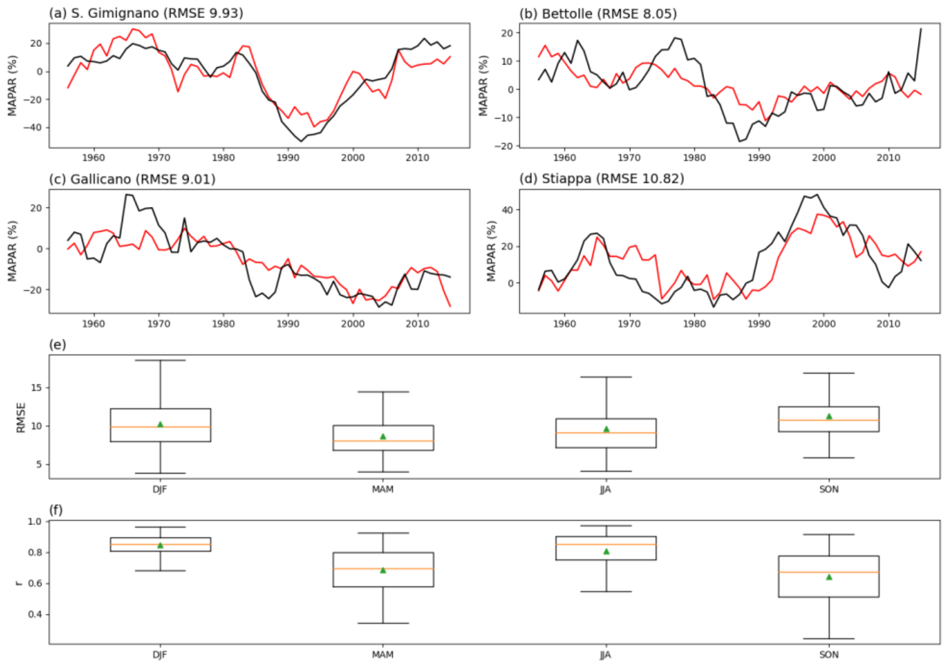

(a) S. Gimignano (RMSE 9.93)
(b) Bettolle (RMSE 8.05)
(c) Gallicano (RMSE 9.01)
(d) Stiappa (RMSE 10.82)
MAPAR (%)
(e)
RMSE
(f)
r
DJF
MAM
JJA
SON

Figure 9. a-d) Four examples of observed MAPAR (black line) and predicted MAPAR (red line) respectively for the seasons DJF, MAM, JJA and SON. ~~We selected these examples because they have Root Mean Square Error (RMSE) values similar to the error medians calculated on the whole dataset;~~ e) the boxplots represent the ~~RMSE~~ Root Mean Square Error (RMSE) of the linear models for the four seasons. f) the boxplots represent the Correlation Coefficient (r) of the linear models for the four seasons. The boxes represent the interval between the 25th and 75th percentiles (Q1 and Q3). IQR is the interquartile range Q3-Q1. The upper whisker will extend to the last datum lower than Q3 + 1.5×IQR. Similarly, the lower whisker will reach the first datum higher than Q1 – 1.5×IQR. The orange lines represent the medians, while the green triangles represent the means ~~(DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November)~~.

Commented [ml2]: In tutte le figure semplificare questa scritta che al primo editor non piace è troppo lunga

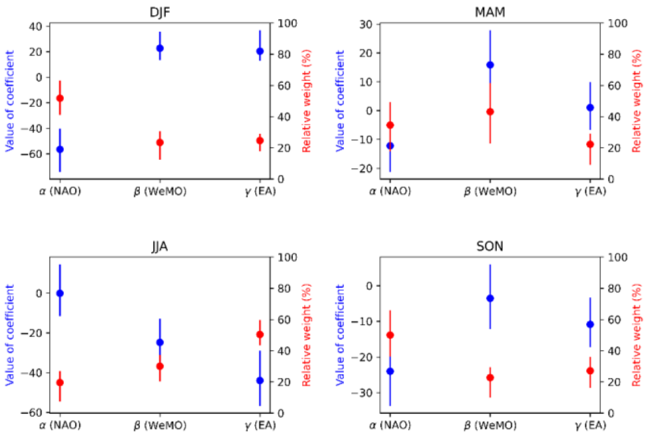


Figure 10. Setting of the linear model coefficients used to understand the relationship between climate patterns and rainfall. The blue circle is the mean absolute value of the coefficient, whereas the red circle represents the mean relative weight of the coefficient on the prediction. The results are reported for each season. The blue and red lines represent the interval between the 25th and 75th percentiles of the coefficient distributions (DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November).

Seasonal rainfall trends of a key Mediterranean area in relation to large-scale atmospheric circulation: how does current global change affect the rainfall regime?

Marco Luppichini[1,2,*], Monica Bini[2,3,4], Michele Barsanti[5], Roberto Giannecchini[2,4,6], Giovanni Zanchetta[2,4,7]

[1] Department of Earth Sciences, University of Study of Florence, Via La Pira 4, Florence, Italy

[2] Department of Earth Sciences, University of Pisa, Via S. Maria, 52, 56126 Pisa, Italy

[3] Istituto Nazionale di Geofísica e Vulcanologia (INGV), Via Vigna Murata 605, 00143 Roma, Italy

[4] CIRSEC Centro Interdipartimentale di Ricerca per lo Studio degli Effetti del Cambiamento Climatico dell'Università di Pisa, Via del Borghetto 80, 56124 Pisa, Italy

[5] Department of Civil and Industrial Engineering, University of Pisa, Largo L. Lazzarino, 56122 Pisa, Italy

[6] Institute of Geosciences and Earth Resources, IGG-CNR, via Moruzzi 1, 56124 Pisa, Italy

[7] Istituto di Geologia Ambientale e Geoingegneria, IGAG-CNR, Rome, Italy

Abstract

Current global warming causes a change in atmospheric dynamics, with consequent variations in the rainfall regimes. Understanding the relationship between global climate patterns, global warming, and rainfall regimes is crucial for the creation of future scenarios and for the relative modification of water management. The aim of this study is to improve knowledge of the relationship between North Atlantic Oscillation (NAO), East Atlantic (EA), and Western Mediterranean Oscillation (WeMO) with the seasonal rainfalls in Tuscany, Italy. The study area occupies a strategic position since it lies in a transition zone between the wet area of northern Europe and the dry area of the northern coast of Africa. This research, based on a statistical correlation method and on linear models, is designed to understand the relationship between seasonal rainfalls and climate patterns. The results of this study demonstrate that the use of linear models can yield more information than traditional statistical correlations. The results show a decrease in rainfall in the warm period of the year, namely in the summer, when its expression is most visible. This phenomenon is ascribable to current global warming, which causes an increase in sea-surface temperatures. An increase in the Northern Atlantic Sea Surface Temperature and in the Mediterranean Sea Surface Temperature causes a reduction of the Iceland Low, with an extension of the Azores High. Moreover, an increase in the Genoa Gulf SST induces a weakening of the Genoa Gulf Low, one of the main cyclogenetic systems of the Mediterranean.

Keywords: Climatic Patterns, Current Global Warming, East Atlantic, North Atlantic Oscillation, Western Mediterranean Oscillation, rainfall trend, Tuscany.

Introduction

Current global warming causes effects at different scale levels, including changes in the hydrological cycle (Allan, 2011; Bates et al., 2008). The effects are visible in air temperature trends and, more generally, in rainfall, in the form of frequency and intensity of extreme events and changes in soil moisture (Blöschl et al., 2019; Stagl et al., 2014; Xu et al., 2011), with wide implications in terms of socio-economic conditions and financial policy (European Environment Agency, 2019). The Mediterranean region is an ideal research testbed for current climatic changes both for its location for its historico-cultural importance, and for having been considered a hot spot for future climatic changes (Giorgi, 2006). The Mediterranean, located between the European humid domain and the North African arid belt, provides alternating circulation regimes with large spatial and temporal variability (Dünkeloh and Jacobeit, 2003). In this context, a correct characterization of rainfall regimes can improve the management of water resources (Tramblay et al., 2020) and of extreme events (Cardoso Pereira et al., 2020; Myhre et al., 2019). Several studies have identified a general decrease (although with some exceptions) in the annual rainfall amount in the area of the Mediterranean basin (Bertola et al., 2019; Blöschl et al., 2019; Caloiero et al., 2018, 2011; Colantoni et al., 2015; Deitch et al., 2017; Dünkeloh and Jacobeit, 2003; Halifa-Marín et al., 2021; Longobardi and Villani, 2010; Martin-Vide and Lopez-Bustins, 2006; Philandras et al., 2011; Ríos-Cornejo et al., 2015); and atmospheric patterns related to mesoscale circulation (Brandimarte et al., 2011; Caloiero et al., 2011; Halifa-Marín et al., 2021; Lopez-Bustins et al., 2008; Luppichini et al., 2021; Martinez-Artigas et al., 2021; Ríos-Cornejo et al., 2015; Trigo et al., 2004).

During the winter months, one of the main drivers of rainfall variability in southern Europe and in the Mediterranean is the presence of different pressure fields over the Northern Atlantic Ocean and their variability indicated as the North Atlantic Oscillation (NAO) (Hurrell, 1995). NAO is defined by an index measured as a north-southern dipole of pressure anomalies, with one pole located at higher latitudes (Iceland Low 80°N) and the other at the central latitudes of the North Atlantic between 35°N and 40°N (Azores High). The East Atlantic (EA) index is similar to that of NAO but is displaced south-eastward to the approximate nodal lines of the NAO pattern. The EA index is often interpreted as a downward-shifted NAO model, but its strong subtropical link entails a different peculiarity. The EA value is positive when a significant drop in pressure occurs in the Atlantic Ocean; at the same time, the subtropical oceanic anticyclone belt considerably rises in latitude and strengthens. In response, the African anticyclone gains energy and invasiveness over the Mediterranean, subjecting this area to frequent pulses of hot and dry Saharan air in all seasons (Climate Prediction Center, 2021; Mellado-Cano et al., 2019). The NAO and EA indexes present interannual and annual variabilities with positive and negative phases. The rainfall in the Mediterranean can be associated with a negative phase of NAO and/or EA, when we observe an expansion of the Iceland Low. Instead, during a positive phase of NAO and/or EA, Northern Europe is the rainiest area (Rousi et al., 2020). Both NAO and EA are influenced by the Sea Surface Temperature (SST) of the Northern Atlantic Ocean (NASST) and of the Mediterranean (MSST). An increase in NASST and in MSST is correlated to an expansion of the Azores High and to a consecutive reduction of the Iceland Low, which cause a formation of the NAO and EA positive phases (Frankignoul et al., 2003; Robertson et al., 2000; Visbeck et al., 2001). More recently, NAO has been correlated to the Atlantic Multidecadal Oscillation (AMO), a representative index of the NASST trend (Knight et al., 2005). AMO changes the zonal position of the NAO centre of action, moving the cyclonic area closer to Europe or to North America. During a positive phase of AMO, the Icelandic Low moves further towards North America, while the Azores High moves further towards Europe (and vice versa) for the negative phase of AMO (Börgel et al., 2020). The statistical correlation between the NAO and the winter rainfalls in Europe varies over time (Vicente-Serrano and López-Moreno, 2008) and it is a function of NAO and AMO with a different role of the indices from northern Europe to the Mediterranean (Luppichini et al., 2021).

The Western Mediterranean oscillation (WeMO) is an index often used to study variability in rainfall in alternative to NAO in the Mediterranean region. The WeMO index is the difference of atmospheric pressure in a dipole, with the first pole located in Padua (45.40◦N, 11.48◦E) in northern Italy and the second one located in San Fernando, Cádiz (36.28◦N, 6.12◦W) in southwestern Spain (Climatic Research Unit, 2021). Specifically, the former is located in the Po plain (an area with relatively high barometric variability due to the different influence of the central European anticyclone and of the Genoa Gulf Low), while the latter pole is located in the Gulf of Cádiz in the southwest of the Iberian Peninsula, often subject to the influence of the Azores anticyclone and, episodically, to the cut-off of circumpolar lows or to its own cyclogenesis (Halifa-Marín et al., 2021; Lopez-Bustins et al., 2020; Martin-Vide and Lopez-Bustins, 2006). A positive phase of WeMO is associated with a low-pressure area in the Ligurian Sea and with an anticyclone in the Gulf of Cadiz. Instead, a negative phase of the index determines a low in the Gulf of Cadiz and an anticyclone in Central Europe. WeMO is influenced by NASST and MSST, but also by the Genoa Gulf Sea Surface Temperature (GGSST), with positive values correlating to low values of SST (Martín et al., 2012; Martin-Vide and Lopez-Bustins, 2006).

Current global warming causes a progressive increase in NASST, MSST and GGSST (Pastor et al., 2020; Wang and Dong, 2010) so that NAO and EA are likely to be characterized by more positive phases, and WeMO by more negative phases.

The purpose of this study is to understand the rainfall seasonal trends of the last 70 years in Tuscany (central Italy), in relation to mesoscale circulation and to the indices defined above. The rainfall dataset employed derives from several raingauges with high spatial density and temporal activity which allow us to investigate the rainfall trend in great detail and with direct measurements. The rainfall trends are compared with the NAO, EA and WeMO indices by means of mathematical and statistical methods, so as to understand the climatic trends influencing the rainfall regime in the area We investigated the link between the different indices by using traditional statistical methods (Spearman, 1904)

Many land dynamics (e.g., drought, floods, solid transport, coastal erosion) are linked to the rainfall regime which can create management criticalities (e.g., Billi and Fazzini, 2017; Bini et al., 2021; Piccarreta et al., 2004). The study of variations in the amount of rainfall related to climatic indices allows to lay the foundations for future studies and land management. The observations put forward in this work and the methods adopted could be extended to other Mediterranean areas by increasing knowledge about these issues.

Methods

Study area

Tuscany has a strategic location because it is located in the northern sector of the Mediterranean, in the proximity of the Genoa Gulf, by far the most active cyclogenetic centre of the Mediterranean (Trigo et al., 2002).

As expected, the mean annual precipitation (MAP) in Tuscany is influenced by morphology (Figure 1a). The rainiest areas are located at the highest altitudes (Apuan Alps and Northern Apennines; Figure 1b). In particular, the Apuan Alps in north-western Tuscany show some of the highest rainfall amounts in Italy (Giannecchini and D'Amato Avanzi, 2012; Rapetti and Vittorini, 1994), often characterized by high intensity (D'Amato Avanzi et al., 2004; Giannecchini, 2006). In Tuscany, MAP is in a range of 400-3000 mm/year with a clear gradient from the northern to the southern and it is linked to the morphology (Figure 1a). The main rainy season is autumn, with a progressive decrease that generally starts in December. The mean rainfall in the DJF season is ca 300 mm, ca 250 mm in MAM, ca 130 mm in JJA, and ca 350 mm in SON.

FIGURE 1

Dataset

Rainfall dataset and processing

The raingauge dataset was provided by the Tuscany Region Hydrologic Service (SIR) network and includes 1103 raingauges (Figure 1c). The daily data were obtained by an automated download procedure through an HTTP request in March 2021. The dataset is the best one available in this area and it is managed by the SIR which validates and checks the data. The dataset is used in several research works because it is referenced and managed by a public body. In particular, Luppichini et al. 2021 used this dataset to understand the relationship between NAO and winter rainfall in this area. The activity period of each raingauge is variable. The older stations have been monitoring since the beginning of the last century, even if a temporal continuity of the data is not always guaranteed for some stations. SIR provides the daily rainfall data for each raingauge in the operation period. To obtain longer and more complete time series from this dataset, we grouped the stations according to a stringent protocol. This procedure is necessary to reconstruct the time series of the stations that have experienced minor changes in position or that have undergone an administrative variation (e.g., a slight change in name or identification code). The stations have consecutive intermittent activity times due to the decommissioning of one and the subsequent installation of a new one. In these cases, we merged the stations by assigning the same, or part of the same name, with a difference in altimetry (less than 20%) of the measurement, and a maximum distance (less than 2 km). The geographic coordinates of the merged stations derived from a cartesian mean of the original coordinates of the origin stations.

By using the data available and following the procedure described above, a total of 117 time series were obtained from 1950 to 2020. The rainfall data can also be useful for comparison with the results of the linear models which predict rainfall anomalies. The rainfall values are expressed as percentage anomalies of rainfall (PAR), and are calculated as follows:

$$PAR_{s,i} = \frac{x_{s,i} - \overline{x_\iota}}{\overline{x_\iota}} \cdot 100 \tag{1}$$

where, $x_{s,i}$ is the annual seasonal rainfall amount of the i-th year and s-th season, $\overline{x_\iota}$ is the annual rainfall amount mean of the period 1961-1990.

The values of PAR are calculated for the four seasons: winter (DJF: December, January and February); spring (MAM: March, April and May –); summer (JJA: June, July and August); autumn (SON: September, October and November). Mean Average PAR (MAPAR) is a ten-year mobile average of PAR calculated for each season, and the values are associated with the central year. We chose to use a ten-year mobile average because this time range is within the standard 10–30 year time scale considered to be decadal variability (Meehl et al., 2009).

Climatic Dataset

The NAO dataset is provided by the Climate Analysis Section of the US National Center for Atmospheric Research (NCAR). This dataset is based on the principal (PC)-based index component of the NAO, which are the time series of the leading Empirical Orthogonal Function (EOF) of SLP anomalies over the Atlantic sector, 20°-80°N, 90°W-40°E. This index is used to measure the yearly NAO, by tracking the seasonal movements of the Icelandic Low and Azores High. The dataset has a monthly frequency from January 1889 to December 2020. PC-based indices are more optimal representations of the full spatial patterns of the NAO (National Center for Atmospheric Research Staff (Eds), 2021).

The EA dataset used in this study is provided by the National Weather Service of NOAA. The frequency of the dataset is on a monthly basis, from 1950 to 2020. The index is standardized by 1981-2010 climatology (Climate Prediction Center, 2021).

The WeMO index is provided by the Climatic Research Unit (CRU) of the University of East Anglia (Climatic Research Unit, 2021). The time series started in 1821 and has a monthly frequency.

The trends of NASST, MSST, and GGSST are calculated from the Extended Reconstructed Sea Surface Temperature (ERSST) dataset version 5 (NOAA, 2021), and they are expressed using a 10-year mobile window of anomalies. The anomalies are referred to the mean of the 1961-1990 period. NASST is calculated in the area 0N-65N 80W-0E; MSST in the area 38N-49N 0E-28E; and GGSST in the area 42.8N-44.8N 7.6E-10.76E.

Statistical Correlation and Linear Models

. We investigated the link between the different indices by using traditional statistical methods (Spearman, 1904), but also by introducing in this field an innovative approach, which employs a linear model to understand the influence of each index on the rainfall prediction. The combination of these different methods helped us to comprehend the accuracy and the advantages of the new method proposed.

We calculated the correlation coefficient to identify a possible relationship between atmospheric teleconnection and rainfall amount. Several authors use a statistical method of correlation to quantify the relationship between atmospheric indices and rainfalls (Brandimarte et al., 2011; Faust et al., 2016; Kalimeris et al., 2017; Kotsias et al., 2020; Koyama and Stroeve, 2019; López-Moreno et al., 2011; Vicente-Serrano and López-Moreno, 2008). In particular, some authors (Caloiero et al., 2011; Izquierdo et al., 2014; Luppichini et al., 2021; Nalley et al., 2019; Vergni et al., 2016) use Spearman's correlation coefficient (SCC) (Spearman, 1904) to understand the relationship between atmospheric index and rainfall amount. This relationship is suitable for monotonically-related variables, even when their relationship is not linear. The range of Spearman's coefficients is between -1 and 1; positive values indicate a tendency of one variable to increase or decrease together with another variable, whereas negative values indicate a trend in which the increase in the values of one variable is associated with the decrease in the values of the other variable, and vice versa. We have divided the time series into four seasons: winter from December to February (DJF), spring from March to May (MAM), summer from June to August (JJA) and autumn from September to November (SON). We calculated the SCC among the three atmospheric teleconnections and the rainfall for the four seasons using a 10-year moving time window from 1950 to 2020. We assigned the correlation result to the year halfway through each ten-years.

However, the trends in the time series can influence the SCC (Arianos and Carbone, 2009; Boris et al., 2009; Iqbal et al., 2020; Podobnik and Stanley, 2008). To exclude the influence of the trends on the results of this study, we investigated further using the detrended cross-correlation analysis (DCCA) proposed by Kristoufek, (2014) in the framework developed by Ide et al. (2017). The DCCA results are in perfect agreement with the SCC results. Therefore, we could exclude an influence of the trends on the use of SCC in this study. More information can be found in the supplementary material.

We can create linear models capable of predicting the rainfall amount by using the NAO, WeMO and EA time series. The equation of a linear model predicting the rainfall (R_p), is the following:

$$R_p = \alpha NAO + \beta WeMO + \gamma EA + \delta \tag{2}$$

We can analyse the best estimates of the model parameters (α, β, γ) to understand the role of each input in the prediction of rainfall. If we want to obtain the best prediction models, we should use models that are more complex than a simple linear model. However, the simplicity of the linear models allows to analyse the influence of the inputs, since one of the tasks of this work is to show that more complex models (for instance with the inclusion of synergies between the input data) are not necessary to explain the rainfall observed. We therefore created a linear model for each raingauge time series for each season. The different range of the three atmospheric teleconnections could influence the information expressed by the parameters of models α, β and δ. For this reason, we scaled the time series of NAO, WeMO and EA in the range between 0 and 1 for the studied period (1950-2020), by applying the following equation:

$$T = \frac{Ts - Ts_m}{Ts_{\mathrm{M}} - Ts_m} \tag{3}$$

where T is the index time series in the 0-1 range, Ts_{M} is the maximum value of the index, and Ts_m is the minimum value of the index. We fitted a linear model for each time series, using the SciPy library in Python Language and, in more detail, the "curve_fit" method (Virtanen et al., 2020). We validated the fits calculating the Root Mean Square Error (*RMSE*) and the Correlation Coefficient (*r*) as follows:

$$RMSE = \left(\frac{1}{N}\sum_{i=0}^{N}(F_i - V_i)^2\right)^{0.5} \tag{4}$$

$$r = \frac{\left(\frac{1}{N}\sum_{i=0}^{N}(F_i * V_i)\right)}{\left(\frac{1}{N}\sum_{i=0}^{N}F_i^2\right)^{0.5} \cdot \left(\frac{1}{N}\sum_{i=0}^{N}V_i^2\right)^{0.5}} \tag{5}$$

where F_i are the forecast values, V_i are the observed values and N the number of years.

Results

Rainfall Trends

Figure 2 reports the values of PAR calculated for each time series used in this work, and obtained from equation 1. The graphs indicate a small variability of PAR between each time series, excluding the possibility of different influences on the linear model outcomes by the input stations and a significant variability in the study area. The MAPAR of the study area is shown in Figures 3-6 for the four seasons. These variations of MAPAR over time are different in the four seasons. From 1950 to 1985, the DJF season was characterized by a slow rainfall reduction followed by a sudden decrease around the 90's. The first years of the 1990's presented a MAPAR reduction of 40%. Starting from 2000, the DJF MAPAR increased progressively until reaching the amount recorded before 1990 (Figure 3). Until the 1990s, the MAM MAPAR was characterized by an oscillation, from the 1990's to the 2010's, MAM MAPAR has the minimum values which are in the range between -10 and -20%. MAM MAPAR increased after 2008 (Figure 4). The JJA MAPAR started to decrease in 1965 with minimum values of -30% around 2005. The last years were marked by a weakly increase of JJA MAPAR (Figure 5). SON MAPAR had a certain variability over an approximate 20-year period. The maximum SON MAPAR amount was recorded around 1965 and 1995, while the minimum values were those of the period 1970-1990 (Figure 6).

FIGURE 2

Atmospheric Teleconnection Trends

In DJF, NAO was characterized by an intensification of the positive phase, the EA time series was characterized by an intensification of the positive phase starting from 1985 (Figure 3), and WeMO was characterized by a positive phase with a decrease in the 1990-2010 period.

In MAM, NAO and EA time series were characterized by a progressive increase with an intensification of the positive phase; WeMO has experienced a progressive decrease from a positive phase to a negative persistence phase since 2005 (Figure 4).

In JJA, NAO was characterized by a positive phase until 2005, whereas the index was characterized by a negative phase, except for some years. In this season, EA started to increase progressively in 1995, while WeMO had a progressive decrease with a persistence positive phase since 2005 (Figure 5).

In SON, NAO is variable with periods characterized by negative alternated with positive phases. In this season, EA had a higher index fluctuation, with a negative phase until 1980, followed by a more positive ten-year phase and then by a negative phase until 2000. From 2000 to 2020, EA increased reaching its maximum values. WeMO was characterized by two distinct positive phases around 1975 and 1995, but the overall trend has decreased with a negative phase since 2005 (Figure 6).

Sea surface temperature trends

The variations of NASST, MSST and GGSST started to display a clear increasing trend in the 1980’s in all seasons. Such increase only started around the 2010’s for DJF and GGSST, while it started to increase in the 1980s in the other seasons. The increase in SST was greater in the summer than in the other seasons (Figures 3-6).

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

Statistical Correlation

Figure 7 reports the results obtained from SCC and Figure 8 shows the spatial distribution of the p-values obtained. In the DJF season, rainfall is correlated with WeMO and anticorrelated with NAO and EA. Rainfall increases during a negative phase of NAO or EA and a positive phase of WeMO. During this period, each atmospheric teleconnection has a similar effect on the rainfall amount. In the MAM season, the strongest correlation is with WeMO, and even in this case a positive phase of the index corresponds to a rainfall increase in the study area. NAO and EA are weakly anticorrelated with the rainfall amount. The strongest correlation is with EA in the JJA season, and a negative phase of this index indicates an increase in rainfall in the area , while a positive phase of EA corresponds to reduced precipitation in summer. NAO and WeMO are weakly correlated with rainfall, but do not show a clear behaviour. Even in the SON season, the strongest correlation is with EA. The correlation in this season is positive, which indicates that a positive EA phase determines increased precipitation in the area. The spatial correlation distribution is homogenous with no clear spatial pattern, especially when the correlations are strong, providing a precise indication of the relationship (Figure 7).

FIGURE 7

FIGURE 8

Linear Models

In Figure 9a-d, we report four examples of the MAPAR prediction by means of linear models referred to the DJF, MAM, JJA and SON seasons. The cases shown represent the results of the lineal models because they have RMSE values similar to the error medians calculated on the entire dataset (Figure 9e). For the case shown in Figure 9a, α, β and γ are respectively -96.56, 42.53, and 4.85; for the case reported in Figure 9b they are -21.39, -15.54 and -15.76, for the case reported in Figure 9c they are -30.71, -56.10 and -1.34; for the case reported in Figure 9c they are -48.05, 7.54 and 6.71. Figure 9e and 9d also report the RMSE and r of the entire dataset. SON, followed by MAM, which is the season with the highest average errors.

Figure 10 shows the mean values of coefficients α, β and γ for the linear models in each season (blue circles). We can observe a change in the values of the three coefficients from one season to another. In Figure 10, the red circles show the relative weights of each coefficient. In the DJF season, the coefficient with the greatest weight is α with a mean value of about 55%, followed by β and γ. The coefficients indicate that NAO has more influence on the rainfall trend than WeMO and EA on DJF. In this season, the coefficient values indicate that an increase in rainfall is linked to a negative phase of NAO (α is negative) and a positive phase of WeMO (β is positive). In the MAM season, β (WeMO) has the highest weight in the results of the models, followed by α (NAO) and γ (EA). Therefore, the coefficients denote that the amount of rainfall is correlated with a positive phase of WeMO and with a negative phase of NAO. Also in this season, EA has less influence on the model than the other two indices. In the JJA season EA is the index with the greatest coefficient (γ). In particular, the coefficients suggest that the summer rainfall is linked to a negative phase of EA. Less important, the coefficients indicate that the summer rainfall is linked to a negative phase of WeMO. In the SON season, NAO has the greatest weight and is followed by WeMO and EA, which have less influence on the rainfall trend. In this case, the coefficients are all negative, so that rainfall is correlated to a negative phase of these indices.

FIGURE 9

FIGURE 10

Discussion

Mathematical and statistical relationship between atmospheric teleconnections and rainfall

The statistical correlation calculated with Spearman's method represents a first indication of the influence of climate patterns on the local rainfall trend. In accordance with several studies (Caloiero et al., 2011; Deser et al., 2017; Ferrari et al., 2013; George et al., 2004; López-Moreno et al., 2011; Luppichini et al., 2021; Riaz et al., 2017; Vergni and Chiaudani, 2015; Vicente-Serrano and López-Moreno, 2008; West et al., 2019), NAO influence is predominant in winter, with an anticorrelation between index and rainfall amount. In agreement with the obtained SCC, an increase in the Azores High, and consequently a decrease in the Iceland Low, determine reduced winter rainfall in the study area. The correlation between NAO and rainfall decreases during the successive seasons with a minimum correlation in summer. In winter and in spring, the correlation with WeMO is strong and it is characterized by a positive sign. This implies the formation of the Genoa Gulf Low and its reinforcement increases the amount of rainfall in the study area. This can be ascribed to the direction of the moist air masses coming from the Atlantic Ocean and directed to the north-western coast of Spain and to the Mediterranean (Degeai et al., 2020; Martín et al., 2012; Martin-Vide and Lopez-Bustins, 2006). In this dynamic state the moist air masses can reach Tuscany, enhancing local cyclogenesis and rainfall. The SCC values indicate that the influence of the Genoa Gulf Low decreases in summer and autumn . The correlation between rainfall and EA is strong in winter and summer; in summer, the correlation with rainfall is mainly with EA. In winter, the link between EA and rainfall is the same for NAO. In summer, the greater representativeness of EA than of NAO on the Azores High allows a better understanding of the link between rainfall and global climate in this season. In detail, the formation of the Azores High and of the African High results in an increase in the EA index, and this means that there is reduced precipitation in the study area. In autumn, the statistical correlations do not allow to create a link between large-scale circulation and rainfall. Indeed, we can observe a weak anticorrelation with NAO, a weak correlation with EA, and no correlation with WeMO. This method seems unsuitable to represent the autumn season with its atmospheric dynamics.

The results of the linear models are conformant to the statistical correlation results for the DJF, MAM and JJA seasons, while we observe some differences in SON. The strong correspondence between the two methods in DJF, MAM and JJA makes it possible to validate our linear model. In autumn, the analysis of the linear models identifies an important role of NAO, and therefore a link between northern Atlantic atmospheric circulation and rainfall in the study area. In autumn, the coefficients of NAO (α) are set negative and this means that an increase in the index is linked to a decrease in rainfall in the study area. This mathematical result is more plausible than that obtained from the analysis of correlations based on the notions of atmospheric physics introduced previously. The linear model-based method has allowed us to refine our investigations and to improve our knowledge of the dynamics in the Mediterranean over the seasons.

The use of our linear models offers the advantage of clarifying the role and influence of large-scale atmospheric circulation on rainfall over the study region in different seasons, and this may appear controversial when using only the statistical correlation. These linear methods can also be useful for rainfall prediction, although it is not the aim of this paper to produce the best model for predictions. A more complex model may be better suited to reduce the overall model; however, it would have been difficult to understand the influence of each input parameter, which is the main scope of this paper.

Long-term rainfall trends and relation with climate patterns

This study has identified a confused trend for the DJF, MAM and SON rainfall, while the JJA rainfall clearly tends to decrease. These results agree with those of other studies based on different rainfall datasets (Caloiero et al., 2018; Deitch et al., 2017; Philandras et al., 2011). More specifically, Deitch et al. (2017) studied the seasonal trend of rainfall in the Mediterranean area, demonstrating a negative trend for summer rainfall and no trend for winter/autumnal rainfall in Tuscany.

The DJF seasons are characterized by significantly decreased precipitation between 1984 and 2005 (Figure 3). This period is marked by a positive phase of NAO and EA and a negative phase of WeMO. Starting around 1984, the increase in NAO and EA is due to an increase in NASST (Figure 3). An increase in NASST is correlated to an expansion of the Azores High and a consecutive reduction of the Iceland Low, resulting in the formation of the NAO and EA positive phases (Börgel et al., 2020; Frankignoul et al., 2003; Robertson et al., 2000; Visbeck et al., 2001). The successive increase in rainfall from 2005 to 2020 seems to have been caused by an increase in the WeMO, and therefore by an increase in the Genoa Gulf Low persistence. This could indicate a change of the main climatic driver with respect to the previous period (Figure 3).

The MAM season presents a decrease in the amount of rainfall in the period between 1985 and 2008 (Figure 4). The WeMO constantly decreases with progressive intensification of the negative phase. This indicates a gradual reduced intensity of the Genoa Gulf Low. The GGSST has progressively increased since 1985. Furthermore, NAO and EA are in a persistent positive phase. Since 2008, there has been a weak increase in the precipitation trend. The JJA rainfall trends have the highest correlation with EA, while NAO and WeMO have a lower influence (Figure 7 and 10). The increase in NASST, MSST and GGSST induces the NAO and EA indices to a positive phase, and WeMO to a negative phase. This process induces a progressive reduction of rainfall trends in this season. SON is characterized by rainfall trend variability with two wet periods and two dry periods (Figure 6). Each dry period is marked by an increase in NAO, whereas the wet period results from an increase in WeMO linked to a weak decrease in GGSST (Figure 6). The increase in sea surface temperature is greater in the warm periods of the year and it is caused by current global warming. From these observations, we can evince that the warm periods of the year are marked by a greater decrease in precipitation resulting in less water availability in the environmental system.

Conclusions

This study helps to gain a better knowledge of the rainfall trends of the last 70 years in Tuscany, a key area of the Mediterranean Basin, strongly influenced by the cyclogenetic activity related to the Genoa Gulf Low. These trends are analyzed on the basis of the trend of the main atmospheric drivers of the northern hemisphere. The location of the study area allows to understand the influences of Atlantic atmospheric circulation and of the Mediterranean atmospheric circulation on rainfall. Along with Spearman's traditional coefficient analysis, this study proposes a new mathematical method to investigate the relationship between climate pattern and rainfall. The method based on the use of linear models has resulted to be valid, with similar results derived from a statistical correlation. This new method has allowed for a more detailed comprehension of the link between climate patterns and precipitation in the study area. In Tuscany, the rainfall amount is influenced by Northern Atlantic atmospheric circulation and by the Genoa Gulf Low. The influences of the two atmospheric systems vary during the year: in winter, rainfall is strongly correlated to the three indices; in spring, the main influence is represented by WeMO, indicating an important role played by the Genoa Gulf Low; in summer, the main driver is EA, which represents better than NAO the influence of the Azores High in this season; in autumn, the strongest correlation is with NAO.

The amount of rainfall in the study area is influenced by the SSTs which induce a variation in the Northern Atlantic and Mediterranean atmospheric circulations (Börgel et al., 2020; Frankignoul et al., 2003; Robertson et al., 2000; Visbeck et al., 2001). Current global warming determines an increase in the SSTs and this increase is higher in the warm seasons of the year (James et al., 2006). The results of this study show that in these seasons there is the greatest reduction of water availability, on account of a direct decrease in precipitation. For this reason, current global warming could be responsible for less rainfall in this area, and this occurs mainly in the warm seasons when temperature increase is highest. These aspects can be deepened by future studies that can strengthen the relationships found and the considerations made in this work.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Acknowledgements: The authors are grateful to the Tuscany Region Hydrologic Service for providing the data used in this work.

Funding: This research was funded by project no. 249792 "Dalla Preistoria all'Antropocene: Nuove Tecnologie per la valorizzazione dell'eredità culturale della Versilia (PANTAREI)" Tuscany Region (call POR FSE 2014-2020, Resp. M. Bini); by the collaborative research agreement no. 579999-2019 "Autorità di Bacino Distrettuale Appennino Settentrionale" (Resp. Monica Bini and Roberto Giannecchini); and by the project: "Cambiamenti globali e impatti locali: conoscenza e consapevolezza per uno sviluppo sostenibile della pianura Apuo-versiliese" Fondazione Cassa Risparmio di Lucca, (Resp. M. Bini).

Reference

Allan, R.P., 2011. Human influence on rainfall. Nature 470, 344–345. https://doi.org/10.1038/470344a

Arianos, S., Carbone, A., 2009. Cross-correlation of long-range correlated series. Journal of Statistical Mechanics: Theory and Experiment 2009, P03037.

Bates, B., Kundzewicz, Z.W., Wu, S., Burkett, V., Doell, P., Gwary, D., Hanson, C., Heij, B., Jiménez, B., Kaser, G., Kitoh, A., Kovats, S., Kumar, P., Magadza, C.H.D., Martino, D., Mata, L., Medany, M., Miller, K., Arnell, N., 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change.

Bertola, M., Viglione, A., Hall, J., Blöschl, G., 2019. Flood trends in Europe: are changes in small and big floods different? Hydrology and Earth System Sciences Discussions 1–23. https://doi.org/10.5194/hess-2019-523

Billi, P., Fazzini, M., 2017. Global change and river flow in Italy. Global and Planetary Change 155, 234–246. https://doi.org/https://doi.org/10.1016/j.gloplacha.2017.07.008

Bini, M., Casarosa, N., Luppichini, M., 2021. Exploring the relationship between river discharge and coastal erosion: An integrated approach applied to the pisa coastal plain (italy). Remote Sensing 13. https://doi.org/10.3390/rs13020226

Blöschl, G., Hall, J., Viglione, A., Perdigão, R.A.P., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G.T., Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G.B., Claps, P., Frolova, N., Ganora, D., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T.R., Kohnová, S., Koskela, J.J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Salinas, J.L., Sauquet, E., Šraj, M., Szolgay, J., Volpi, E., Wilson, D., Zaimi, K., Živković, N., 2019. Changing climate both increases and decreases European river floods. Nature 573, 108–111. https://doi.org/10.1038/s41586-019-1495-6

Börgel, F., Frauen, C., Neumann, T., Meier, H.E.M., 2020. The Atlantic Multidecadal Oscillation controls the impact of the North Atlantic Oscillation on North European climate. Environmental Research Letters 15.

Boris, P., Davor, H., M, P.A., Eugene, S.H., 2009. Cross-correlations between volume change and price change. Proceedings of the National Academy of Sciences 106, 22079–22084. https://doi.org/10.1073/pnas.0911983106

Brandimarte, L., di Baldassarre, G., Bruni, G., D'Odorico, P., Montanari, A., D'Odorico, P., Montanari, A., 2011. Relation Between the North-Atlantic Oscillation and Hydroclimatic Conditions in Mediterranean Areas. Water Resources Management 25, 1269–1279. https://doi.org/10.1007/s11269-010-9742-5

Caloiero, T., Caloiero, P., Frustaci, F., 2018. Long-term precipitation trend analysis in Europe and in the Mediterranean basin. Water and Environment Journal 32, 433–445. https://doi.org/https://doi.org/10.1111/wej.12346

Caloiero, T., Coscarelli, R., Ferrari, E., Mancini, M., 2011. Precipitation change in Southern Italy linked to global scale oscillation indexes. Nat. Hazards Earth Syst. Sci. 11, 1683–1694. https://doi.org/10.5194/nhess-11-1683-2011

Cardoso Pereira, S., Marta-Almeida, M., Carvalho, A.C., Rocha, A., 2020. Extreme precipitation events under climate change in the Iberian Peninsula. International Journal of Climatology 40, 1255–1278. https://doi.org/https://doi.org/10.1002/joc.6269

Climate Prediction Center, 2021. East Atlantic [WWW Document]. URL https://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml (accessed 9.22.21).

Climatic Research Unit, 2021. Mediterranean Oscillation Indices (MOI) [WWW Document]. URL https://crudata.uea.ac.uk/cru/data/moi/ (accessed 9.22.21).

Colantoni, A., Delfanti, L., Cossio, F., Baciotti, B., Salvati, L., Perini, L., Lord, R., 2015. Soil Aridity under Climate Change and Implications for Agriculture in Italy. Applied Mathematical Sciences 9, 2467–2475. https://doi.org/10.12988/ams.2015.52112

D'Amato Avanzi, G., Giannecchini, R., Puccinelli, A., 2004. The influence of the geological and geomorphological settings on shallow landslides. An example in a temperate climate environment: the June 19, 1996 event in northwestern Tuscany (Italy). Engineering Geology 73, 215–228. https://doi.org/https://doi.org/10.1016/j.enggeo.2004.01.005

Deitch, M.J., Sapundjieff, M.J., Feirer, S.T., 2017. Characterizing Precipitation Variability and Trends in the World's Mediterranean-Climate Areas. Water (Basel) 9. https://doi.org/10.3390/w9040259

Deser, C., Hurrell, J.W., Phillips, A.S., 2017. The role of the North Atlantic Oscillation in European climate projections. Climate Dynamics 49, 3141–3157. https://doi.org/10.1007/s00382-016-3502-z

Dünkeloh, A., Jacobeit, J., 2003. Circulation dynamics of Mediterranean precipitation variability 1948–98. International Journal of Climatology 23, 1843–1866. https://doi.org/https://doi.org/10.1002/joc.973

European Environment Agency, 2019. Economic losses from climate -related extremes in Europe. Indicator Assessment.

Faust, J.C., Fabian, K., Milzer, G., Giraudeau, J., Knies, J., 2016. Norwegian fjord sediments reveal NAO related winter temperature and precipitation changes of the past 2800 years. Earth and Planetary Science Letters 435, 84–93. https://doi.org/https://doi.org/10.1016/j.epsl.2015.12.003

Ferrari, E., Caloiero, T., Coscarelli, R., 2013. Influence of the North Atlantic Oscillation on winter rainfall in Calabria (southern Italy). Theoretical and Applied Climatology 114, 479–494. https://doi.org/10.1007/s00704-013-0856-6

Frankignoul, C., Friederichs, P., Kestenare, E., 2003. Influence of Atlantic SST anomalies on the atmospheric circulation in the Atlantic-European sector. Annals of Geophysics 46.

George, D.G., Järvinen, M., Arvola, L., 2004. The influence of the North Atlantic Oscillation on the winter characteristics of Windermere (UK) and Pääjärvi (Finland).

Giannecchini, R., 2006. Relationship between rainfall and shallow landslides in the southern Apuan Alps (Italy). Natural Hazards and Earth System Science 6, 357–364. https://doi.org/10.5194/nhess-6-357-2006

Giannecchini, R., D'Amato Avanzi, G., 2012. Historical research as a tool in estimating hydrogeological hazard in a typical small alpine-like area: The example of the Versilia River basin (Apuan Alps, Italy). Physics and Chemistry of the Earth, Parts A/B/C 49, 32–43. https://doi.org/10.1016/J.PCE.2011.12.005

Giorgi, F., 2006. Climate change hot-spots. Geophysical Research Letters 33. https://doi.org/https://doi.org/10.1029/2006GL025734

Halifa-Marín, A., Lorente-Plazas, R., Pravia-Sarabia, E., Montávez, J.P., Jiménez-Guerrero, P., 2021. Atlantic and Mediterranean influence promoting an abrupt change in winter precipitation over the southern Iberian Peninsula. Atmospheric Research 253. https://doi.org/10.1016/j.atmosres.2021.105485

Hurrell, J.W., 1995. Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. Science (1979) 269, 676 LP – 679. https://doi.org/10.1126/science.269.5224.676

Ide, J.S., Cappabianco, F.A., Faria, F.A., Li, C.-S.R., 2017. Detrended Partial Cross Correlation for Brain Connectivity Analysis.

Iqbal, J., Lone, K.J., Hussain, L., Rafique, M., 2020. Detrended cross correlation analysis (DCCA) of radon, thoron, temperature and pressure time series data. Physica Scripta 95, 085213. https://doi.org/10.1088/1402-4896/ab9fb1

Izquierdo, R., Alarcón, M., Aguillaume, L., Àvila, A., 2014. Effects of teleconnection patterns on the atmospheric routes, precipitation and deposition amounts in the north-eastern Iberian Peninsula. Atmospheric Environment 89, 482–490. https://doi.org/https://doi.org/10.1016/j.atmosenv.2014.02.057

James, H., Makiko, S., Reto, R., Ken, L., W, L.D., Martin, M.-E., 2006. Global temperature change. Proceedings of the National Academy of Sciences 103, 14288–14293. https://doi.org/10.1073/pnas.0606291103

Kalimeris, A., Ranieri, E., Founda, D., Norrant, C., 2017. Variability modes of precipitation along a Central Mediterranean area and their relations with ENSO, NAO, and other climatic patterns. Atmospheric Research 198, 56–80. https://doi.org/https://doi.org/10.1016/j.atmosres.2017.07.031

Knight, J.R., Allan, R.J., Folland, C.K., Vellinga, M., Mann, M.E., 2005. A signature of persistent natural thermohaline circulation cycles in observed climate. Geophysical Research Letters 32. https://doi.org/10.1029/2005GL024233

Kotsias, G., Lolis, C.J., Hatzianastassiou, N., Levizzani, V., Bartzokas, A., 2020. On the connection between large-scale atmospheric circulation and winter GPCP precipitation over the Mediterranean region for the period 1980-2017. Atmospheric Research 233, 104714. https://doi.org/https://doi.org/10.1016/j.atmosres.2019.104714

Koyama, T., Stroeve, J., 2019. Greenland monthly precipitation analysis from the Arctic System Reanalysis (ASR): 2000–2012. Polar Science 19, 1–12. https://doi.org/https://doi.org/10.1016/j.polar.2018.09.001

Kristoufek, L., 2014. Measuring correlations between non-stationary series with DCCA coefficient. Physica A: Statistical Mechanics and its Applications 402, 291–298. https://doi.org/https://doi.org/10.1016/j.physa.2014.01.058

Longobardi, A., Villani, P., 2010. Trend analysis of annual and seasonal rainfall time series in the Mediterranean area. International Journal of Climatology 30, 1538–1546. https://doi.org/https://doi.org/10.1002/joc.2001

Lopez-Bustins, J.A., Arbiol-Roca, L., Martin-Vide, J., Barrera-Escoda, A., Prohom, M., 2020. Intra-annual variability of the Western Mediterranean Oscillation (WeMO) and occurrence of extreme torrential precipitation in Catalonia (NE Iberia). Natural Hazards and Earth System Sciences 20, 2483–2501. https://doi.org/10.5194/nhess-20-2483-2020

Lopez-Bustins, J.-A., Martin-Vide, J., Sanchez-Lorenzo, A., 2008. Iberia winter rainfall trends based upon changes in teleconnection and circulation patterns. Global and Planetary Change 63, 171–176. https://doi.org/https://doi.org/10.1016/j.gloplacha.2007.09.002

López-Moreno, J.I., Vicente-Serrano, S.M., Morán-Tejeda, E., Lorenzo-Lacruz, J., Kenawy, A., Beniston, M., 2011. Effects of the North Atlantic Oscillation (NAO) on combined temperature and precipitation winter modes in the Mediterranean mountains: Observed relationships and projections for the 21st century. Global and Planetary Change 77, 62–76. https://doi.org/https://doi.org/10.1016/j.gloplacha.2011.03.003

Luppichini, M., Barsanti, M., Giannecchini, R., Bini, M., 2021. Statistical relationships between large-scale circulation patterns and local-scale effects: NAO and rainfall regime in a key area of the Mediterranean basin. Atmospheric Research 248, 105270.

Martín, P., Sabatés, A., Lloret, J., Martin-Vide, J., 2012. Climate modulation of fish populations: The role of the Western Mediterranean Oscillation (WeMO) in sardine (Sardina pilchardus) and anchovy (Engraulis encrasicolus) production in the north-western Mediterranean. Climatic Change 110, 925–939. https://doi.org/10.1007/s10584-011-0091-z

Martinez-Artigas, J., Lemus-Canovas, M., Lopez-Bustins, J.A., 2021. Precipitation in peninsular Spain: Influence of teleconnection indices and spatial regionalisation. International Journal of Climatology 41, E1320–E1335. https://doi.org/https://doi.org/10.1002/joc.6770

Martin-Vide, J., Lopez-Bustins, J.-A., 2006. The Western Mediterranean Oscillation and rainfall in the Iberian Peninsula. International Journal of Climatology 26, 1455–1475. https://doi.org/https://doi.org/10.1002/joc.1388

Meehl, G., Goddard, L., Murphy, J., Boer, G., Danabasoglu, G., Dixon, K., Giorgetta, M., Greene, A., Hawkins, E., Hegerl, G., Karoly, D., Kimoto, M., 2009. Decadal Prediction: Can It Be Skillful? Bull Am Meteorol Soc 90, 1467–1485. https://doi.org/10.1175/2009BAMS2778.1

Mellado-Cano, J., Barriopedro, D., García-Herrera, R., Trigo, R.M., Hernández, A., 2019. Examining the North Atlantic Oscillation, East Atlantic Pattern, and Jet Variability since 1685. Journal of Climate 32, 6285–6298. https://doi.org/10.1175/JCLI-D-19-0135.1

Myhre, G., Alterskjær, K., Stjern, C.W., Hodnebrog, Ø., Marelle, L., Samset, B.H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M., Stohl, A., 2019. Frequency of extreme precipitation increases extensively with event rareness under global warming. Scientific Reports 9, 16063. https://doi.org/10.1038/s41598-019-52277-4

Nalley, D., Adamowski, J., Biswas, A., Gharabaghi, B., Hu, W., 2019. A multiscale and multivariate analysis of precipitation and streamflow variability in relation to ENSO, NAO and PDO. Journal of Hydrology 574, 288–307. https://doi.org/https://doi.org/10.1016/j.jhydrol.2019.04.024

National Center for Atmospheric Research Staff (Eds), 2021. The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (PC-based). [WWW Document]. https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based.

NOAA, 2021. Extended Reconstructed SST [WWW Document]. URL https://www.ncei.noaa.gov/products/extended-reconstructed-sst (accessed 9.28.21).

Pastor, F., Valiente, J.A., Khodayar, S., 2020. A warming Mediterranean: 38 years of increasing sea surface temperature. Remote Sensing 12. https://doi.org/10.3390/RS12172687

Philandras, C., Nastos, P., Kapsomenakis, J., Douvis, K., Tselioudis, G., Zerefos, C., 2011. Long Term Precipitation Trends and Variability within the Mediterranean Region. Natural Hazards and Earth System Sciences 11, 3235–3250. https://doi.org/10.5194/nhess-11-3235-2011

Piccarreta, M., Capolongo, D., Boenzi, F., 2004. Trend analysis of precipitation and drought in Basilicata from 1923 to 2000 within a southern Italy context. International Journal of Climatology 24, 907–922. https://doi.org/https://doi.org/10.1002/joc.1038

Podobnik, B., Stanley, H.E., 2008. Detrended Cross-Correlation Analysis: A New Method for Analyzing Two Nonstationary Time Series. Physical Review Letters 100, 84102. https://doi.org/10.1103/PhysRevLett.100.084102

Rapetti, F., Vittorini, S., 1994. Le precipitazioni in Toscana: osservazioni sui casi estremi. RIVISTA GEOGRAFICA ITALIANA 101, 47–76.

Riaz, S.M.F., Iqbal, M.J., Hameed, S., 2017. Impact of the North Atlantic Oscillation on winter climate of Germany. Tellus, Series A: Dynamic Meteorology and Oceanography 69. https://doi.org/10.1080/16000870.2017.1406263

Ríos-Cornejo, D., Penas, Á., Álvarez-Esteban, R., del Río, S., 2015. Links between teleconnection patterns and precipitation in Spain. Atmospheric Research 156, 14–28.

Robertson, A.W., Mechoso, C.R., Kim, Y.-J., 2000. The Influence of Atlantic Sea Surface Temperature Anomalies on the North Atlantic Oscillation. Journal of Climate 13, 122–138. https://doi.org/10.1175/1520-0442(2000)013<0122:TIOASS>2.0.CO;2

Rousi, E., Rust, H.W., Ulbrich, U., Anagnostopoulou, C., 2020. Implications of Winter NAO Flavors on Present and Future European Climate. Climate 8, 13. https://doi.org/10.3390/cli8010013

Spearman, C., 1904. The proof and measurement of association between two things. The American Journal of Psychology 15, 72–101. https://doi.org/10.2307/1412159

Stagl, J., Mayr, E., Koch, H., Hattermann, F.F., Huang, S., 2014. Effects of Climate Change on the Hydrological Cycle in Central and Eastern Europe BT - Managing Protected Areas in Central and Eastern Europe Under Climate Change, in: Rannow, S., Neubert, M. (Eds.), . Springer Netherlands, Dordrecht, pp. 31–43.

Tramblay, Y., Llasat, M.C., Randin, C., Coppola, E., 2020. Climate change impacts on water resources in the Mediterranean. Regional Environmental Change 20, 83. https://doi.org/10.1007/s10113-020-01665-y

Trigo, I.F., Bigg, G.R., Davies, T.D., 2002. Climatology of Cyclogenesis Mechanisms in the Mediterranean.

Trigo, R.M., Pozo‐ Vázquez, D., Osborn, T.J., Castro‐ Díez, Y., Gámiz‐ Fortis, S., Esteban‐ Parra, M.J., Pozo-Vázquez, D., Osborn, T.J., Castro-Díez, Y., Gámiz-Fortis, S., Esteban-Parra, M.J., 2004. North Atlantic Oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. International Journal of Climatology: A Journal of the Royal Meteorological Society 24, 925–944. https://doi.org/10.1002/joc.1048

Vergni, L., Chiaudani, A., 2015. RELATIONSHIP BETWEEN THE NAO INDEX AND SOME INDICES OF EXTREME PRECIPITATION IN THE ABRUZZO REGION.

Vergni, L., di Lena, B., Chiaudani, A., 2016. Statistical characterisation of winter precipitation in the Abruzzo region (Italy) in relation to the North Atlantic Oscillation (NAO). Atmospheric Research 178–179, 279–290. https://doi.org/https://doi.org/10.1016/j.atmosres.2016.03.028

Vicente-Serrano, S.M., López-Moreno, J.I., 2008. Nonstationary influence of the North Atlantic Oscillation on European precipitation. Journal of Geophysical Research: Atmospheres 113. https://doi.org/10.1029/2008JD010382

Virtanen, P., Gommers, R., Oliphant, T.E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S.J., Brett, M., Wilson, J., Millman, K.J., Mayorov, N., Nelson, A.R.J., Jones, E., Kern, R., Larson, E., Carey, C.J., Polat, \.Ilhan, Feng, Y., Moore, E.W., VanderPlas, J., Laxalde, D., Perktold, J., Cimrman, R., Henriksen, I., Quintero, E.A., Harris, C.R., Archibald, A.M., Ribeiro, A.H., Pedregosa, F., van Mulbregt, P., SciPy 1.0 Contributors, 2020. SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. Nature Methods 17, 261–272. https://doi.org/10.1038/s41592-019-0686-2

Visbeck, M.H., Hurrell, J.W., Polvani, L., Cullen, H.M., 2001. The North Atlantic Oscillation: Past, present, and future. Proceedings of the National Academy of Sciences 98, 12876. https://doi.org/10.1073/pnas.231391598

Wang, C., Dong, S., 2010. Is the basin-wide warming in the North Atlantic Ocean related to atmospheric carbon dioxide and global warming? Geophysical Research Letters - GEOPHYS RES LETT 37. https://doi.org/10.1029/2010GL042743

West, H., Quinn, N., Horswell, M., 2019. Regional rainfall response to the North Atlantic Oscillation (NAO) across Great Britain. Hydrology Research 50, 1549–1563. https://doi.org/10.2166/nh.2019.015

Xu, H., Taylor, R.G., Xu, Y., 2011. Quantifying uncertainty in the impacts of climate change on river discharge in sub-catchments of the Yangtze and Yellow River Basins, China. Hydrol. Earth Syst. Sci. 15, 333–344. https://doi.org/10.5194/hess-15-333-2011

Figures

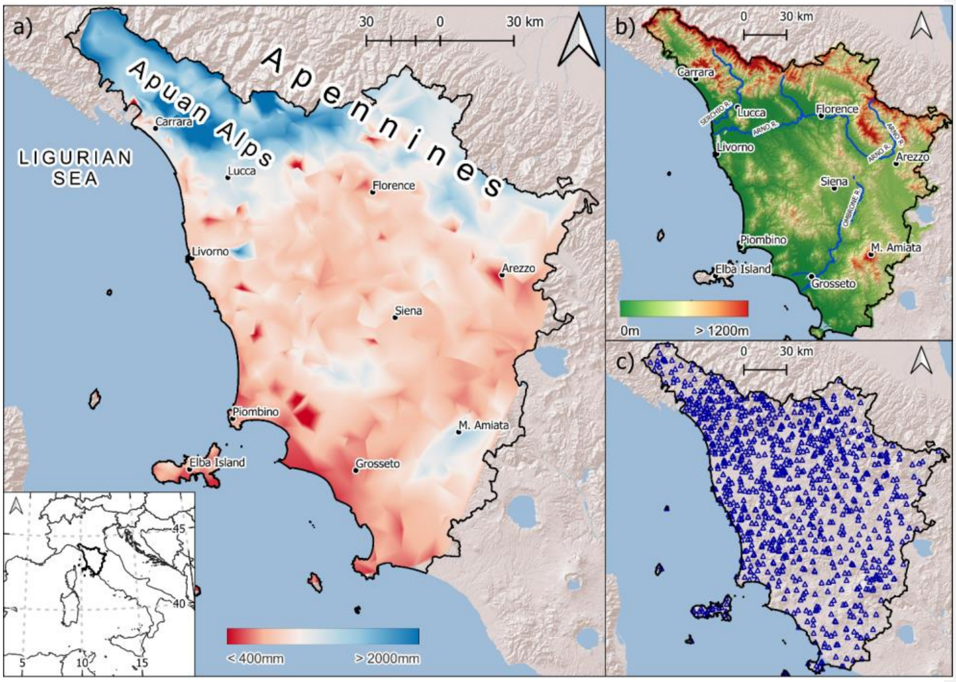


Figure 1. a) mean annual precipitation (MAP) of Tuscany linked to the morphology: the rainiest areas correspond to the mountainous areas; b) morphology of Tuscany; c) the 1103 raingauges of the Tuscany Region Hydrologic Service network used in this work.

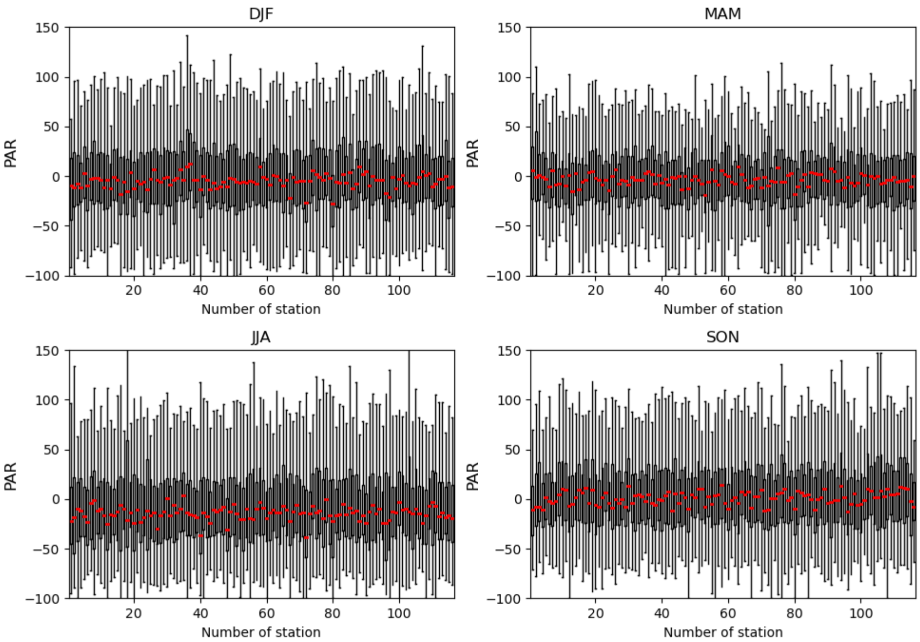
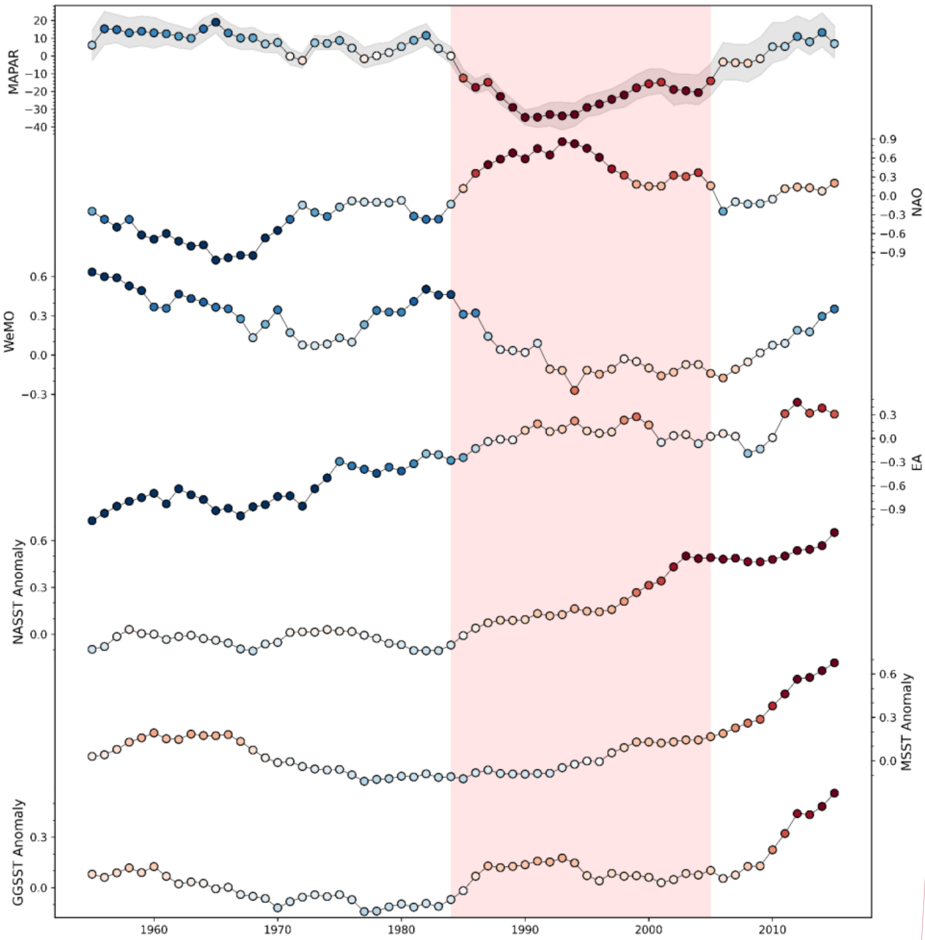


Figure 2. For the four seasons, Percentage Anomaly of Rainfall (PAR) of the 117 rainfall time series used in this work. Each boxplot is referred to a rainfall time series and represents the distribution of rainfall anomaly values with respect to the annual rainfall amount of the 1961-1990 period, in agreement with the equation 1 in the text. The boxes represent the interval between the 25th and 75th percentiles (Q1 and Q3). IQR is the interquartile range Q3-Q1. The upper whisker will extend to the last datum lower than Q3 + 1.5×IQR. Similarly, the lower whisker will reach the first datum higher than Q1 – 1.5×IQR. The red lines represent the medians (DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November).



Commented [ml1]: Cambiare fig MAPAR

Figure 3. DJF season, trends of Mobile Average Percentage Anomaly Rainfall (MAPAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature (GGSST). The trends are smoothed by a 10-year mobile window and the colour of the points varies between blue and red: blue is linked to wet periods, red to dry periods. The grey band on MAPAR represents the 25th and 75th percentile, the dots represent the mean value. The pink band is referred to the main dry period of the time series.

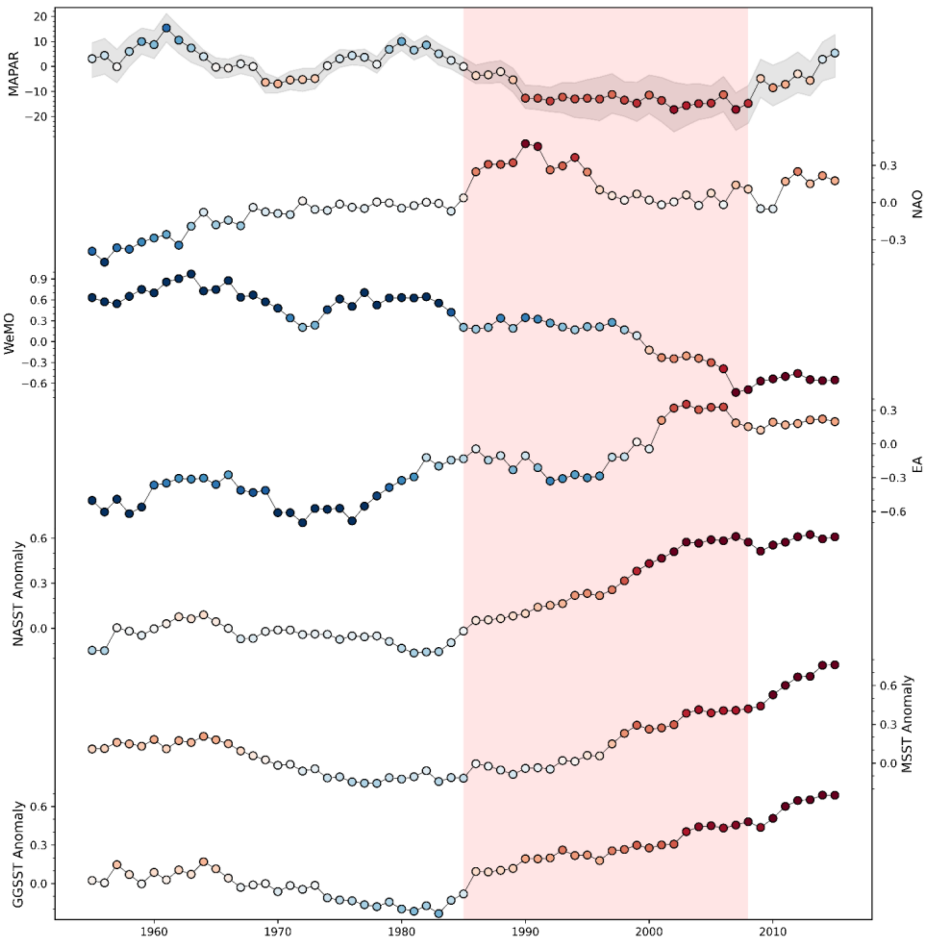


Figure 4. MAM season, trends of Mobile Average Percentage Anomaly Rainfall (MAPAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature (GGSST) for the MAM season. The trends are smoothed by a 10-year mobile window and the colour of the points goes from blue to red: blue is linked to wet periods, red to dry periods. The grey band on MAPAR represents the 25th and 75th percentiles, the dots represent the mean value. The pink band refers to the main dry period of the time series.

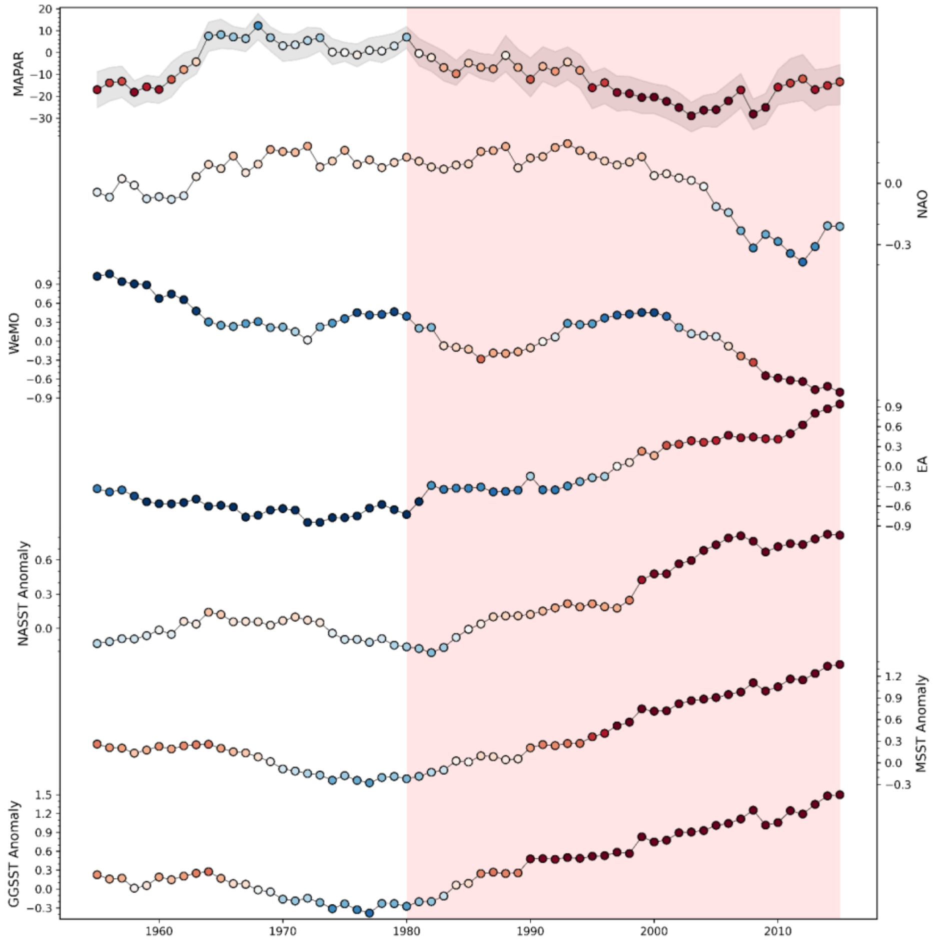


Figure 5. JJA, trends of Mobile Average Percentage Anomaly Rainfall (MAPAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature (GGSST). The trends are smoothed with a 10-year mobile window and the colour of the points varies between blue to red: blue is linked to wet periods, while red is linked to dry periods. The grey band on MAPAR represents the 25th and 75th percentile, the dots represent the mean value. The pink band refers to the main dry period of the time series.

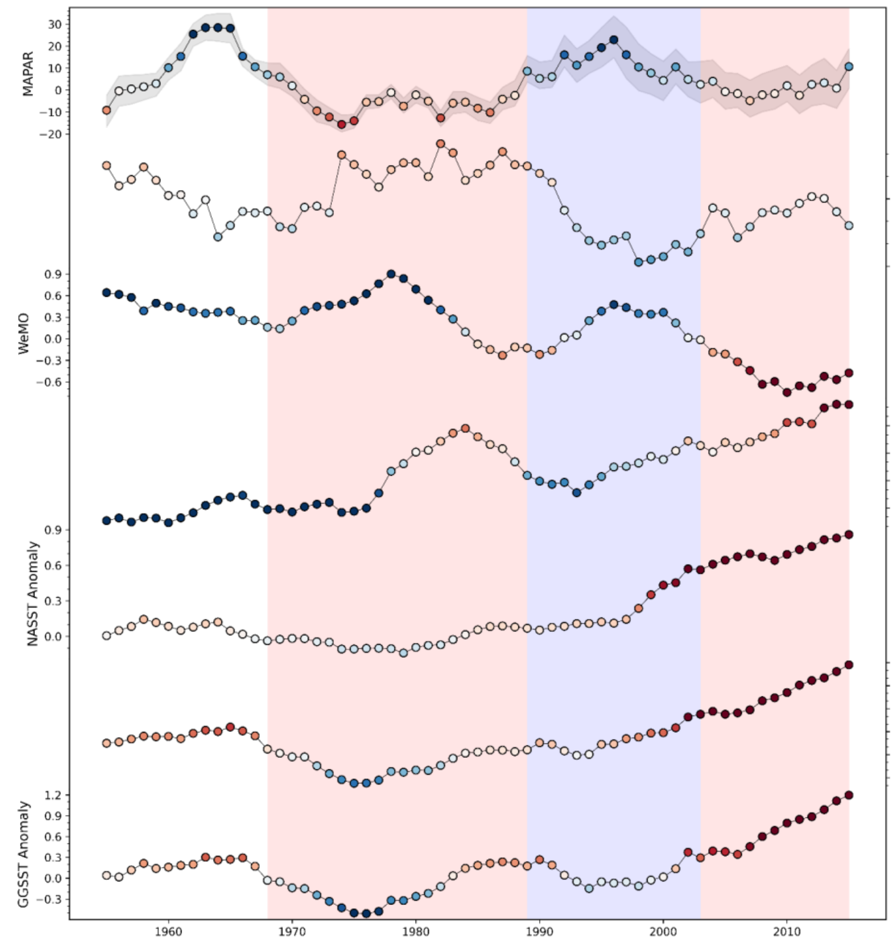


Figure 6 SON season, trends of Mobile Average Percentage Anomaly Rainfall (MAPAR), NAO, WeMO, EA, North Atlantic Sea Surface Temperature (NASST), Mediterranean Sea Surface Temperature (MSST), and Genoa Gulf Sea Surface Temperature (GGSST). The trends are smoothed with a 10-year mobile window and the colour of the points varies between blue to red: blue indicates wet periods, red indicates dry periods. The grey band on MAPAR represents the 25th and 75th percentile, the dots represent the mean value. The pink band is referred to the main dry period of the time series, while the blue band is referred to the main wet period of the time series.

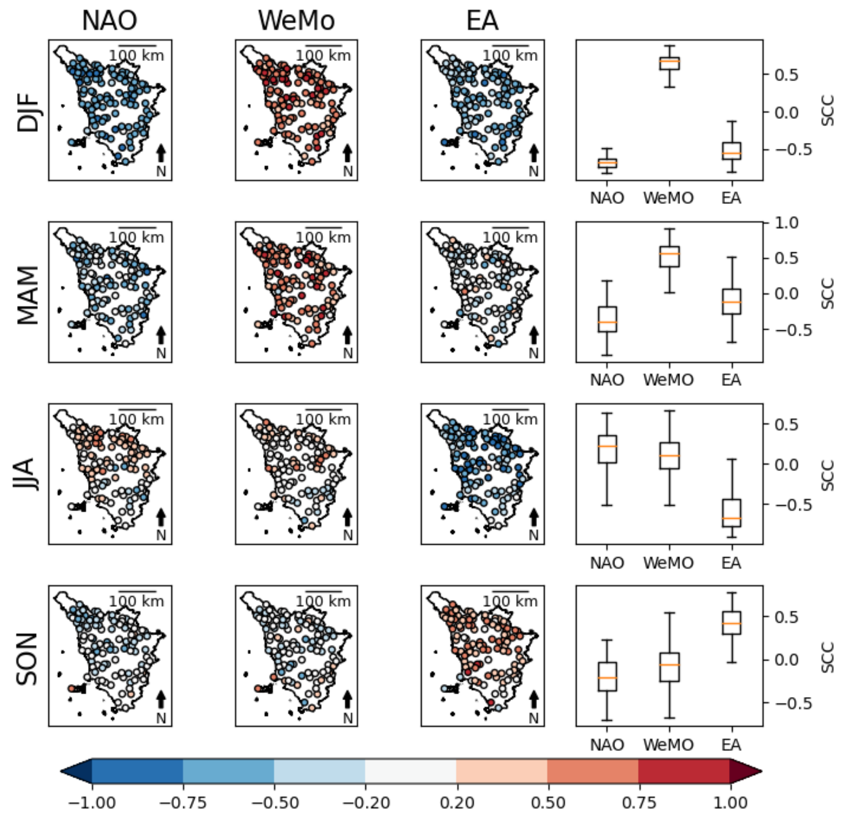
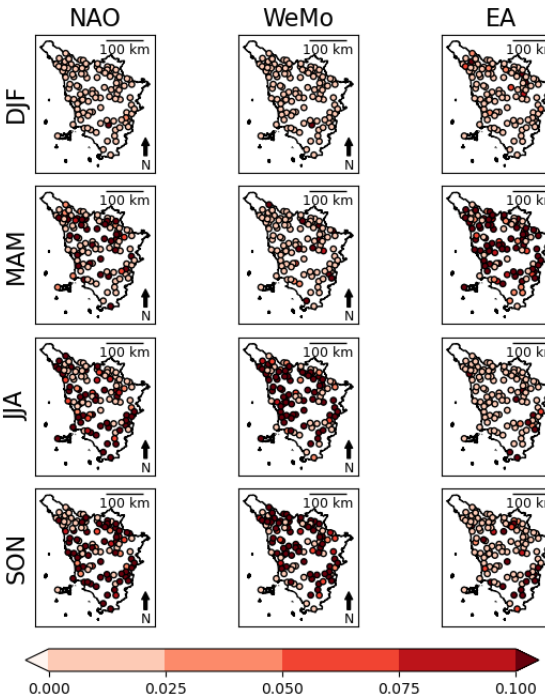


Figure 7. Spearman's correlation coefficients (SCC) between season rainfall and climatic patterns. For each season, we report the correlation with NAO, EA and WeMO and the relative boxplots. The boxes represent the interval between the 25th and 75th percentiles (Q1 and Q3). IQR is the interquartile range Q3-Q1. The upper whisker will extend to the last datum lower than Q3 + 1.5×IQR. Similarly, the lower whisker will reach the first datum higher than Q1 – 1.5×IQR. The orange lines represent the medians.



606

607 **Figure 8.** P-values of Spearman's correlation coefficients (SCC).

608

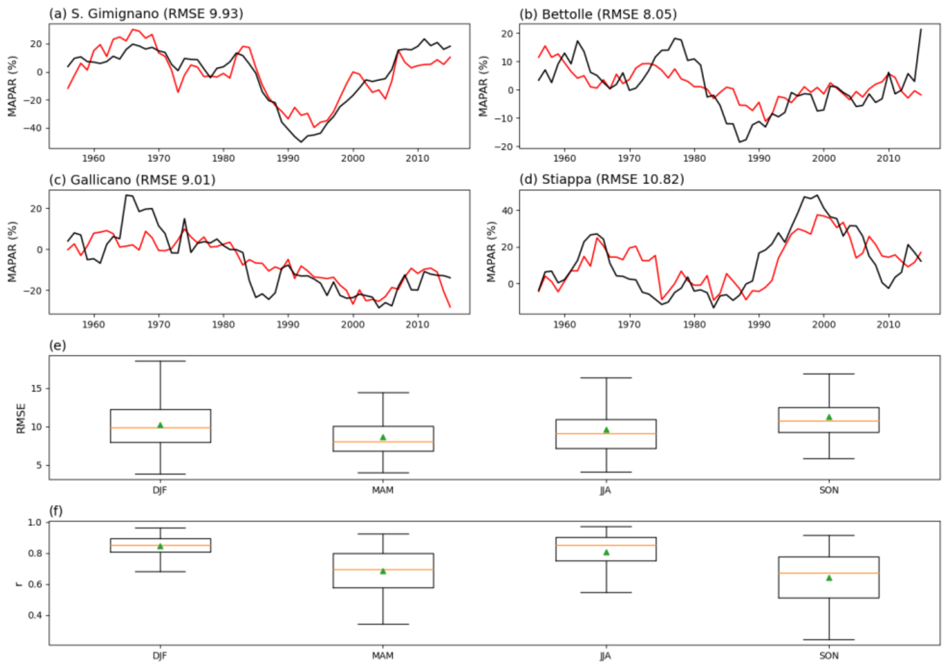


Figure 9. a-d) Four examples of observed MAPAR (black line) and predicted MAPAR (red line) respectively for the seasons DJF, MAM, JJA and SON. e) the boxplots represent the Root Mean Square Error (RMSE) of the linear models for the four seasons. f) the boxplots represent the Correlation Coefficient (r) of the linear models for the four seasons. The boxes represent the interval between the 25th and 75th percentiles (Q1 and Q3). IQR is the interquartile range Q3-Q1. The upper whisker will extend to the last datum lower than Q3 + 1.5×IQR. Similarly, the lower whisker will reach the first datum higher than Q1 – 1.5×IQR. The orange lines represent the medians, while the green triangles represent the means.

Commented [ml2]: In tutte le figure semplificare questa scritta che al primo editor non piace è troppo lunga

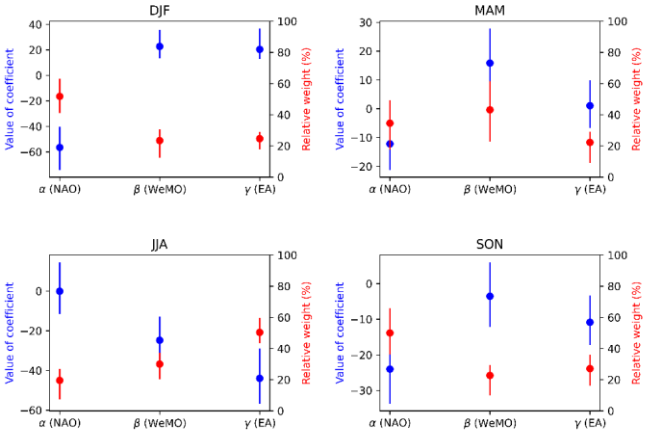


Figure 10. Setting of the linear model coefficients used to understand the relationship between climate patterns and rainfall. The blue circle is the mean absolute value of the coefficient, whereas the red circle represents the mean relative weight of the coefficient on the prediction. The results are reported for each season. The blue and red lines represent the interval between the 25th and 75th percentiles of the coefficient distributions (DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November).

Reviewer #1: This manuscript presents a simple and straightforward method for correlating precipitation patterns with large-scale atmospheric and water temperature variables in the region of Tuscany, Italy. The methods in general are interesting and potentially useful for a wide audience, and I believe it represents a useful contribution to the field; but there are some flaws in the logic and, I believe, some over-interpretation (which I describe below); and the manuscript needs extensive editing and revision to be suitable for publication in a scientific journal like the Journal of Hydrology.

As I describe in detail below, my main concerns are:
1. Most of the introduction is a list of atmospheric and water temperature indices, with general statements of how they vary and are related to other weather-related conditions. These metrics need to be presented and synthesized in a more systematic way. In its current state, these indices feel arbitrarily placed in the introduction, without connection beyond interrelationships. I think this needs to be revised to be clearer and better-related (or perhaps better-balanced; see below).

2. There are two issues related to logic that I think the authors needs to explain and address: First, the authors need to explain the PAR term more clearly and why they define the PAR term relative to a mean of only a fraction of the total data (1960-1990, rather than the entire period 1950-2020); and if this is the reason why the PAR values in the JJA graph in Figure 2 are virtually all below zero. The authors also need to explain the methods relative to Figures 2 and 3 more clearly. I have guessed from context, and my interpretation may be mistaken because the methods are not sufficiently described. Second, I am skeptical of whether the PAR patterns shown in Figures 3 through 6 (possibly the 10 year averaged PAR values) match the PAR in Figure 2 (especially DJF) and most importantly, whether this represents a declining trend (as described in the results) or increased variability (so that the PAR is driven by a few low values).

3. The manuscript also needs extensive editing, with many suggestions provided below.

Detailed comments:
Lines 21-23: missing some words; and it feels a little too uncertain. ("show a possible decrease"? Either they do or they don't, right?)

We removed the word “possible”. In this way the phrase is more affirmative.

Line 30: Check with instructions for authors about naming headings. I think just "Introduction" is sufficient; the idea of identifying goals is implied. (similar for Methods—just Methods). Also, note that J Hydrology requires headings and subheadings to be numbered.

We added the headings and subheadings and modify “Introduction” and “Methods”

Line 39: not sure this is certain. What shows increasing water demand? Is population increasing? Demand has increased since year zero, but is it increasing recently?

In according to reduce the introduction as suggested, we removed this phrase which was not necessary for the introduction of the work

Lines 53-90: Overall, I think this part of the introduction would benefit from improved organization. I've read this introduction several times, and it may be sufficient to end the first paragraph at the Trigo et al reference, and then begin the next paragraph with a sentence "Several atmospheric patterns affect weather in the Mediterranean region. During the winter months…" (picking up with the rest of paragraph 1). Also in the introduction, some of the indices get much more explanation than others. NAO and EA are digestible for a wide range of hydrologists; WeMO has much more detail and feels unnecessarily extensive. I recommend revising to match description of NAO and

EA. Additionally, the connection between NAO, EAP and SST seems disjointed because it appears after WeMO. Overall, I recommend editing this part of the introduction to focus on the indices and how they are related, with sufficient but not overabundant detail.

This part of the introduction was modified in several parts in according with the suggestions of all reviewers

Lines 91-103: Some of this part of the introduction dives into methods. Describing rainfall data sets and how they have been used is suitable for the introduction; describing how they are used in this study (e.g., lines 94-96) is better suited for methods. Also, edit to remove phrases such as "allowed us to" and "helped us to" (not appropriate for a technical manuscript).

I also think there is value in additional explanation about water resource limitations in the Mediterranean: why be concerned about water resources? Seasonality? Is it useful to predict the magnitude of summer drought? Of winter torrents?

We removed the sentence, and improve the introduction adding lines 93-97

Line 106 (study area) - this should be under Methods (double-check with Authors guide)
We moved the “Study area” paragraph into Methods

Line 111 and Figure 1: note that the text in Figure 1 gives an upper range of MAP at 3000 mm but the figure implies the upper limit is 2000 mm. this needs to be edited.
We modified the figure

Line 120: data download description should include the date when data were obtained.

We added when the data was obtained

The grouping of data and their use (line 124-134) is not as clear as it could (or should) be.
- Consider omitting the sentence beginning in line 126, "In many cases,…" because it is redundant.
- The phrase "with a difference in quote of the measurement" is not a phrase that has meaning. Revise with a different phrase.
- Remove "see section linear models"; edit sentence line 133-134 (maybe in to two sentences, removing the word "instead").
- Line 133: "absolute values" - is this rainfall values?

We changed the term “quote” with “altimetry, remove the words indicated and divided the sentence of line 125-126 in two sentences

Lines 134-135: There appears to be a breakdown in logic: the period of record for the 117 time series is 1950-2020 (70 years), but PAR only considers mean rainfall between 1961 and 1990 (30 years). Why omit most of the rainfall data set for calculating such an important part of this metric? Was this intentional? If so, what is the rationale?

The anomaly of a variable is the variation relative to the climatological normal. The normal is the long-term average of the same variable and is used as a baseline value. The normal is typically computed by calculating a climatology over a period of at least 30 years (the climate normal period).

Line 134-136: The PAR is not clear. The variable xi is labeled as the rainfall amount. Can you be more specific? Is it the annual rainfall for year i? or is it the average for the previous 5 years and the following five years (i.e., a 10-year mobile window)? If the 10 year mobile window is an added calculation, a way to graphically represent the PAR, it should be described as such. Also, is PAR a seasonal calculation? Is xi a seasonal xi and mean xi a seasonal average? This is not clearly described.

We modified the line 128-138, distinguishing the calculation of the anomalies (PAR) with the mobile average (MAPAR). We have also modified the text in Results and Discussion change the term PAR with the term MAPAR where it's necessary. In this way, we hope that the methodology is clearer.

Lines 151-152: these are some broad areas. Can you describe whether you just use the water portion of these areas?

We think that all information is provided. The dataset used is Sea Surface Temperatures, for this is only the temperature on the seas.

Line 161: vice versa is two words.

Thanks, we modified it

167-168: a little too colloquial. Remove first sentence, revise the second to read "We created linear models to predict…"

We removed the first sentence

Lines 171-172: revise sentence

We modified the sentence

Figure 2: Figure 2 is important to show the date range on the x-axis for each graph. This is critical for making the PAR characterization for Figures 3-6 (as described in the Results section) understandable and believable. Consider making these full width of the page, stacked four high, rather than side-by-side in a 2-by 2-grid. I have other concerns about the results and their interpretation below.

We have modified the text in methods and results to try to clarify figures 2 and figures 3-6 regarding the PAR quantity. Figure 2 shows the PAR values obtained with equation 2 for each station on the x axis. We modified the Figure 2, and we hope that now it is clearer.

Also, for Figure 2: I am trying to figure out why the PAR values (red dots) for the JJA graph are almost all below zero. I have been experimenting with example datasets trying to re-create this pattern and cannot. I believe there is a problem with this figure the authors need to fix; and if I am incorrect, the authors need to explain in the results why a metric that should mostly be centered around zero (like the other three plots in Figure 2) is almost entirely below zero. (is this because the PAR is only based on the mean of values from 1960 to 1990?)

After the distinction between PAR and MAPAR, the modification of the text and of the figures 2, 3-6, we hope that now it is clearer the difference between the figure 2 and the figures 3-6.

Also for Figure 2, the caption (begin line 519): move the season description (lines 523-524) to earlier, following the word "seasons" (line 520). The description of ICR and whiskers can be abbreviated to one sentence (it is currently 3, which is too wordy).

We move the season description to the start of the figure

I've read the methods section and the results section a few times, and I cannot identify the difference between the PAR values in Figure 2 and the PAR values shown in Figures 3 through 6. Despite that both are labeled PAR and appear to be on the same axis, they are clearly different data sets. For example, the decline in PAR shown in the top part of Figure 3 (PAR, DJF) is not shown in the DJF graph for Figure 2. If the differences between the PAR data shown in Figure 2 and Figure 3 is that Figure 2 is the PAR for each year and Figure 3 is the 10-year averaged value for each year, this distinction should be articulated in the Methods section (reflecting that both were calculated) and in the results section. For example, consider line 184. (continued below)

I also recommend the authors be careful about wording. In particular, line 184 states that Figures 3 through 6 express the trend in PAR and other variables. Do they in fact express the trend, or would it be more accurate to say they show the variation in these variables expressed over the 10-year window, and that these data exhibit a trend?

As explained in the previous answers, we hope that with the modification done it is clearer the difference between the figures. We have modified the phrase of line 184.

Line 186-188: Based on the data shown in Figures 2 and 3-6, I am not certain that I agree with the authors' interpretation of the results related to variation in PAR. The authors state that PAR is reduced in the first years of the 1990s, by a magnitude of 30-40%. If I have interpreted the methods and results clearly (see notes above), Figures 3 through 6 are showing PAR averaged over a 10-year moving window. While Figure 3 shows DJF 10-year averaged PAR declining for each year, Figure 2 for DJF suggests this is driven by a handful (maybe five?) of anomalously low values; other than these anomalous values, PAR appears to be within the same range as it had been over the previous decades.

Also, much of this Rainfall Trends paragraph is not suitably written for a scientific journal article. Terms like "we can observe", "we observe," "very different", "between ca -10 and 20%", "a weakly increase", "presented a certain variability", and the typing error FiguresFigure are stylistic problems with this section and need to be changed. A larger problem is that the authors are interpreting the results of data analyses in a way that, I believe, is not consistent with the data. The changes shown in Figures 3 through 6 are changes in 10-year averaged PAR, not annual PAR and not annual rainfall. I recommend the authors re-write this section to improve the overall technical quality of the writing and to more clearly interpret the results presented.

The Figure 2 and the Figure 3-6 cannot be compared among them. This figures represent the same data but in different way. As above indicated, we hope that now is clearer the distinction. We have modified this paragraph with the reviewer’s suggestions.

Lines 195-208 (Results, Atmospheric teleconnection trends): I suggest the authors structure this by season rather than by index. Presentation of these variables may be sufficient in their current condition, but organizing by season has two benefits: the authors can describe similarities and differences by season, which is significant to the regression analysis; and the graphs are already created by season. Also, stylistically, revise to remove phrases such as "we observe". Also, while it is suitable to generalize about trends or patterns, phrases indicating exceptions like "except for some years" and "except for some cases" are too vague and insufficient for a technical manuscript. These need to be more clearly described and phrased another way relative to the overall pattern, or removed.

We rewritten the paragraph with a reorganization as suggesting by the reviewer

Lines 210-212 (Sea surface temperature trends) is clear and succinct; I suggest the authors revise for stylistic purposes to avoid phrases like "Figures 3-6 show…". Also, line 212: consider replacing the word "higher"4 with "greater".

We modified the word higher with greater and change the begin of the paragraph.

Lines 224-225: revise to remove phrase "on the other hand." These sentences can probably be combined to improve clarity.

We modified it merging the two sentences

Lines 227-228: are the authors certain that a positive EA phase determines increased precipitation? Couldn't other factors determine the precipitation pattern? I think you would need to test this with a circulation model to say for certain that the positive EA determines increased population.

In results, we only present the results obtained by the elaborations. We discuss in line 292-295: "In autumn, the statistical correlations do not allow to make a link between large-scale circulation and rainfall. Indeed, we can observe a weak anticorrelation with NAO, a weak correlation with EA, and no correlation with WeMO. This method seems unsuitable to represent the autumn season with its atmospheric dynamics."

In the results, we would not want to change the phrase. In this paragraph, we have to describe only the results, in discussion we compare the two elaboration applicated, that in this case the statistical correlation does not describe well the behaviour in the autumn. This is write in lines 298-304: "In autumn, the analysis of the linear models identifies an important role of NAO, and therefore a link between the northern Atlantic atmospheric circulation and the rainfall in the study area. In autumn, the coefficients of NAO (are set negative and this means that an increase in the index is linked to a decrease in rainfall in the study area. This mathematical result is more plausible than that obtained from the analysis of correlations based on the notions of atmospheric physics that we introduced previously. The linear model-based method allowed us to refine our investigations and to improve our knowledge of the dynamics in the Mediterranean over the seasons. "

Figure 7 caption should be revised as suggested for Figure 2 caption.

We changed it

Line 232 (Figures 8a-d): the results are quite striking. Which terms are used for these relationships? All? What are the coefficients used? I think these should be reported (possibly in the table recommended below to replace Figure 9?).

We explicated the coefficients α, β and γ for the four cases reported in figure 8.

Figure 8: the caption only needs to include the first sentence (through "…and SON") and then "e) the boxplots…four seasons." Everything else is stated in methods. It could also include the sentence "The orange lines represent the medians, while the green triangles represent the means.", but the seasonal explanation (lines 566-567) can be omitted.

We modified the caption as suggest by the reviewer

Lines 236-249: some of this may be more suitable in the Discussion. review this paragraph to include only those topics that are reflected in the results; additional description of the meaning of relationships are better suited in the Discussion.

We modified these lines; we removed or modified the discussion sentences. We left the general considerations which allow to understand and read the Figure 9

Consider replacing Figure 9 with a table.

We apologize with the reviewer, but we think that the Figure 9 is very important for the paper and their information is better represented in this way than the use of a table. A graphical representation allows to understand immediately the relationship among the different coefficients.

Line 255, and elsewhere in the discussion: no need to refer to figures here unless something specific is being discussed.

We removed the refers to figures where they are not necessary.

Also, line 255: is this the first paper that links climate patterns on local rainfall? Or just for Tuscany? (this is not the first research to link climate patterns to local or regional rainfall.)

No, we didn’t affirm it in the manuscript. In introduction we talk about of several works which study the relationship between synoptic conditions and rainfalls at different scales. The study doesn’t want only quantify the relationship between rainfall and indices, but understanding the trends of the first ones basing on the second ones. Lines 87-88: “The purpose of this study is to understand the rainfall seasonal trends of the last 70 years in Tuscany (central Italy), in relation to mesoscale circulation and to the indices defined above.”

Lines 284-289 (and this section of the Discussion in general): if the value of this method is not to develop the best prediction, what is its value? Could it be to illustrate the general utility of simple tools for these predictions, which could be applied more broadly elsewhere? Or by data analysts who may lack the technical know-how of PhD-level climatologists? For example, managers in a region may be able to use these methods (albeit with different climate datasets, depending on the region) to predict conditions for planning purposes.

As written in Methods (lines: 183-184) and in Discussion (lines: 307-308), the aim of the use of linear models is not create an instrument for the forecasting, but use them for understand the influences of the inputs (the indices) on the outputs (rainfall as MAPAR)

Line 287: sentence beginning "If we wanted…" seems to undermine the utility of this research. consider re-writing this sentence something like "A more complex model may be better suited to reduce overall model error; however, it would have…". This way, it suggests the value of this research as comparable.

We rewritten it

Line 306: re-write to remove the phrase "As a matter of fact"
Done it

Lines 304-316: synthesize this into one single paragraph, rather than four separate ones.
Done it

Lines 331-337: the connections to global warming feel forced and not clearly connected to the results of the paper. I think these should be removed. Instead, I recommend ending with a statement about the potential utility of these methods applied elsewhere to help understand the relationships between atmospheric patterns and precipitation and to steer management priorities in the future, or something similar to highlight the utility of the method.

We modified these lines. We think that all considerations are based on the bibliography and/or the results of this study. We denote the greatest increase of SST in summer (bibliographic information), this influences the indices (bibliographic information) which are correlated with the rainfall (our results). We changed the term “can” with “could” for a more precautionary sentence.

Reviewer #2: This paper investigates the relationship between several climate patterns and seasonal rainfall over a key Mediterranean area. However, I consider that there are some unclear points needing a major revision. I list my concerns as follows:

1. The title emphasizes the influence of the atmospheric circulation on regional rainfall, but from the manuscript I can not see the related mechanisms being confirmed. Results are only based on correlations or a simple comparation. Exactly how the NAO, EA and WeMO jointly influence the seasonal rainfall over the study region needs to be further analyzed.

We changed the title removed the word “Influence” and indicating better using the term relationship”

2. In the abstract (Lines 24-27), the authors outlined that the changes of SSTs lead to the variation of atmospheric pressure, but the visual information (e.g., the pressure fields related to SSTs and/or seasonal rainfall over the study region) is not provided in the manuscript, which needs to be added if possible.

SST influences the climate patterns as introduced mainly in lines 60 – 70. It’s not the aim of the study to demonstrated it or to quantify the influences. For this discussion, we are based on other studies and on the international knowledge of this phenomena.

3. The analysis in the introduction is relatively weak, and the narration is only a simple list, which needs to be strengthened. Specifically, how seasonal rainfall in the Mediterranean region is affected by the atmospheric circulation, which can be concluded from the previous studies, needs to be further outlined in this part.

We have modified the introduction also as suggesting by the other reviewers

4. It would be better if the quality of the rainfall datasets in this paper can be evaluated if it has not been evaluated by previous studies. Also, the approach of merging stations (Lines 126-130) is originally defined by the authors or some previous studies? The authors should state this point more clearly if possible.
We modified the paragraph by adding information on the dataset used. The procedure is all explained because we use this elaboration of the dataset for the first time. If some previous work had used the same procedure, we would have mentioned it. The quality of the dataset is guaranteed by the provider, future works will study if this database with more than 6 million of data is well validated. This dataset is used by high-resolution works in this study area. We added this in text lines 115-118

5. The trends are calculated based on a 10-year mobile window (Line 150). However, I consider that the window length is too short since 10-year trends are likely to be dominated by the climate internal variability. In that case, the influence of the current global warming is likely to be wrongly estimated.
We motivated the choose of range time: lines 137 - 138.

6. To confirm the contributions of atmospheric circulation on rainfall, I consider that correlation needs to be based on detrended series. And if the contributions are confirmed, the trend correlation can be further investigated by the SCC used in this paper to describe the effect of global warming, as well as the different contributions of trends of climate patterns on those of seasonal rainfalls in the study region.

We thank the reviewer for the observation, there are several works, in this field, which use this method in not appropriate way (lines 161 -166). We have demonstrated that the SCC, in the study area, is little influenced by the trends of the time series. For this we have added the lines 174 – 179 and added more details in supplementary material. Furthermore, this work proposed the use of a different method for the investigation of this relationship (lines 182-194). We think that the second method use is more efficient but we have to compare it with the most used method in this thematic area (lines 305 – 310).

7. The statistical significance of all the results of correlation analysis needs to evaluated in the manuscript.
We added it, it is the new Figure 8.

8. Besides RMSE, other metrics (e.g., anomaly correlation coefficient) needs to be added for more comprehensive evaluation of the linear model.

We added the metric of Correlation Coefficient (r) adding text in methods (lines 193 -194) and in results lines 256-257

Reviewer #3: This study aims to analyze the influence of large-scale atmospheric circulation on the rainfall of a key Mediterranean area. The subject of the study fits to the major themes of the journal. The quality of the graphic material of the manuscript are good. However, I have two major concern regarding this study.
(1) The authors made a deep review about the global climate events (NAO, EA and WeMO) and their possible teleconnection with regional climate. However, the authors did not pointed out the innovation or possible new findings of this study. The motivation of this study should be further clarified.

We modified the introduction of the paper in according also with the other reviewer suggestions

(2) The Mediterranean is located between the European humid domain and the North African arid belt, and annual mean precipitation is quite different from the northern and southern parts (Figure 1a). This study mainly focuses on the entire study area without considering the spatial heterogeneity, which may cause bias in results, especially in Figures 2, 3, 4, 5, and 6. It may be better to analyze in different sub-regions separately, such as the northern and southern parts.

We have tested and analyzed the spatial variability of the results but there isn’t significant evidences of this. This can be noted by the variability of PAR (Figure 2) as commented in lines 198 – 199. The area is quite homogenous.

Comments and suggestions:

1) The significance of Spearman's correlation analysis should be given in Figure 7.

We added it, it is the new Figure 8.

2) The linear model may not be an innovative approach to predict rainfall based on large-scale atmospheric circulation indexes in Lines 100-101.

We removed the sentence

3) The datasets are described repeatedly in Lines 94-99 and dataset section.

We modified it, in according also with the other reviewers

Marco Luppichini: Conceptualization, Methodology, Software, Investigation, Data curation, Formal analysis, Writing-Original draft preparation

***Monica Bini**:* Conceptualization, Supervision, Writing-Reviewing and Editing

Michele Barsanti: Writing- Reviewing and Editing.

Roberto Giannecchini: Writing- Reviewing and Editing.

Giovanni Zanchetta: Conceptualization, Supervision, Writing-Reviewing and Editing.

Abstract

Current global warming causes a change in atmospheric dynamics, with consequent variations in the rainfall regimes. Understanding the relationship between global climate patterns, global warming, and rainfall regimes is crucial for the creation of future scenarios and for the relative modification of water management. The aim of this study is to improve knowledge of the relationship between North Atlantic Oscillation (NAO), East Atlantic (EA), and Western Mediterranean Oscillation (WeMO) with the seasonal rainfalls in Tuscany, Italy. The study area occupies a strategic position since it lies in a transition zone between the wet area of northern Europe and the dry area of the northern coast of Africa. This research, based on a statistical correlation method and on linear models, is designed to understand the relationship between seasonal rainfalls and climate patterns. The results of this study demonstrate that the use of linear models can yield more information than traditional statistical correlations. The results show a decrease in rainfall in the warm period of the year, namely in the summer, when its expression is most visible. This phenomenon is ascribable to current global warming, which causes an increase in sea-surface temperatures. An increase in the Northern Atlantic Sea Surface Temperature and in the Mediterranean Sea Surface Temperature causes a reduction of the Iceland Low, with an extension of the Azores High. Moreover, an increase in the Genoa Gulf SST induces a weakening of the Genoa Gulf Low, one of the main cyclogenetic systems of the Mediterranean.

Highlights (3 to 5 bullet points (maximum 85 characters including spaces per bullet point)

Highlights

1. Seasonal ~~R~~rainfall t~~T~~rend in Tuscany (Italy) during the last 70 years
2. Statistical and mathematical correlation between atmospheric teleconnections and rainfall amount
3. Influence of the atmospheric teleconnection variations on the rainfall regime
4. Influence of current global climate change on the rainfall regime in an area of the Mediterranean