Hydrology and Earth System Sciences Discussions

Coupled decadal variability of the North Atlantic Oscillation, regional rainfall and spring discharges in the Campania region (Southern Italy)

P. De Vita, V. Allocca, F. Manna, and S. Fabbrocino

Dipartimento di Scienze della Terra – University of Naples "Federico II", Naples, Italy

Correspondence to: P. De Vita (padevita@unina.it)

Abstract

Climate change is one of the issues most debated by the scientific community with a special focus to the combined effects of anthropogenic modifications of the atmosphere and the natural climatic cycles. Various scenarios have been formulated in order to
⁵ forecast the global atmospheric circulation and consequently the variability of the global distribution of air temperature and rainfall. The effects of climate change have been analysed with respect to the risks of desertification, droughts and floods, remaining mainly limited to the atmospheric and surface components of the hydrologic cycle. Consequently the impact of the climate change on the recharge of regional aquifers
¹⁰ and on the groundwater circulation is still a challenging topic especially in those areas whose aqueduct systems depend basically on springs or wells, such as the Campania region (Southern Italy).

In order to analyse the long-term climatic variability and its influence on groundwater circulation, we analysed decadal patterns of precipitation, air temperature and spring
¹⁵ discharges in the Campania region (Southern Italy), coupled with the North Atlantic Oscillation (NAO).

The time series of precipitation and air temperature were gathered over 90 yr, in the period from 1921 to 2010, choosing 18 rain gauges and 9 air temperature stations among those with the most continuous functioning as well as arranged in a homoge-
²⁰ neous spatial distribution. Moreover, for the same period, we gathered the time series of the winter NAO index (December to March mean) and of the discharges of the Sanità spring, belonging to an extended carbonate aquifer (Cervialto Mount) located in the central-eastern area of the Campania region, as well as of two other shorter time series of spring discharges. The hydrogeological features of this aquifer, its relevance
²⁵ due to the feeding of an important regional aqueduct system, as well as the unique availability of a long-lasting time series of spring discharges, allowed us to consider it as an ideal test site, representative of the other carbonate aquifers in the Campania region.

The time series of regional normalised indexes of mean annual precipitation, mean annual air temperature and mean annual effective precipitation, as well as the time series of the normalised annual discharge index were calculated. Different methods were applied to analyse the time series: long-term trend analysis, through smoothing numerical techniques, cross-correlation and Fourier analysis.

The investigation of the normalised indexes has highlighted long-term complex periodicities, strongly correlated with the winter NAO index. Moreover, we also found robust correlations among precipitation indexes and the annual discharge index, as well as between the latter and the NAO index itself.

Although the effects of the North Atlantic Oscillation had already been proved on long-term precipitation and streamflow patterns of different European countries and Mediterranean areas, the results obtained appear original because they establish a link between a large-scale atmospheric cycle and the groundwater circulation of regional aquifers. Therefore, we demonstrated that the winter NAO index can be considered as an effective proxy to forecast the decadal variability of groundwater circulation in Mediterranean areas and in estimating critical scenarios for the feeding of aqueduct systems.

1 Introduction

In the last decades, the international scientific community has intensely debated the climate change on a global scale (WMO, 1979) and the influences of the anthropogenic activities. Since 1979, several international research programs (e.g., World Climate Programme – WCP, World Climate Data and Monitoring Programme – WCDMP) have been developed in order to analyse the state of knowledge on climate change, to start a global monitoring of the climate systems and to fully understand the causes of its variability. Different groups of international experts (Intergovernmental Panel on Climate Change – ICCP) have been called to analyse the different cause and effect of these changes on the environment. Numerous reports have been published (ICCP, 1990,

2001, 2007) that summarized the state of the art and evaluated different scenarios for the impact of greenhouse gas pollution on the global climate.

On the national scale, many hydrological and climatological studies (Lo Vecchio and Nanni, 1995; Brunetti et al., 2000, 2001, 2006), following different methodological approaches, have analysed the decadal climatic variations in Italy and the Mediterranean area by the long-term trends of annual precipitation and mean annual air temperature time series.

Other studies in Italy have analysed the relationship between climate change and groundwater circulation (Dragoni and Sukhija, 2008; Cambi and Dragoni, 2010). Particularly, for the Campania region, in order to assess the impact of the climate variability on the water budget, a reduction of precipitation of about 20 % in the last 20 yr was estimated (Ducci and Tranfaglia, 2008).

In recent years, numerous studies have analysed the influence of the North Atlantic Oscillation (hereinafter NAO) on the annual variability of precipitation (Hurrell and Van Loon, 1997; Rodriguez-Puebla et al., 1998; Uvo, 2003; Muñoz-Díaz and Rodrigo, 2004; Lopez-Moreno and Vicente-Serrano, 2008; Rodriguez-Puebla and Nieto, 2010; Vincente-Serrano and Trigo, 2011) and the consequent effects on surface hydrology (Shorthouse and Arnell, 1997; Cullen et al., 2002; Rimbu et al., 2002; Karabörk et al., 2005; López-Moreno et al., 2007; Massei et al., 2009; Morán-Tejeda et al., 2011). Some of the more recent studies (Beranova and Huth, 2008; Vicente-Serrano and Lopez-Moreno, 2008) have also shown a non-stationary influence of the NAO on the climate in Europe.

In the Mediterranean area, a relationship between the NAO and river discharges has been found in the Middle East (Cullen and Demenocal, 2000; Cullen et al., 2002) and in Turkey (Karabörk et al., 2005), where there has also been found a relationship between lake levels and the NAO (Kücük et al., 2009). The influence of the NAO on river discharges has been analysed in various watersheds in the Iberian Peninsula (López-Moreno et al., 2007; Trigo et al., 2004; Moran-Tejeda, et al., 2011), where reasonably significant correlations between the NAO and streamflows have been found,

particularly in winter. A recent study (Lacruz-Lorenzo et al., 2011) analysed the nature of this relationship and its spatial and temporal variability and assessed a potential influence of the temporal evolution of the NAO on the Iberian streamflows. None of the abovementioned studies analysed the impact of the climatic variability due to the NAO on the annual, interannual and decadal groundwater regime.

The objective of this study has been to analyse, on the regional scale, the relationship between the NAO, expressed by the NAO Index (hereinafter NAOI), and patterns of precipitation, air temperature and spring discharge in the Campania region over a multi-decadal period. We analysed datasets, covering the period of 90 yr (1921–2010), made up of data gathered from 18 rain gauges and 9 temperature gauges, chosen among other ones by considering the regular functioning in the whole period and their homogeneous distribution over the territory. We also analysed the discharge time series of the Sanità spring fed by the groundwater circulation of an extended fractured carbonate aquifer that is unique for the continuity of recording since the beginning of the last century, together with two other shorter time series of spring discharges.

The present research represents the continuation and the updating of previous studies conducted on the climatic variability of Southern Italy due to the NAO (De Vita and Fabbrocino, 2005, 2007).

2 Hydrogeological and climate characteristics of the Campania region

The Campania region is located in the southern part of the Italian peninsula and has an extension of about 13 590 km^2. It can be subdivided by the fundamental geomorphological features in the Apennine mountain ranges that reach altitudes from 1000 to 2000 m a.s.l., accounting for 30 % of the whole regional area, coastal plains, accounting for a further 18 %, and a remnant part, consisting of low-altitude hills and alluvial valleys. The regional hydrogeological setting (Fig. 1) is basically characterised by extended carbonate aquifers, with a high permeability degree due to fracturing and karst. These aquifers are confined by aquitards, constituted of flysch and basinal series

11237

(Celico, 1978, 1983; Celico et al., 2000; Allocca et al., 2007, 2009). Morphologically the first aquifers correspond to the higher mountains (carbonate massifs), instead the second ones to the low-altitude hills. Both two types of hydrostratigraphic units originate from tectonic units thrust in the Apennines chain.

5   The climate of the Campania region is of a Mediterranean type with hot dry summers and moderately cool and rainy winters. Mean annual air temperatures are in the range of about 10–12 °C in the mountainous interior, 13–15 °C in the coastal areas, and 12–13 °C in the plains surrounded by the carbonate massifs. Particularly, the rainfall regime in the Campania region varies from the coastal, or the Mediterranean type,
10 and the Apennine sublittoral (Bandini, 1931; Tonini, 1959), characterised by a principal maximum in autumn-winter and a minimum in summer. The precipitation regime and distribution over the region is mainly controlled by the position of the Appennine mountain ranges which, acting as a barrier against humid air masses coming from the Thyrrhenian Sea, induce orographic precipitation (Henderson-Sellers and Robinson,
15 1986). Due to the increase of the condensation process, precipitation is generally fairly correlated with altitude, especially on the mean annual scale. The lowest mean annual rainfall, about 700–900 mm, occurs in the western and eastern parts of the Campania region; the highest, about 1700–2000 mm, occurs in the central part of the Apennine ridge.

20 The most important hydrogeological units of the region are found in the carbonate massifs, formed by limestone, dolomitic limestone and dolomitic series (Trias–Paleogene) of carbonate platform facies, which constitute aquifers with the highest groundwater yield, varying from 0.015 to 0.038 $m^3 s^{-1} km^{-2}$ (Allocca et al., 2007, 2009). The hydrogeological behaviour of these aquifers is conditioned by the peculiar porosity
25 and permeability, both derived from tectonic brittle deformation and karst. Carbonate aquifers are typically characterized by a basal groundwater flow, outflowing in huge basal springs, with average discharge frequently greater than 1.0 $m^3 s^{-1}$. The patterns of groundwater flow are greatly conditioned both by the altimetry of the boundary with the juxtaposing lower permeability flysch deposits and by position and permeability of

cataclastic bands, associated with main faults and thrusts, which acting as aquitards determine the fractioning of the groundwater flow into several groundwater basins. Differently, whereas carbonate aquifers are juxtaposed with permeable Plio-Quaternary epiclastic and alluvial deposits, a groundwater exchange can exist. A subordinate
5 perched groundwater flow also occurs in the surficial part of carbonate mountains, whereas the different deepening of epikarst (Celico et al., 2010), as well as stratigraphic and tectonic factors, can generate seasonal and ephemeral springs. Given their high quality and availability to exploitation, groundwaters of carbonate aquifers represent strategic resources for the socio-economic development of the Campania
10 region and Southern Italy.

3   The North Atlantic Oscillation

The NAO has been recognized since the last century as one of the principal patterns of atmospheric circulation affecting the climate in the Northern Hemisphere (Walker and Bliss, 1932), and especially in the North Atlantic sector (Wallace and Gutzler,
15 1981; Barnston and Livezey, 1987). However, it has only become the subject of wider scientific interest in recent years for the impact on the annual and decadal climate variability (van Loon and Rogers, 1978; Rogers, 1984; Barnston and Livezey, 1987; Hurrell, 1995; Hurrell and van Loon, 1997). This phenomena is recognised as an oscillation of the atmospheric masses over the tropical zone of the Azores Islands
20 (barometric high) and Iceland (barometric low), consisting in the annual and decadal variably of the difference of barometric pressure if considered in the same period of the year. Therefore, it is characterized by a north-south dipole with its centres located in the area of the Icelandic cyclone and Azores anticyclone, respectively.

Several studies have been shown the relevance of the NAO to the winter surface
25 climate of the Northern Hemisphere in general and over the Atlantic-European sector in particular (Hurrell, 1995, 1996; Pozo-Vazquez et al., 2001). The NAO significantly extends its control on climate (Hurrell and van Loon, 1997) also in Northern Africa

(Hasanean, 2004), Western and Northern Asia (Türkes and Erlat, 2005; Kryjov, 2002), and Eastern North America (Sheridan, 2003; Tootle et al., 2005).

A large number of studies were carried out on the effects of the NAO on climatic parameters in Europe, mainly on precipitation and air temperature (Hurrell and van Loon, 1997). The NAO causes annual and decadal variations of the climatic parameters in the coastal area of the Eastern Atlantic Ocean (Barnston and Livezey, 1987). Such a periodic anomaly resulted well correlated with the climatic characteristics of the Northern Hemisphere, namely with the atmospheric precipitation and with the air temperatures (Hurrell, 1995). The influence of this periodic atmospheric phenomenon is extended in the European continent at least as far as Turkey, as was demonstrated by the good correlation between mean climatic parameters of this continental area and the NAOI (Cullen and deMenocal, 2000; Türkes and Erlat, 2005). Recent studies have revealed that the impact of the NAO in Mediterranean areas can be widely conceived as extendable also to snow accumulation, crop production, landslides and soil erosivity (Vicente-Serrano and Trigo, 2011).

The NAO is expressed by the NAO Index (hereinafter NAOI) (Walker and Bliss, 1932; Rogers, 1984; Hurrell, 1995), which is defined by the barometric anomaly, with respect to the standard difference, between the Iceland's barometric low and the Azores's barometric high, considered in the same period of the year. This index varies yearly with a complex periodicity, but can belong to the same phase (positive or negative) for some consecutive years or decades. The positive value of the NAOI indicates the existence of an atmospheric pressure greater than the mean value over the tropical zone of the Azores Islands and an atmospheric pressure lower than the mean value over Iceland, therefore a greater barometric difference between the aforesaid poles. In the positive period of the NAOI, the Mediterranean and the central-southern areas of Europe have mild winters with lower atmospheric precipitation while the northern parts of the European continent are affectedby intense perturbations. Instead, the negative value of the NAOI indicates an anomalous reduction of the barometric difference between the Azores and the Icelandic poles. During the negative phases, the lower barometric

gradient does not allow the formation of intense perturbations on Northern Europe but it induces less intense perturbations on the Mediterranean and central-southern areas of Europe, causing humid winters in these areas (Rogers, 1990, 1997; Hurrell, 1995; Hurrell and van Loon, 1997; Alexandersson et al., 1998).

Numerous authors have analyzed the temporal structure of NAO (Greatbach, 2000; Wanner et al., 2001; Hurrell et al., 2003) concluding that there is no preferred time scale of NAO variability and that the spectrum of the winter NAOI demonstrate a general increase of power with period length. In detail, a quasi-biennial periodicity, a deficit in power from 3 to 5 yr and an increase in power from 8 to 10 yr, which resulted more enhanced in the second half on the 20th century (Hurrell and van Loon, 1997), were recognized. Concerning the decadal variability of the NAO, other authors (Feldstein, 2000; Czaja et al., 2003; Viesbeck et al., 2003) have concluded that it depends on coupling with external forcing (e.g. the ocean).

Due to the teleconnection of the NAO with climate variability of Northern Hemisphere, different authors carried out research regarding the forecasting of the NAO (Hurrell, 2003; Cohen and Barlow, 2005) to be used as a proxy.

4 Hydrologic data and methods of analysis

The comparison among atmospheric, hydrological time series, recorded at different levels of time aggregation, required a preliminary homogeneisation for aggregating precipitation, air temperature and spring discharge data to the annual time scale, comparable with that of NAOI. Different methods of analysis have been applied to investigate decadal variability and correlations among time series: trend analysis by smoothing numerical techniques, cross-correlation, statistical tests for correlation significance, spectrum and cross-spectrum analyses by Fourier transform. In particular, the trend analysis was performed both with linear regression techniques and with low-pass numerical filtering of time series to put in evidence their decadal components. In this approach we used the moving average over 11 yr centred on the sixth year. Moreover,

we calculated moving 5 % and 95 % percentiles over 11 yr, centred in the sixth year, with the purpose of estimating the variability around the mean value and of recognising anomalous annual values, outside of the 90 % frequency range.

4.1 NAO Index time series

Different NAOIs exist depending on the barometric stations and on the period of the year considered (Hurrell, 2003). For the case study, the analysis was performed by using a subset (1921–2010) of the winter NAOI (December through March mean – DJFM) time series calculated by the records of the Lisbon (Portugal) and Stikkishlomur (Iceland) barometric stations, since 1864. The data set were gathered from the website http://www.cgd.ucar.edu/cas/jhurrell/indices.html.

4.2 Precipitation and air temperature time series

For the study of fundamental climatic variables, the annual total precipitation and the mean air temperature were gathered from the official monitoring network for the period 1921–2010 (90 yr). Since 2000, the management of the monitoring network has been changed from national technical service (Italian Hydrographic and Tidal Service) and national agencies (APAT-ISPRA) to regional Civil Protection agency.

In particular, we selected 18 rain gauge stations (Fig. 1) on the basis of the temporal continuity of the record, and of the homogeneous distribution over the territory of the Campania region. Similarly, we identified 9 thermometric stations (Fig. 1). The smaller number of available thermometric stations reflects the sparser density of the air temperature monitoring network due to the less spatial variability of air temperature, which mainly depends on the altitude more than the location.

The assessment of a climate trend at regional scale was performed by the definition of an index representative of the annual anomaly of precipitation, with respect to the mean value, over the region, which was able to minimize variations due to local

11242

factors. Therefore, for each rain gauge station, the Annual Precipitation Index (API) was calculated as:

$$API_{ji} = \frac{AP_{ji} - MAP_j}{MAP_j} \tag{1}$$

with API_{ji} = Annual Precipitation Index for the j rain gauge station and the i year (%); AP_{ji} = Precipitation for the j rain gauge station and the i year (mm); MAP_j = Mean Annual Precipitation of the whole time series for the j rain gauge station (mm yr^{-1}).

In order to get a regional index, we calculated, for each year of the time series, the mean API value for the 18 rain gauge stations, defined as the Mean Annual Precipitation Index (hereinafter MAPI):

$$MAPI_i = \frac{\sum_{j=1}^{18} API_{ji}}{18} \tag{2}$$

with $MAPI_i$ = Mean Annual Precipitation Index at regional scale for the i year (%); API_{ji} = Annual Precipitation Index at the j rain gauge station for the i year (%).

In the same way and with reference to the identical observation period (1921–2010), the Annual air Temperature Index (ATI) was calculated as:

$$ATI_{ki} = \frac{AT_{ki} - MAT_k}{MAT_k} \tag{3}$$

with ATI_{ki} = Annual air Temperature Index for the k air temperature gauge station and the i year (%); AT_{ki} = Annual air Temperature for the k air temperature gauge station and the i year (°C); MAT_k = Mean Annual air Temperature of the whole time series for the k air temperature gauge station (°C).

Accordingly, we calculated, for each year of the time series, the mean value of the 18 rain gauge stations, defined as the Mean Annual air Temperature Index (hereinafter MATI).

$$MATI_i = \frac{\sum_{k=1}^{9} ATI_{ki}}{9} \tag{4}$$

11243

with MATI$_i$ = Mean Annual air Temperature Index at regional scale for the i year (%); ATI$_{ki}$ = Annual air Temperature Index for the k air temperature gauge station and the i year (%).

4.3 Effective precipitation time series

In order to assess the mean annual effective precipitation, which regulates the groundwater recharge, we estimated the mean annual real evapotranspiration, for each rain gauge stations, by applying Turc's empirical formula (Turc, 1954), as several studies have confirmed its reliability for Mediterranean areas and Southern Italy (Santoro, 1970; Boni et al., 1982; Celico, 1983):

$$ET_{ji} = \frac{AP_{ji}}{\sqrt{0.9 + \left(\frac{AP_{ji}}{300 + 25 \cdot AT_{ji} + 0.05 \cdot AT_{ji}^3}\right)^2}} \tag{5}$$

with ET$_{ji}$ = Real evapotranspiration for the j rain gauge station and the i year (mm yr^{-1}); AP$_{ji}$ = Precipitation for the j rain gauge station and the i year (mm yr^{-1}); AT$_{ji}$ = Annual air Temperature for the j rain gauge station and the i year (mm yr^{-1}).

For the rain gauge stations withouth of air temperature gauges (Fig. 1) we extrapolated mean annual air temperature values by means of linear correlations with altitude that resulted statistically robust in all cases.

For each rain gauge station, the Annual Effective Precipitation Index (AEPI) was calculated as:

$$AEPI_{ji} = \frac{AEP_{ji} - MAEP_j}{MAEP_j} \tag{6}$$

with AEPI$_{ji}$ = Annual Effective Precipitation Index for the j rain gauge station and the i year (%); AEP$_{ji}$ = Annual Effective Precipitation for the j rain gauge station and the

11244

i year (mm); MAEP$_j$ = Mean Annual Effective Precipitation of the whole time series for the j rain gauge station (mm yr^{-1}).

Finally, for each year of the time series, the mean value of the 18 rain gauge stations, defined as the Mean Annual Effective Precipitation Index (hereinafter MAEPI) was calculated as:

$$\text{MAEPI}_i = \frac{\sum_{j=1}^{18} \text{AEPI}_{ji}}{18} \tag{7}$$

with MAEPI$_i$ = Mean Annual Effective Precipitation Index at regional scale for the i year (%); AEPI$_{ji}$ = Annual Effective Precipitation Index at the j rain gauge station for the i year (%).

4.4 Spring discharge time series

We considered the discharge time series of the Sanità spring (1921–2010), unique for the Campania region and Southern Italy, both for the length and for the continuity of the recording as well as for the hydrogeological representativeness of the feeding aquifer. The Sanità spring (420 m a.s.l.) represents the sole groundwater outflow of the Mount Cervialto carbonate hydrogeological unit, extended for over 128 km^2 and confined by hydrostratigraphic units with lower degree of permability, constituted of pre-orogenic and syn-orogenic terrigenous basinal series (Celico, 1978, 1983). It is located in the upper part of the Sele river watershed (Fig. 1), close to the town of Caposele (Province of Avellino). The spring was tapped in 1906 by the Apulian Aqueduct, which by extension and capability is among the most important and exemplary works of hydraulic engineering ever made in Italy. The spring discharges have been measured, with a bi-weekly frequency, since 1920 and with a continuous monitoring since 1964, allowing the estimation of the mean annual discharge as corresponding to 3.95 m^3 s^{-1}. The carbonate aquifer of the Mount Cervialto hydrogeological unit suffered a strong seismic shaking due to the proximity (<10 km) of the epicentre of the 23 November 1980

11245

earthquake ($Ms = 6.9$ and a focal depth of 16 km) that resulted in anomalous high discharges of the Sanità spring during the period 1980–1981, followed by the recovering of normal discharge values until 1984 (Celico, 1981; Celico and Mattia, 2002). The hydrogeological effect of the same earthquake was simplistically believed by non-scientists as responsible of the decrease of spring discharges and of the loss of minor springs in the Campania region during the 80s and 90s, not considering the consequences of the decrease in precipitation for the same period.

The same time series was already analysed by other authors in order to discover a method of analysis and forecasting of drought periods (Fiorillo, 2009; Fiorillo and Guadagno, 2010).

On the basis of such time series, we calculated the Mean Annual Discharge Index (hereinafter MADI) for the Sanità spring as:

$$MADI_i = \frac{MAD_i - MAD}{MAD} \qquad (8)$$

with $MADI_i$ = Mean Annual Discharge Index for the i year (%); MAD_i = Mean Annual Discharge for the i year ($m^3 yr^{-1}$); MAD = Mean Annual Discharge of the whole time series ($m^3 yr^{-1}$).

With the same approach we calculated analogous indexes for the time series of annual minimum and maximum discharge, thus defining the $MADI_{max}$ and the $MADI_{min}$ time series. The latter was considered particularly significant for the assessment and forecasting of annual low flow values, due to the dependence of the aqueduct feeding.

We considered also other shorter time series of spring discharges, chosen among those of greater duration available for the Campania region, relative to the Cassano Irpino and Maretto springs and, respectively belonging to the Mount Terminio and the Mount Matese carbonate hydrogeological units (Fig. 1). The recording period considered was 1965–2010 for the first time series and 1965–2000 for the second one, thus with a partial overlapping interval with the Sanità spring time series, respectively of 45 and 35 yr.

11246

5 Results

5.1 Correlation of the NAOI and regional climatic indexes

The time series of NAOI and of the three standardised indexes we constructed, MAPI, MATI and MAEPI (Fig. 2), were firstly analysed with a least squares linear regression
[5] approach as other authors have done for precipitation data in Southern Italy (Cotecchia et al., 2003; Polemio and Casarano, 2008; Ducci and Tranfaglia, 2008). This analysis showed a general linear decreasing trend for MAPI and MAEPI with no high statistical significance (probability of null hypothesis > 5 %), respectively with annual decreasing rates of −0.13 %, respect to the mean value (1160.2 mm yr^{-1}), ($r = -0.203$; Prob. t-
[10] Student and Prob. F-Fisher equal to 5.43 %), and −0.26 %, respect to the mean value (625.2 mm yr^{-1}), ($r = -0.196$; Prob. t-Student and Prob. F-Fisher equal to 7.23 %). Instead, for the MATI a statistically more significant linear trend was found with an annual increasing rate of 0.6 %, respect to the mean value of (14.3 °C), ($r = 0.262$; Prob. t-Student and Prob. F-Fisher equal to 1.54 %).

[15]   Beyond the linear trends, we recognised the existence of patterns of the time series featured by a complex cyclicity, from the annual to the decadal time scales. For the MAPI and MAEPI time series, fluctuations around the mean value were observed with respective extremes of ±35 % and ±60 %. The greater fluctuations estimated for the MAEPI, were considered as linked to the non-linear effect of the evapotranspiration that
[20] enhances the extremes of effective precipitation respect to those of precipitation. The fluctuation of the MATI time series were observed as ranging around the mean value, approximately in the interval of ±15 %.

   The long-term pattern of the winter NAOI (Fig. 2a) was observed with a complex cyclical dynamics, clearly detectable through the pattern approximated by the 11-yr
[25] moving average. The graphical inspection clearly showed how the NAOI tends to belong to the same phase for consecutive years (Hurrell and van Loon, 1997). In particular, during the examined time span, two negative phases, corresponding to the periods 1930–1944 and 1958–1978, two positive phases in the period 1945–1956 and, more

significantly, for the years subsequent to 1980 (Fig. 2a) were observed. The long-term trend, as approximated by the 11-yr moving average, was clearly recognised as oscillating around the normal value, at least until the early 80s. However, during the last decades of the time series, a dominance of positive values was identified, never reached during the previous periods. Turning our attention to the variability of the phenomenon, we observed that the fluctuations around the normal value tend to be greater since the 1960's if compared to the previous decades, with an absolute maximum reached in 1989 and a minimum peak observed in 1969.

As previously discussed, for the long-term trend estimated for the MAPI we found a linear declining trend over the whole observed time period. In addition, a complex cyclical dynamic was recognised by the observation of the 11-yr moving average pattern respect to the normal value (mean value of the whole time series) (Fig. 2b). Two phases characterized by values above the normal value, respectively in the periods 1930–1944 and 1958–1978, and three phases below the normal value, in the years preceding the 1930 and in the periods 1944–1958 and 1980–1990, were identified (Fig. 2b). The fluctuations around the mean value of the moving average were observed as varying between -18% (1990) and $+12\%$ (1938). In detail, starting from the 1987 and until the l994, we observed the lowest values ($< -30\%$) recorded for the entire time series of the MAPI, although some similar values were found also in 1932 and 1946, and, more recently, in 2001 and 2007 (Fig. 2b). Maximum values of the time series were observed at $+31\%$ (1933), $+35\%$ (1969) and $+41\%$ (2010). Interestingly, for the last part of time series of the MAPI and similarly to the NAOI, a downward shift in the level of the calculated index was discovered. Therefore, during the last three decades, we found the lowest values for the annual precipitation, consistently with the evidence discovered by other researchers (Ducci and Tranfaglia, 2008).

The long-term trend of the MATI (Fig. 2c) displayed an increasing pattern for the mean air temperature, although that we also observed a complex cyclical dynamic, witnessed by fluctuations of the 11-yr moving average around the mean value, which reached the minimum at -7% (1940) and the maximum at $+5\%$ (1997). In detail, the

11248

minimum value of the MATI was observed with −15 % (1944) and the maximum with +14 % (1994). More generally, the last two decades of the time series were characterized by the highest air temperature recorded over the whole time series and this evidence is consistent with what was previously found by other researchers (Ducci and
5 Tranfaglia, 2008).

The decadal trend of the MAEPI (Fig. 2d) showed very remarkable fluctuations around the mean value, with cyclical long-term dynamics visibly correlated to the alternation of the phases of the NAOI and with a very similar pattern to that observed for the MAPI series. In detail, the 11-yr moving average of MAEPI was observed fluc-
10 tuating between an absolute minimum of −29 % and an absolute maximum of +28 %, respectively for 1938 and 1990, therefore confirming the amplification effect due to the nonlinear behaviour of the actual evapotranspiration. In detail, the extreme values of the time series, spreading from +72 % (1933) and −61 % (2001) were identified as matching those of the MAPI time series. Similarly to the NAOI and the MAPI, there
15 was evidence also for the MAEPI of a downward shift in the calculated moving average toward the last decades of the time series, highlighted by a prevalence of negative values since the 80s.

The variability of MAPI and MAEPI, identified as the difference between the 5 % and the 95 % 11-yr moving percentiles, appeared inconstant during the time series with
20 higher spreading, respectively from +30 % to −20 % and from +60 % and −30 %, in the periods characterised by the negative phase of the NAO. Instead, a lower variability in the positive phase of the NAO was observed, respectively from +5 % to −30 % and from +20 % to −50 % (Fig. 2b,d).

The integrated analysis among the different components of long-term time series
25 showed, after filtering with the 11-yr moving averages, a strong co-movement and a good overlapping of the positive and negative peaks, quite clearly discernible, among the NAOI, MAPI and MAEPI (Fig. 3). Particularly, the more simplified periodicity of time series showed two decadal cycles and the beginning of a third cycle approximately starting from 1990.

We verified the existence of a significant correlation between the winter NAOI and MAPI by means of cross-correlation analysis carried out between the raw data of these two time series. In this case the absolute maximum value of the correlation ($r = -0.422$; Prob. t-Student 0.003 %; Prob. F-Fisher 0.004 %) was found at the lag time, respec-
tively variable from 0 to +1 yr (Fig. 4). Considering the 11-yr moving averages time series, the absolute maximum value of the correlation resulted increased and more statistically significant ($r = -0.767$; Prob. t-Student < 0.0001 %; Prob. F-Fisher < 0.0001 %).

In order to understand the spatial influence of the NAO over the Campania region, we reconstructed the distribution of the correlation coefficient calculated between the
11-yr moving average of the winter NAOI and of the annual precipitation time series of each rain gauge station (Fig. 5). We found absolute higher values of correlation coefficient for rain gauge stations located westward of the Apennine morphological divide and closer to the Tyrrhenian coast line. Instead a decrease of the coefficient for rain gauge stations located eastward of principal mountain ranges was recognised. This
distribution appeared consistent with the direction of humid air masses that, moving eastward from the Atlantic Ocean and the Mediterranean Sea, impact over the first mountain ranges determining locally greater precipitation.

The cross-correlation analysis between the winter NAOI and MAEPI (Fig. 6) revealed a correlation stronger than the preceding both for the raw data of time series ($r = -0.431$; Prob. t-Student and Prob. F-Fisher equal to 0.004 %) and for 11-yr moving averages time series ($r = -0.744$; Prob. t-Student and Prob. F-Fisher < 0.0001 %). Also in these cases the maximum correlation values were found, respectively at the lag time of 0 and +1 yr.

The lower values of the correlation coefficient calculated for the raw series respect
to the filtered series suggested that the greater influence of the NAO on the regional precipitation pattern occur at the decadal time scale. This indicated an interaction model that sees a long-term trend shared by the two time series, NAOI and MAPI, and some high-frequency fluctuations due to randomness of short-term, not necessarily common to both phenomena. In order to better understand this aspect, we carried out

specific analyses on periodicities of time series (Sect. 5.3).

The cross-correlation between the NAOI and MATI (Fig. 7) resulted statistically significant for the raw data of time series ($r = 0.3633$; Prob. t-Student and Prob. F-Fisher equal to 0.063 %) and more robust for the 11-yr moving averages ($r = 0.5971$; Prob. t-Student and Prob. F-Fisher lower than 0.0001 %). For both the maximum correlation was found at a time lag of +9 yr. We have considered the interpretation of such an interesting result beyond the scope of the paper and as the opening of a complementary research regarding the teleconnections among different atmospheric, oceanic and astronomical cycles that should be analysed on a continental scale.

5.2 Correlation of the NAOI and spring discharges

As already described for the MAPI and MAEPI time series, also for the MADI we discovered a high annual fluctuation around the mean value (Fig. 8a) of the whole time series with extremes of +37.6 % (1941) and −25.2 % (2002) and a general decreasing trend of −0.14 % per year, respect to the mean value ($3.95\,\mathrm{m^3\,s^{-1}}$), ($r = -0.300$; Prob. t-Student = 0.52 % and Prob. F-Fisher = 0.40 %). An analogous behaviour was observed for the $\mathrm{MADI_{min}}$ time series (Fig. 8b) with a general linear decreasing trend with −0.07 % per year, respect to the mean value ($3.41\,\mathrm{m^3\,s^{-1}}$), ($r = -0.1830$; Prob. t-Student = 9.28 % and Prob. F-Fisher = 8.35 %). For this time series, the extremes resulted more limited and spread in the range from +20 % (1940) to −20 % (1992), excluding the period 1980–1981 that was influenced by the earthquake of the 23 November 1980.

In addition to a general decreasing trend, a complex multi-year cyclicality, as clearly visible by the 11-yr moving average filter, was identified. From the pattern of the 11-yr moving average, two phases of maxima were recognised, corresponding to years 1930–1944 and 1958–1978, and two phases of minima, corresponding to the years before 1930, the period 1944–1958 and the years after 1980 (Fig. 8a,b).

As already observed for the MAPI and MAEPI time series, the variability of MADI, identified as the difference between the 5 % and the 95 % 11-yr moving percentiles, was

11251

observed higher in the negative phase of the NAO, respectively varying from +30 % and −15 % and lower in the positive phase of the NAO, with variations of +5 % and −20 % (Fig. 8a). Instead, for the MADI$_{min}$ time series a lower variability was recognised (Fig. 8b).

The decadal fluctuations of the MADI were also observed as strongly correlated with those of the NAOI. The integrated analysis of the long-term components of the two series, expressed by the 11-yr moving averages, showed clear phase coherence between time series, by the matching of the relative peaks (Fig. 9), except for the period 1980–1981, influenced by the earthquake shaking.

This observation was confirmed by the analysis of cross-correlation between NAOI and MADI (Fig. 10), carried out both on the raw data of time series ($r = −0.506$; Prob. t-Student and Prob. F-Fisher < 0.0001 %) and for the 11-yr moving averages ($r = −0.780$; Prob. t-Student and Prob. F-Fisher < 0.00001 %). The maximum correlation was found, respectively at the lag time of 0 and +1 yr.

Further elaborations consisting of linear correlations between 11-yr moving averages of NAOI and MADI indexes (Sect. 4.4) confirmed the strong influence of the NAO on decadal patterns of minimum (MADI$_{min}$), mean (MADI) and maximum (MADI$_{max}$) time series of annual discharges of the Sanità spring (Fig. 11).

The comparison of the discharge time series of the Sanità spring, with two other time series of spring discharge belonging to the Cassano Irpino and Maretto springs, even if for a limited overlapping period, respectively 1965–2010 and 1965–2000 (Fig. 12), permitted the recognition of a coherent descending pattern until 1990 and a rising trend in the following years, according to the pattern of the NAOI for the same period (Fig. 2a).

5.3 Cross-spectrum analysis of NAOI, MAPI and MADI

We applied the Fourier analysis to NAOI, MAPI and MADI time series in order to understand their temporal structures, periodicities and respective coherency. As known, the purpose of this analysis is to decompose complex time series with cyclical components

11252

into fundamental underlying sinusoidal functions (sine and cosine), finding their amplitudes and wavelengths and reconstructing the power spectrum.

The observed spectrum for winter NAOI resulted similar to what was previously observed by other authors (Sect. 3) with principal periodogram peaks characterised by periodicities from 2 to 3 yr, from 5 to 9 yr, at 30 yr and at 45 yr (Fig. 13). The principal periodogram peaks for MAPI and MADI time series were simultaneously observed at 2, 5, 15, 22 and 45 yr and discovered as matching those belonging to the NAOI for periodicities from 2 to 3 yr, at 5 yr and at 45 yr (Fig. 13).

In order to analyse the correlations between NAOI and MAPI and MADI time series at different frequencies, namely to find periodicities of MAPI and MADI time series synchronous with the NAO, we performed a cross-spectral analysis (Shumway and Stoffer, 2006) obtaining cross-amplitude values for the cross periodogram, corresponding to a measure of covariance between the respective frequency components in the two series.

From this analysis (Fig. 14) it was possible to understand better the correlation between winter NAOI, MAPI and MADI time series discovering that correlations exist for periodicities from 2 to 3 yr, from 3 to 4 yr, for a period around 5 yr, for a period of 8 yr and for periods from 30 to 45 yr. The longer periodicities, which were identified as characterized by the greatest cross-amplitude, can be anyway clearly recognized by the observation of the fluctuation of the 11-yr moving averages, whose minima peaks occur simultaneously for the three time series approximately after 45 yr (Figs. 4 and 9).

6 Conclusions

In the Campania region and in Southern Italy, the interannual and decadal patterns of rainfall had already been revealed as describing a declining trend since the beginning of the last century (Polemio and Casarano, 2008; Ducci and Tranfaglia, 2008). Besides this observation, we discovered a complex cyclical periodicity of rainfall patterns mainly teleconnected with the North Atlantic oscillation, confirming what was previously

observed for other regions of Western Europe and North America (Hurrell and van Loon, 1997; Vincente-Serrano and Trigo, 2011). We carried out integrated analysis on normalised indexes of precipitation, air temperature and effective precipitation, estimated for the Campania region, as well as on normalised index of a unique long-lasting
[5] spring discharge time series, belonging to a representative regional carbonate aquifer. These analyses revealed significant correlations with the winter NAO index in the period 1921–2010 (90 yr). Particularly, correlations between the winter NAO index and the annual spring discharge, considering either maximum, mean and minimum annual values, were found. The analysis of the temporal structure of time series showed stronger
[10] correlations for periodicities varying from the interannual to decadal time scales with greatest correlation at the periodicity from 30 to 45 yr. This periodicity has controlled the decadal variability of precipitation and of spring discharge because it is possible to observe, since the beginning of meteorological recording (1920), two long-term cycles with minima corresponding to 1925, 1948 and 1990 as well as the beginning of a new
[15] cycle after 1990. To this new cycle can be attributed the increase of the precipitation and of the spring discharges as well as the rising of piezometric levels in alluvial plains and the return of disappeared springs.

The obtained results can be considered a first attempt to extend the understanding of the impact of the NAO on the hydrological variability over Europe and Mediterranean
[20] areas, including also the underground component of the hydrological cycle on large and strategic regional aquifers. Moreover, the achieved correlations can be conceived as a basis in formulating behavioural models of regional carbonate aquifers and in planning appropriate management scenarios of aqueduct feeding from the interannual to the decadal time scales. This consideration is enhanced by the wider interest of the
[25] scientific community, including multidisciplinary expertise, in the North Atlantic oscillation, which concerns its monitoring, interpretation, not exclusively attributed to natural causes, and forecasting.

References

Alexandersson, H., Schmith, T., Iden, K., and Tuomenvirta, H.: Long-term variations of the storm climate over NW Europe, Glob. Ocean Atmos. Syst., 6, 9–120, 1998.

Allocca, V., Celico, F., Celico, P., De Vita, P., Fabbrocino, S., Mattia, S., Monacelli, G., Musilli, I., Piscopo, V., Scalise, A. R., Summa, G., and Tranfaglia G.: Note illustrative della Carta idroge-ologica dell'Italia meridionale, Istituto Poligrafico e Zecca dello Stato, ISBN 88-448-0215-5, 1–211, with enclosed three hydrogeological maps, ISBN 88-448-0223-6, 2007.

Allocca, V., Celico, F., Celico, P., De Vita, P., Fabbrocino, S., Mattia, C., Monacelli, G., Musilli, I., Piscopo, V., Scalise, A. R., Summa, G., and Tranfaglia, G.: La carta idrogeologica dell'Italia meridionale. Metodi ed analisi territoriali per l'identificazione e la caratterizzazione dei corpi idrici sotterranei (Direttiva 2000/60/CE), L'ACQUA, 4, 21–32, 2009.

Bandini, A.: Tipi pluviometrici dominanti sulle regioni italiane, Il Servizio Idrografico Italiano, Ministero dei Lavori Pubblici, Roma, 1931.

Barnston, A. G. and Livezey, R. E.: Classification, seasonality, and persistence of low-frequency atmospheric circulation patterns, Mon. Weather Rev., 115, 1083–1126, 1987.

Beranová, R. and Huth, R.: Time variations of the effects of circulation variability modes on European temperature and precipitation in winter, Int. J. Climatol., 28, 139–158, 2008.

Bjerknes, J.: Atmospheric teleconnections from the equatorial Pacific, Mon. Weather Rev., 97, 163–172, 1969.

Boni, C., Bono, P., and Capelli, G.: Valutazione quantitativa dell'infiltrazione efficace in un ba-cino dell'Italia centrale: confronto con analoghi bacini rappresentativi di diversa litologia, Geol. Appl. Idrogeol., 17, 437–452, 1982.

Brunetti, M., Maugeri, M., and Nanni, T.: Variations of temperature and precipitation in Italy from 1866–1995, Theor. Appl. Climatol., 65, 165–174, 2000.

Brunetti, M., Calacino, M., Maugeri, M., and Nanni, T.: Trends in the daily intensity of precipita-tion in Italy from 1951 to 1996, Int. J. Climatol., 21, 299–316, 2001.

Brunetti M., Maugeri, M., Monti, F., and Nanni, T.: Temperature and precipitation variability in Italy in the last two centuries from homogenized instrumental time series, Int. J. Climatol., 26, 345–381, 2006.

Cambi, C., and Dragoni, W.: Groundwater, recharge variability and climatic changes: some consideration out of the modeling of an apenninic spring, Hydrogeology, 4, 11–25, 2000.

Celico, F. and Mattia, C.: Analisi degli effetti indotti dal sisma del 23/11/1980 sugli equilibri idro-geologici della sorgente Sanità (Campania), mediante simulazione ragionata delle dinamiche di ricarica e esaurimento, Quadern. Geol. Appl., 1, 5–18, 2002.

Celico, F., Celico, P., De Vita, P., and Piscopo, V.: Groundwater flow and protection in the Southern Apennines (Italy), Hydrogeology, 4, 39–47, 2000.

Celico, F., Naclerio, G., Bucci, A., Nerone, V., Capuano, P., Carcione, M., Allocca, V., and Celico, P.: Influence of pyroclastic soil on epikarst formation: a test study in Southern Italy, Terra Nova, 22, 110–115, 2010.

Celico, P.: Schema idrogeologico dell'Appennino carbonatico centro-meridonale, Memorie e Note Istituto di Geologia Applicata, Napoli, 14, 1–97, 1978.

Celico, P.: Relazioni tra idrodinamica sotterranea e terremoti in Irpinia (Campania), Rendiconti Società Geologica Italiana, 4, 103–108, 1981.

Celico, P.: Idrogeologia dei massicci carbonatici, delle piane quaternarie e delle aree vulcaniche dell'Italia centro-meridionale (Marche e Lazio meridionale, Abruzzo, Molise e Campania), Quaderni della Cassa per il Mezzogiorno, 4/2, 1–203, 1983.

Cohen, J. and Barlow, M.: The NAO, the AO, and global warming: How closely related?, J. Climate, 18, 4498–4513, 2005.

Cohen, J., Frei, A., and Rosen, R. D.: The role of boundary conditions in AMIP-2 simulations of the NAO, J. Climate, 18, 973–981, 2005.

Cotecchia, V., Casarano, D., and Polemio, M.: Piovosità e siccità in Italia meridionale tra il 1821 ed il 2001, L'ACQUA, 2, 99–106, 2003.

Cullen, H. M. and deMenocal, P. B.: North Atlantic Influence on Middle Eastern Climate and Water Supply, in: Proceedings from a Meeting on Atlantic Climate Variability Lamont-Doherty Earth Observatory, 1997.

Cullen, H. M. and deMenocal, P. B.: North Atlantic influence on Tigris-Euphrates streamflow, Int. J. Climatol., 20, 853–863, 2000.

Cullen, H. M., Kaplan, A., Arkin, P. A., and deMenocal, P. B.: Impact of the North Atlantic influence on the middle eastern climate and streamflow, Climatic Change, 55, 315–338,

2002.

Czaja, A., Robertson, A. W., and Huck, T.: The role of Atlantic ocean-atmosphere coupling in affecting North Atlantic Oscillation variability, in: The North Atlantic Oscillation: Climatic Significance and Environmental Impact, Geophysical Monograph, American Geophysical Union,
5   134, doi:10.1029/134GM01, 2003.

De Vita, P. and Fabbrocino, S.: L'oscillazione del Nord Atlantico e la variabilità pluriennale delle risorse idriche sotterranee negli acquiferi carbonatici dell'Italia meridionale, Giornale di Geologia Applicata, 2, 357–362, doi:10.1474/GGA.2005-02.0-52.0078, 2005.

De Vita, P. and Fabbrocino, S.: Influence of the North Atlantic Oscillation on the climatic variabil-
10   ity and groundwater resources in carbonate aquifers of Southern Italy, Italian J. Eng. Geol. Environ., 1, 33–48, 2007.

Dragoni, W., Sukhija, B. S.: Climate change and groundwater: a short review, vol. 288, Geological Society, Special Publications, London, 1–12, 2008.

Ducci, D. and Tranfaglia, G.: The effect of climate change on the hydrogeological resources
15   in Campania region – Italy, in: Groundwater and Climatic Changes, vol. 288, edited by: Dragoni, W., Geological Society, Special Publications, London, 25–38, doi:10.1144/SP288.3, 2008.

Feldstein, S. B.: Teleconnections and ENSO: The timescale, power spectra, and climate noise properties, J. Climate, 13, 4430–4440, 2000.

20 Fiorillo, F.: Spring hydrographs as indicators of droughts in a karst environment, J. Hydrol., 373, 290–301, 2009.

Fiorillo, F. and Guadagno, F. M.: Karst spring discharges analysis in relation to drought periods, using the SPI, Water Resour. Manage., 24, 1867–1884, doi:10.1007/s11269-009-9528-9, 2010.

25 Greatbatch, R. J.: The North Atlantic oscillation, Stoch. Environ. Risk Assess., 14, 213–242, 2000.

Hasanean H. M.: Wintertime surface temperature in Egypt in relation to the associated atmospheric circulation, Int. J. Climatol., 24, 985–999, 2004.

Henderson-Sellers, A. and Robinson, P. J.: Contemporary Climatology, John Wiley & Sons,
30   New York, 1986.

Hurrell, J. W.: Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation, Science, 269, 676–679, 1995.

Hurrell, J. W.: EOS bookshelf: the North Atlantic oscillation, EOS, 84, 73, 2003.

11257

Hurrell, J. W. and van Loon, H.: Decadal variations in climate associated with the North Atlantic oscillation, Climatic Change, 36, 301–326, 1997.

Hurrell, J. W., Kushirn, Y., Ottersen, G., and Visbeck, N.: An overview of the North Atlantic oscillation, in: The North Atlantic Oscillation: Climatic Significance and Environmental Impact, Geophysical Monograph, American Geophysical Union, 134, doi:10.1029/134GM01, 2003.

ICCP – International Climate Change Partnership: Climate Change, The IPPC Scientific Assessment (ISBN052140360X), edited by: Houghton, J. T., Jenkins, G. J., and Ephraums, J. J., Cambridge University Press, 1–414, 1990.

ICCP – International Climate Change Partnership: The scientific basis, Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change (ICCP), edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., Van der Linden, P. J., and Xiaosu, D., Cambridge University Press, 2001.

IPCC - International Climate Change Partnership: Climate Change 2007 Synthesis Report, Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Pachauri, R. K. and Reisinger, A., available at http://www.ipcc.ch/ipccreports/ar4-syr.htm, last access: December 2011, Geneva, Switzerland, 1–104, 2007.

Karabörk, M. C., Kahya, E., and Karaca, M.: The influences of the Southern and North Atlantic oscillation on climatic surface variables in Turkey, Hydrol. Process., 19, 1185–1211, 2005.

Kücük, M., Kahya, E., Cengiz, T. M., and Karaca, M.: North Atlantic oscillation influences on Turkish lake levels, Hydrol. Process., 23, 893–906, 2009.

Lo Vecchio, G. and Nanni, T: The variation of the atmospheric temperature in Italy during the last hundred years and its relationship with solar output, Theor. Appl. Climatol., 51, 159–146, 1995.

López-Moreno, J. I. and Vicente-Serrano, S. M.: Positive and negtive phases of the wintertime North Atlantic oscillation and drought occurrence over Europe: multitemporal-scale approach, J. Climate, 21, 1220–1241, 2008.

López-Moreno, J. I., Beguería, S., Vicente-Serrano, S. M., and García-Ruiz, J. M.: Influence of the North Atlantic Oscillation on water resources in Central Iberia: precipitation, streamflow anomalies, and reservoir management strategies, Water Resour. Res., 43, W09411, doi:10.1029/2007WR005864, 2007.

Lorenzo-Lacruz, J., Vicente-Serrano, S. M., López-Moreno, J. I., González-Hidalgo, J. C., and Morán-Tejeda, E.: The response of Iberian rivers to the North Atlantic Oscillation, Hydrol.

Earth Syst. Sci., 15, 2581–2597, doi:10.5194/hess-15-2581-2011, 2011.

Massei, N., Laignel, B., Deloffre, J., Mesquita, J., Motelay, A., Lafite, R., and Durand, A.: Long-term hydrological changes of the Seine River flow (France) and their relation to the North Atlantic oscillation over the period 1950–2008, Int. J. Climatol., 30, 2146–2154, 2009.

5   Mazzarella, A.: Rainfall multifractal dynamic processes in Italy, Theor. Appl. Climatol., 63, 73–78, 1999.

Morán-Tejeda, E., Lóper-Moreno, I., Ceballos-Barbancho, A., and Vicente-Serrano, S. M.: Evaluating Duero's basin (Spain) response to the NAO phases: spatial and seasonal variability, Hydrol. Process., 25, 1313–1326, 2011.

10   Muñoz-Díaz, D. and Rodrigo F. S.: Impacts of the North Atlantic oscillation on the probability of dry and wet winters in Spain, Clim. Res., 27, 33–43, 2004.

Polemio, M. and Casarano, D.: Climate Change, Drought and Groundwater Availability in Southern Italy, vol. 288, Geological Society, Special Publications, London, 39–51, 2008.

Pozo-Vazquez, D., Esteban-Parra, M. J., Rodrigo F. S., and Castro-Diez, Y.: The association
15   between ENSO and winter atmospheric circulation and temperature in the North Atlantic region, J. Climate, 14, 3408–3420, 2001.

Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L. P., Jones, C., Meier, H., Samuelsson, P., and Willén, U.: European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios, Clim. Dynam., 22,
20   13–31, 2004.

Rimbu, N., Boroneant, C., Buta, C., and Dima, M.: Decadal variability of the Danube river flow in the lower basin and its relation with the North Atlantic oscillation, Int. J. Climatol., 22, 1169–1179, 2002.

Rodriguez-Puebla, C. and Nieto, S.: Trends of precipitation over the Iberian Peninsula and the
25   North Atlantic oscillation under climate change conditions, Int. J. Climatol., 30, 1807–1815, 2010.

Rodriguez-Puebla, C., Encinas, A. H., Nieto, S., Garmendia, J.: Spatial and temporal patterns of annual precipitation variability over the Iberian Peninsula, Int. J. Climatol., 18, 299–316, 1998.

30   Rogers, J. C.: The association between the North Atlantic oscillation and the southern oscillation in the Northern Hemisphere, Mon. Weather Rev., 112, 1999–2015, 1984.

Rogers, J. C.: Patterns of low-frequency monthly sea level pressure variability (1899–1986) and associated wave cyclone frequencies, J. Climate, 3, 1364–1379, 1990.

Rudari, R., Boni, G., Castelli, F., Entekabi, E., Roth, G.: North Atlantic oscillation influences on winter-time european climate patterns, in: Proceedings of the 2nd EGS Plinius Conference on Mediterranean Storms, Italy, 313–321, 2000.

Santoro, M.: Sulla applicabilità della formula di Turc per il calcolo della evapotraspirazione effettiva in Sicilia, Proc. I International Conference on Groundwater, I.A.H., Palermo, 1970.

Shorthouse, C. A. and Arnell, N. W.: Spatial and temporal variability in European river flows and the North Atlantic oscillation, in: FRIEND 97: Regional Hydrology – Concepts and Models for Sustainable Water Management, IAHS, 1997.

Shumway, R. H. and Stoffer, D. S.: Time Series Analysis and its Application, 2nd Edn., Springer, 1–588, 2006.

Tonini, D.: Elementi di idrografia ed idrologia, Libreria Universitaria, Venezia, 1959.

Tootle, G., Piechota, T., and Singh, A.: Coupled oceanic-atmospheric variability and US streamflow, Water Resour. Res., 12, 1–11, 2005.

Trigo, R. M., Pozo-Vázquez, D., Osborn, T. J., Castro-Díez, Y., Gámiz-Fortis, S., and Esteban-Parra, M. J.: North Atlantic oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula, Int. J. Climatol., 24, 925–944, 2004.

Turc, L.: Le bilan d'eau des sols: relations entre les précipitations, l'évaporation et l'éecolument, Ann. Agronom., Paris, 5, 491–595, 1954.

Turc, L.: Evaluation des besoins en eau d'irrigation, èvapotranspiration potentielle, Ann. Agronom., 121, 13–49, 1961.

Türkes, M. and Erlat, E.: Climatological responses of winter precipitation in Turkey to variability of the North Atlantic Oscillation during the period 1930–2001, Theor. Appl. Climatol., 81, 45–69, 2005.

Uvo, C.: Analysis and regionalization of Northern European winter precipitation based on its relationship with the North Atlantic oscillation, Int. J. Climatol., 23, 1185–1194, 2003.

van Loon, H. and Rogers, J. C.: The seesaw in winter temperatures between Greenland and Northern Europe, Part I: General description, Mon. Weather Rev., 106, 296–310, 1978.

Vicente-Serrano, S. M. and López-Moreno, J. I.: Differences in the non-stationary influence of the North Atlantic oscillation on European precipitation under different scenarios of greenhouse gas concentrations, Geophys. Res. Lett., 35, 1–6, 2008.

Vicente-Serrano, S. M. and Trigo, R. M.: Hydrological, Socioeconomic and Ecological Impacts of the North Atlantic oscillation in the Mediterranean Region (Advances in Global Change Research), Springer, 1–236, 2011.

Viesbeck, M., Chassignet, E. P., Curry, R. G., Delworth, T. L., Dickson, R. R., and Krahmann, G.: The ocean's response to North Atlantic oscillation variability, in: The North Atlantic Oscillation: Climatic Significance and Environmental Impact, vol. 134, Geophysical Monograph, American Geophysical Union, doi:10.1029/134GM01, 2003.

5 Walker, G. T. and Bliss, E. W.: World weather V, Memories Roy. Meteorol. Soc., 4, 53–84, 1932.

Wallace, J. M. and Gutzler, D. S.: Teleconnections and the geopotential heigh during Northern Hemisphere winter, Mon. Weather Rev., 109, 784–812, 1981.

Wanner, H., Brönnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., Stephen-
10 son, D. B., and Xoplaki, E.: North Atlantic oscillation – concepts and studies, Surv. Geophys., 22, 321–381, 2001.

WMO – World Meteorological Organization: World Climate Conference, WMO, in: Proceedings of the World Climate Conference, Geneva, Switzerland, ISBN 92-63-10537-5, 12–23 February 1979, No. 537, 1979.
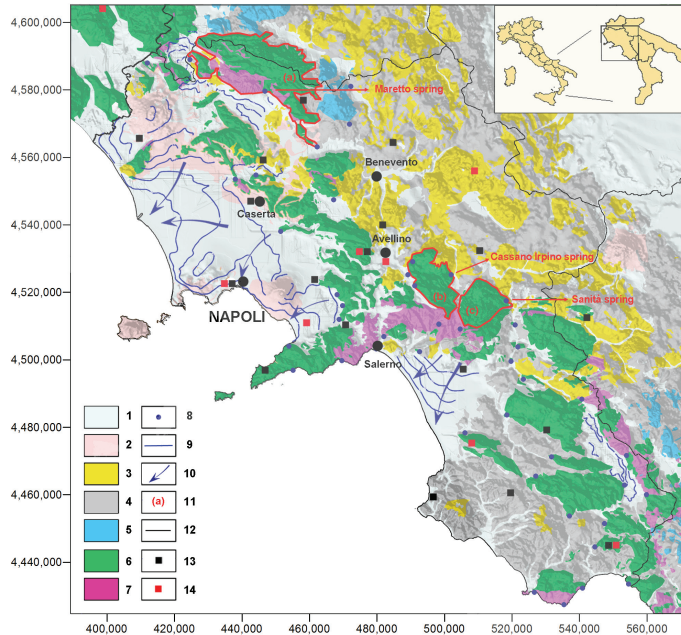
Fig. 1. Hydrogeological map of the Campania region. Principal group of hydrostratigraphic units and symbols: (1) Alluvial and epiclastic units (Quaternary); (2) Volcanic units (Pliocene-Quaternary); (3) Late orogenic molasses and terrigenous units (Upper Miocene-Pliocene); (4) Pre-orogenic and syn-orogenic terrigenous units of inner and thrust-top basins series (Cretaceous-Upper Miocene); (5) Siliceous-marly units of outer basins series (Trias-Paleogene); (6) Limestone and dolomitic limestone units of carbonate platform series (Jurassic-Paleogene); (7) Dolomitic units of carbonate platform series (Trias-Jurassic); (8) Main basal springs of carbonate aquifers; (9) Groundwater head contour lines in alluvial and volcanic aquifers; (10) Main preferential drainage axes of groundwater flow in alluvial aquifers; (11) Identification of the analysed carbonate hydrogeological units: (a) Mount Matese; (b) Mount Terminio; (c) Mount Cervialto; (12) regional boundary; (13) Rain gauge stations; (14) Air temperature monitoring stations.
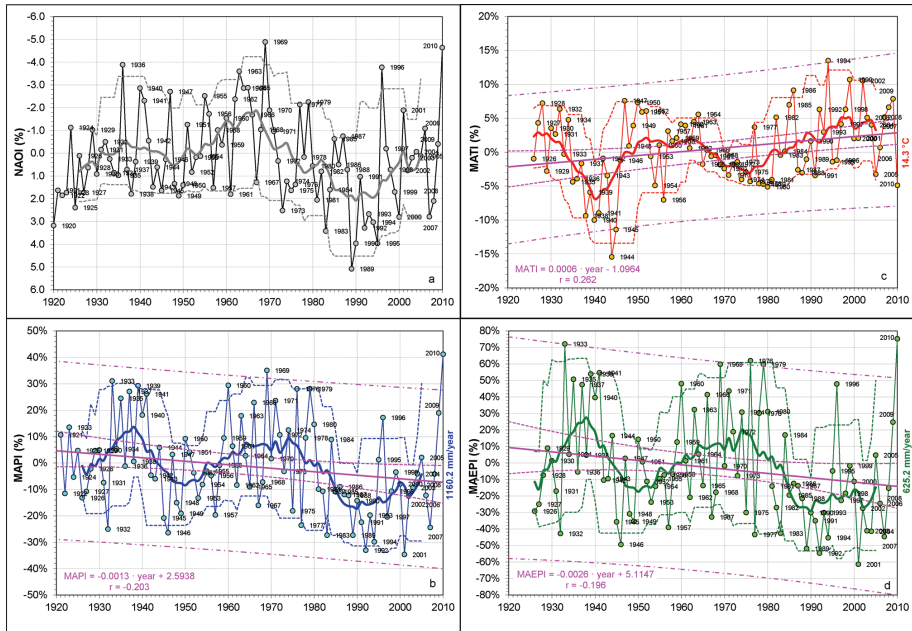
Fig. 2. Time series of: **(a)** winter NAOI time series monitored between Lisbon (Portugal) and Stykkisholmur/Reykjavik (Iceland). **(b)** MAPI; **(c)** MATI; **(d)** MAEPI. Symbols: continuous magenta line = linear trend of the whole time series (equation and coefficient of correlation in the lower left corner); dashed magenta lines = 95 % confidence interval of the expected mean value; dash-dotted magenta lines = 95 % prediction interval of the expected value; continuous thick line = 11-yr moving average centred on the sixth year; dashed lines = 11-yr moving percentiles of 5 and 95 % centred on the sixth year; number in right side of the graphs = absolute mean value of the whole time series.
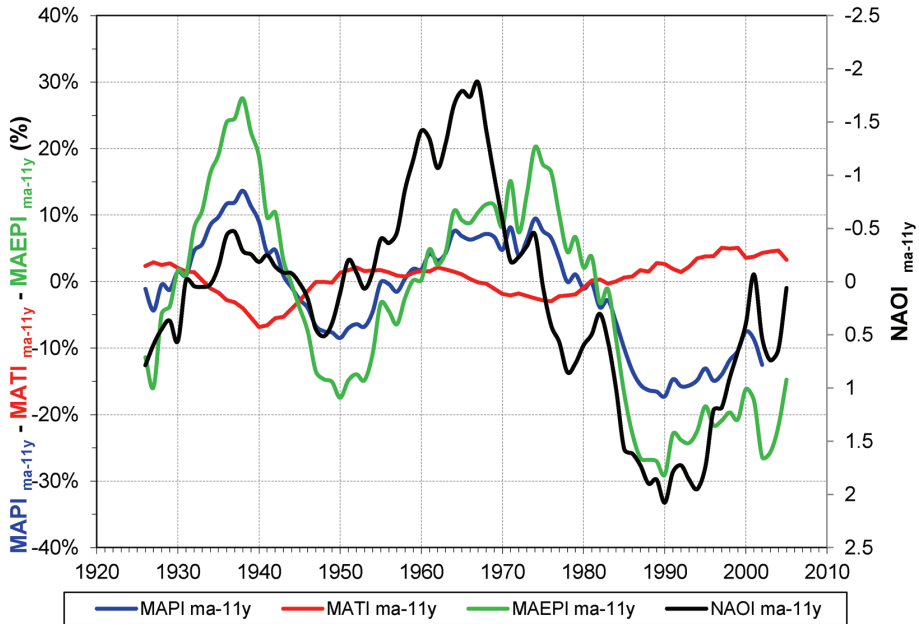
Fig. 3. Comparison of the 11-yr moving averages of winter NAOI, MAPI, MATI and MAEPI time series for the Campania region.
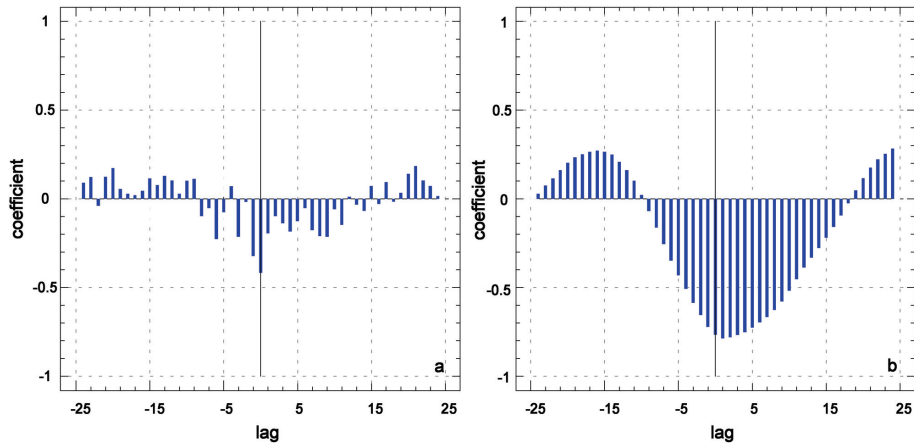
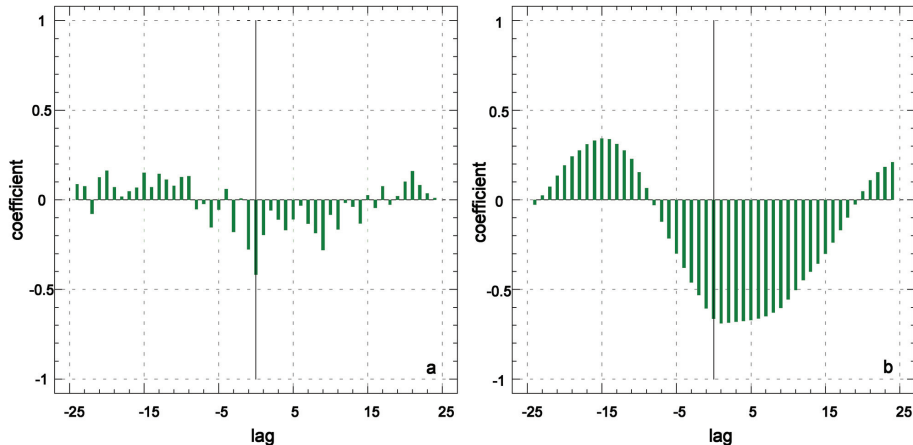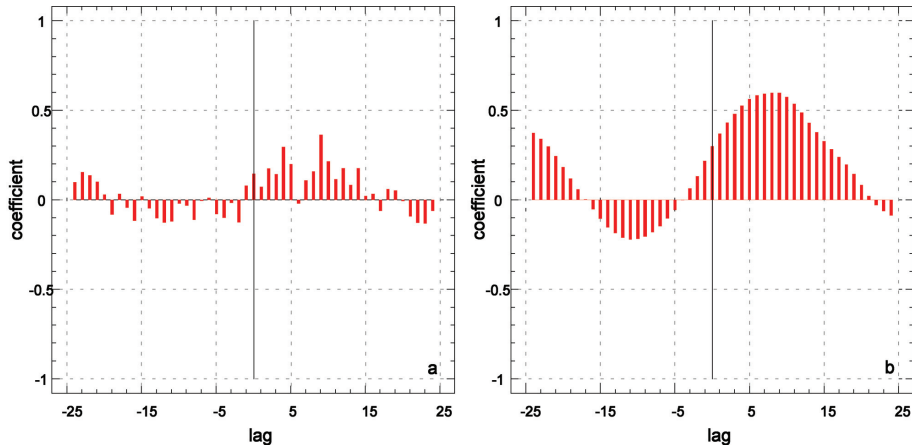**Fig. 4.** Cross-correlation analysis between the winter NAOI and the MAPI carried out on: **(a)** the original time series ($r = -0.422$; Prob. t-Student $= 0.003\%$; Prob. F-Fisher $= 0.004\%$); **(b)** the respective 11-yr moving average time series ($r = -0.767$; Prob. t-Student $< 0.0001\%$; Prob. F-Fisher $< 0.0001\%$).
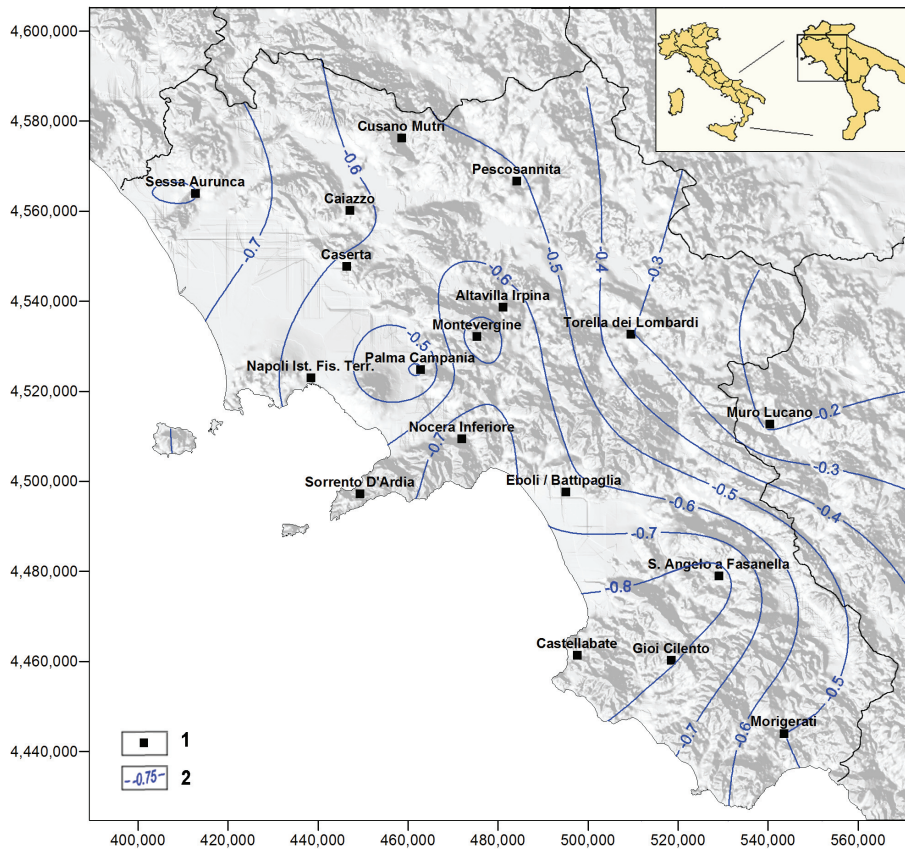
Fig. 5. Spatial distribution of the coefficient of correlation calculated between the 11-yr moving average of the winter NAOI and of the annual precipitation time series of each rain gauge station. Coordinates are in the UTM system ED-50 datum (fuse 33).

Fig. 6. Cross-correlation analysis between the long-term components of the winter NAOI and the MAEPI carried out on: **(a)** the original time series data ($r = -0.431$; Prob. t-Student and Prob. F-Fisher $= 0.004\,\%$); **(b)** the respective 11-yr moving average ($r = -0.744$; Prob. t-Student and Prob. F-Fisher $< 0.0001\,\%$).

Fig. 7. Cross-correlation analysis between the long-term components of the winter NAOI and the MATI carried out on: **(a)** the original time series data ($r = 0.3633$; Prob. t-Student and Prob. F-Fisher = 0.063 %); **(b)** the respective 11-yr moving average ($r = 0.5971$; Prob. t-Student and Prob. F-Fisher < 0.0001 %).
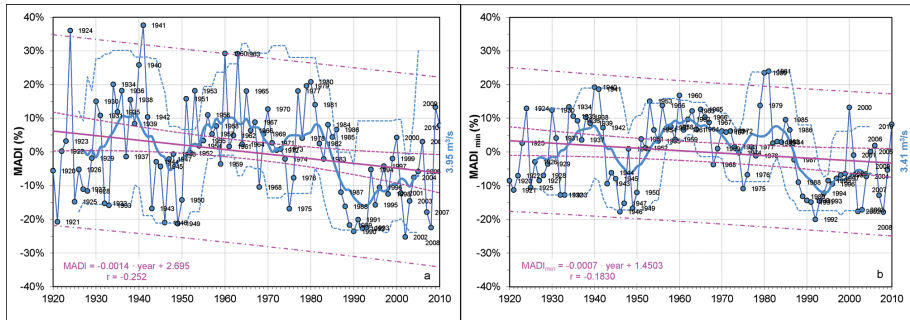
Fig. 8. (a) MADI time series; **(b)** MADI$_{min}$ time series. Symbols: continuous magenta line = linear trend of the whole time series (equation and coefficient of correlation in the lower left corner); dashed magenta lines = 95 % confidence interval of the expected mean value; dash-dotted magenta lines = 95 % prediction interval of the expected value; continuous thick line = 11-yr moving average centred on the sixth year; dashed lines = 11-yr moving percentiles of 5 and 95 % centred on the sixth year; number in right side of the graphs = absolute mean value of the whole time series.
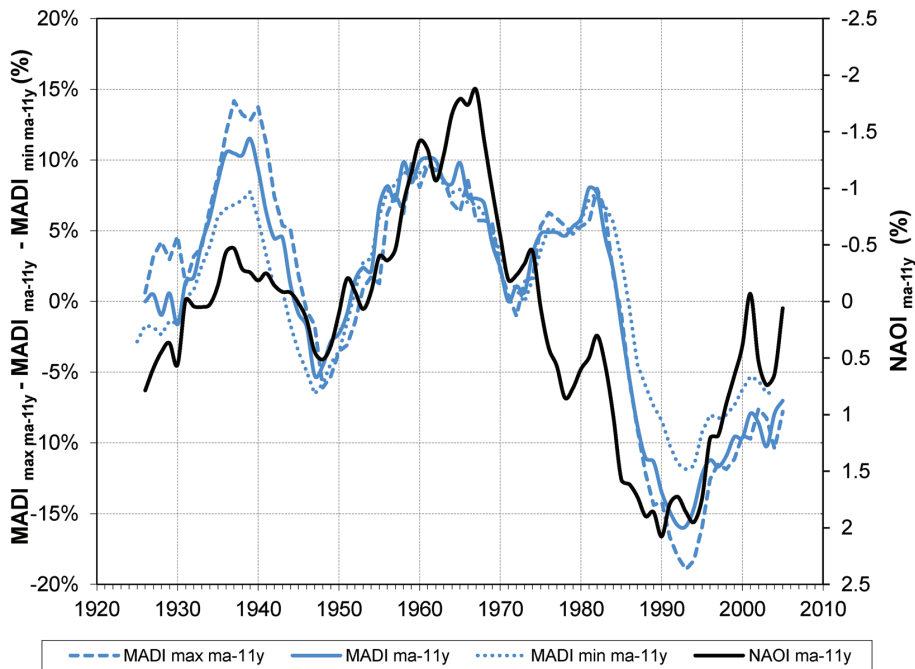
Fig. 9. Comparison between the 11-yr moving averages of the NAOI time series and the MADI$_{max}$, MADI, MADI$_{min}$ time series of the Sanità spring.
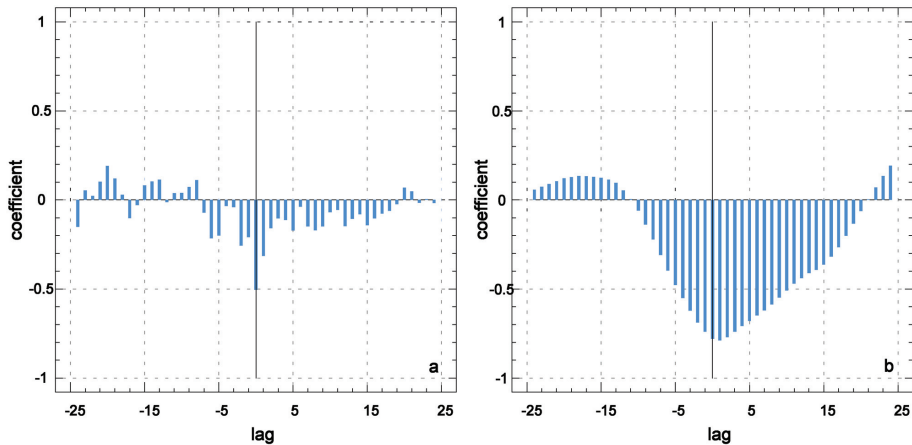
Fig. 10. Cross-correlation analysis between the NAOI and the MADI, carried out on: **(a)** the original time series ($r = -0.506$; Prob. t-Student $< 0.0001\,\%$; Prob. F-Fisher $< 0.0001\,\%$); **(b)** the respective 11-yr moving averages ($r = -0.780$; Prob. t-Student $< 0.00001\,\%$; Prob. Fisher $< 0.00001\,\%$). In the latter case the correlation is higher because of the filtering out of the long-period trend.

11271
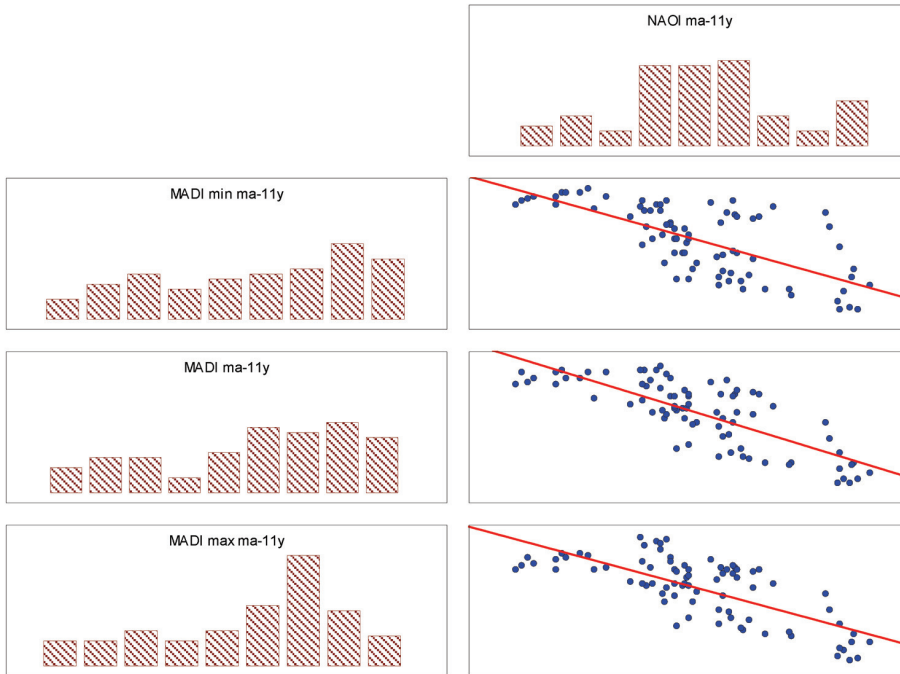
Fig. 11. Matrix correlation between 11-yr moving averages of NAOI and $MADI_{min}$ ($MADI_{min\,ma-11y} = -0.0447 \cdot NAOI_{ma-11y} - 0.0148$), MADI ($MADI_{ma-11y} = -0.0635 \cdot NAOI_{ma-11y} + 0.0159$) and MADI ($MADI_{max\,ma-11y} = -0.0656 \cdot NAOI_{ma-11y} + 0.0161$). Statistical significance tests (*t*-Student and *F*-Fisher) have given probability values lower than 0.00001 % for the null hypothesis.
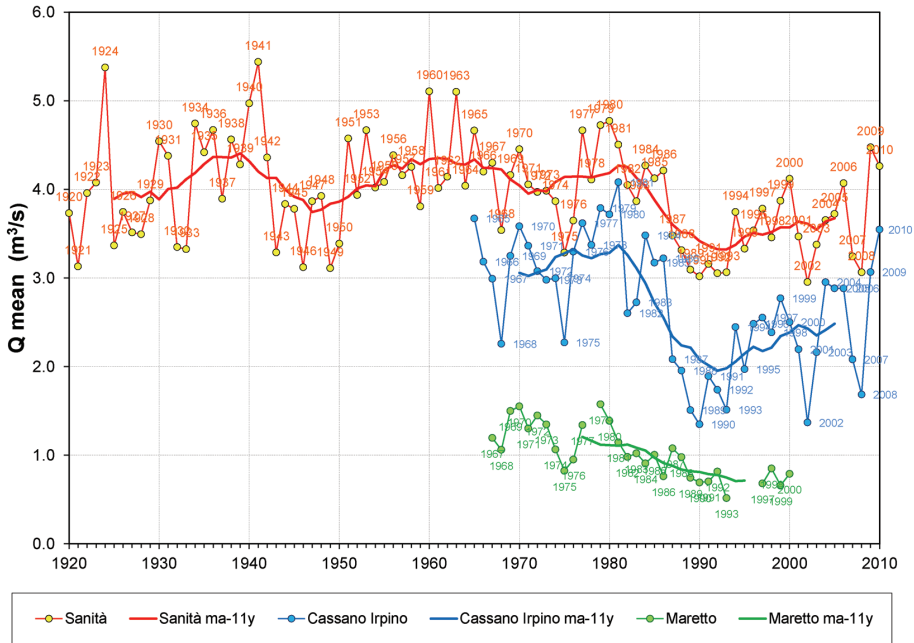
Fig. 12. Graphical comparison of annual mean discharges of Sanità, Cassano Irpino and Maretto springs (Fig. 1). Symbols: continuous thick line = 11-yr moving average centred on the sixth year.
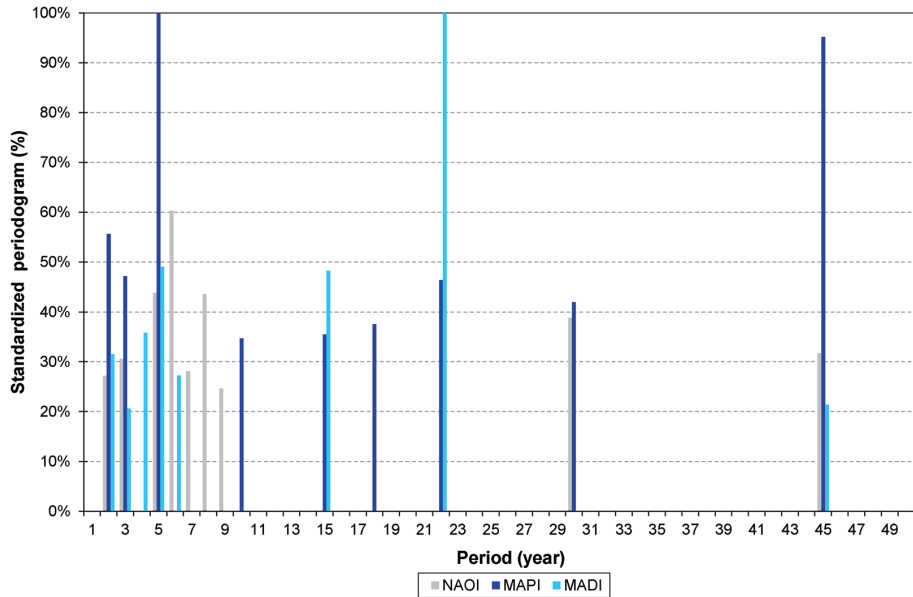
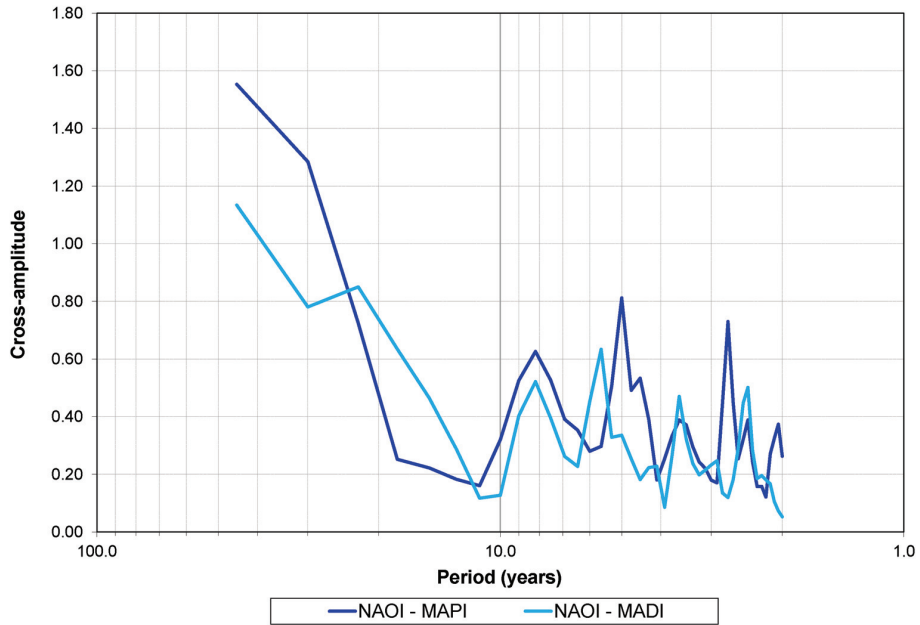**Fig. 13.** Largest periodogram peaks for NAOI, MAPI and MADI time series.

Fig. 14. Cross-amplitude of MAPI and MADI time series against the NAOI time series.