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Relation Between the North-Atlantic Oscillation and Hydroclimatic Conditions in Mediterranean Areas

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Abstract Mediterranean basins are known for their susceptibility to water stress conditions resulting from a reduction in winter-season precipitation. This region is also prone to the effects of the North Atlantic Oscillation (NAO), a large-scale climatic pattern associated with a displacement of air mass between the arctic and the subtropical Atlantic. Even though previous studies have demonstrated the impact of the NAO on winter climate conditions in Europe and Northern Africa, it is still unclear to what extent the NAO is related to hydroclimatic patterns in Mediterranean areas and whether it can explain its recent drought history. To this end, this study investigates the interdependence between the NAO and winter precipitation, river flow and temperature in two Mediterranean regions: Southern Italy and Nile Delta (Egypt). The outcomes show the presence of significant connections between the NAO, winter rainfall and river discharge.

Keywords North Atlantic Oscillation · Climate · Atmospheric circulation · Mediterranean areas · Southern Italy · Nile Delta

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1 Introduction

Known as “North Atlantic Oscillation” (NAO), the air mass displacement between the Arctic and the subtropical Atlantic is the principal mode of climate variability in the northern hemisphere (Barnstorn and Livezey 1987). In particular, the atmospheric circulation across Europe is primarily determined by the persistence of a low-pressure zone centered over Iceland and the existence of the semi-permanent high-pressure belt of the Azores. The interactions between these two poles modify the westerly airflow circulation, which affects the thermal exchange over the North Atlantic and Europe, with important effects on the winter season at the mid-high latitudes. The westerly flow is not stationary; it tends to fluctuate between the northward and the southward directions.

The strength of the NAO is generally expressed through an index (Hurrell 1995; Jones et al. 1997) measuring the difference between the normalized sea level pressure recorded in the Atlantic at high (e.g., Reykjavik, or Akurejry, Iceland) and low (e.g., Gibraltar or Lisbon/Ponta Delgada, Portugal) latitudes. Fluctuations in the NAO index are indicative of oscillations in the transport and convergence of atmospheric moisture (Hurrell 1995) and, in turn, of changes in the temperature and precipitation regime across Europe. Jones et al. (1997) used instrumental records (sea-level pressure from Gibraltar and Reykjavik) extending back to 1823 to compute an index of the strength of the NAO phases.

Interest in the NAO has been recently renewed, particularly because of two concurrent trends observed in the winter season over the last three decades: a trend towards the positive phase of the NAO, and a trend towards warmer Northern Hemisphere winters (Hurrell 1995). Positive NAO winters are associated with higher-than-usual pressures in the subtropics and a lower pressure in the Arctic. As a result, winters are warm and dry in Southern Europe, warm and wet in northern Europe, and cold and dry in Greenland. Conversely, during negative phases of the NAO winters are usually cold in northern Europe, moist and wet in Southern Europe, and milder in Greenland.

Over the last few decades a number of studies have investigated the response of the biosphere and hydrosphere to change in the phases of the North Atlantic Oscillation. These studies have assessed the impact of the NAO on water cycle, ecosystems, and society. Indeed, important dependences have been detected throughout Europe between the NAO and the population dynamics of vertebrates, the migration and breeding of birds (Mysterud et al. 2003), plant phenology (D’Odorico et al. 2002), the dynamics of marine ecosystems (Ottersen et al. 2001), and the abundance and diversity of species in several ecosystems (Stenseth et al. 2003).

Climatic anomalies associated with the NAO have also strong impacts on the regional hydrology and river floods (Kundzewicz et al. 2010), with subsequent effects on the local economies, as shown for North African precipitation (Lamb and Peppler 1991; Meddi et al. 2010), river flow in Mesopotamia and Turkey (Cullen and deMenocal 2000), freezing and thawing of rivers and lakes in Finland (Wettstein and Mearns 2002; Yoo and D’Odorico 2002), hydropower production in Northern Europe (Hurrell et al. 2003; Cherry et al. 2005), storm surges and flooding in the city of Venice (Fagherazzi et al. 2005), interannual variability of winter precipitation in the European Alps (Bartolini et al. 2009).

Despite all these studies on the regional effects of the NAO, the impact of the North Atlantic Oscillation on the hydrological regime in the Mediterranean basin remains understudied (Goodess and Jones 2002). Indeed, this region is known for receiving most of its rainfall in the winter season, when the NAO has the strongest impact on the climate in Europe (Hurrell et al. 2003). Thus, the NAO is expected to modulate the interannual variability of precipitation in Mediterranean areas, with important effects on the economy of these regions that strongly depend on agriculture. It should be noted here that topographical obstacles may increase the strength of changes in precipitation or temperature signals induced by the variability that affects atmospheric circulation patterns (Pfister et al. 2004; Skøien et al. 2003).

In their work on the impact of NAO on the Middle East region, Cullen and deMenocal (2000) stretched their regional analysis to a wider area and made a first attempt in investigating climate signals in scatter stations in the Mediterranean sector. They showed that rainfall in most of the Mediterranean areas is negatively correlated with the NAO, while the southeastern part tends to exhibit a positive correlation. Our study aims at further investigating the effects of the NAO on the hydroclimatic conditions in Mediterranean areas by using longer time series and more dense networks of gauge stations. To this end, we focus on two geographical regions: Southern Italy and Nile Delta (Egypt).

In Southern Italy, the analysis is carried out by studying the inter-dependence between the NAO index and hydrometeorological records observed during the winter months. The considered variables include: (1) monthly precipitation, (2) monthly number of rainy days, (3) monthly average river discharge, and (4) monthly average temperature. In the Nile Delta region, the analysis is carried out by checking the correlation between the NAO winter index and the monthly precipitation time series.

This analysis is motivated by the need to better understand climate patterns in Mediterranean areas, and in particular in Southern Italy and Nile Delta, regions that have recently experienced significant droughts and water shortage.

2 Test Sites

As mentioned above, this study focuses on two Mediterranean areas: Southern Italy and Nile Delta (Egypt).

The first study area (Fig. 1) extends from 36° to 42° Lat N and from 8° to 19° Long E and includes the Italian administrative regions of Sicilia, Sardegna, Calabria, Basilicata, Puglia and Campania. Climate in this area is typically Mediterranean, with warm, dry summers, and mild, rainy winters. The mean annual precipitation (MAP) ranges between about 500 to 800 mm, with the driest areas being in Sardegna and in the south-eastern part of the peninsula.

The east coast (Puglia administrative region) is mainly flat and slightly exposed to winds and is the driest zone of the study area. The inner part of the west coast (Calabria, Campania and Basilicata administrative regions) exhibits significant reliefs. Because of the weaker sea influence and the interception of winds by these mountains, the climate in these western regions is typically continental. Calabria is surrounded by the Tyrrenic Sea to the west and by the Ionian Sea to the east and is,

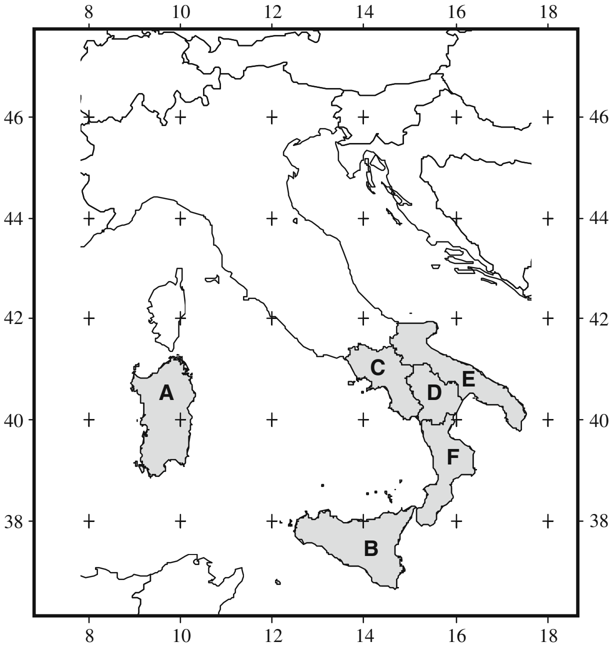

Fig. 1 Southern Italy (*gray region*): **A** Sardegna, **B** Sicilia, **C** Campania, **D** Basilicata, **E** Puglia, **F** Calabria

in general, highly exposed to winds. Due to the presence of the Aspromonte and Sila Mountains, the central part of this region has relatively humid and cold winters.

The islands of Sicilia and Sardegna are more exposed to the winds than the continental areas. Sicilia is characterized both by Mediterranean climate in the south and by continental climate with a larger amount of precipitation in the central and northern part of the island. Sardegna is the driest zone of the study area.

The Nile Delta region (Fig. 3) extends from 29° to 32° Lat N and from 29° to 33° Long E, and has a total area of 23,300 km^2. This area has a crucial economic importance and about half of the Egyptian population lives in the Nile Delta region. The Nile Delta can be divided into West and East sections, with the Nile dividing into two main distributaries, the Damietta and the Rosetta. The Nile Delta region has a Mediterranean climate, characterized by small amount of rainfall. The MAP varies between 100 and 200 mm, and is concentrated in the winter months.

3 Data Set

Data from Southern Italy were collected from the National Hydrographic and Hydrometric Service of Italy (SIMN). The data base consists of monthly precipitation, average temperature and average river discharge. Daily precipitation is available for a reduced number of sites. Only stations with complete and continuous winter records were selected. More specifically, for monthly precipitation the observation period covers 60 to 78 years depending on the administrative region (109 stations), 30 years for temperature (59 stations), 15 years for discharge (107 stations) and 30 years for the daily precipitation records used to calculate the number of wet

Table 1 Total number of stations and years of observation for each hydrometeorological variable and each administrative region of the Southern Italy

Region	Variables							
	Precipitation		Number of wet days		Temperature		Discharge	
	Stations	Years	Stations	Years	Stations	Years	Stations	Years
Campania	20	1921–1984	61	1920–1950	18	1920–1950	20	1925–1991
Calabria	20	1921–1987	–	–	7	1920–1950	20	1925–1984
Basilicata	–	–	–	–	7	1920–1950	9	1924–1980
Puglia	19	1921–1995	–	–	13	1920–1950	17	1925–1996
Sicilia	30	1921–1998	76	1920–1950	8	1920–1950	21	1923–1996
Sardegna	20	1921–1980	–	–	6	1920–1950	20	1921–1975

days (137 stations). These criteria of data selection allowed us to gather data from a large enough number of gauging stations for each hydrometeorological variable in each administrative region. No stations were available for precipitation in Basilicata and for the number of wet days in Basilicata, Calabria, Puglia and Sardegna. Table 1 lists the number of stations available and the years of observations for each hydrometeorological variable in each administrative region of the study area.

The data used in the Nile Delta region are the monthly precipitation time series of the gridded database CRU TS 1.2 (Mitchell et al. 2003), developed by the Tyndall Centre for Climate Change Research and the Climate Research Unit (CRU) of the University of East Anglia. This data set provides the longest time series in the group and a good spatial resolution (grid spacing of about 20 km). The CRU dataset is constructed with the anomaly approach (New et al. 1999) interpolating station data with a procedure that considers latitude, longitude and elevation as parameters. This type of gridded dataset can be valuable in the study of spatio-temporal climate patterns as it provides long and uninterrupted time series for all the grid points (Bartolini et al. 2009).

The monthly NAO index used in this study is the normalized winter sea level pressure difference between Gibraltar and Reykjavik, as constructed by Jones et al. (1997). The period in which this index is available extends from 1864 to 2000. As mentioned before, only values of the NAO index in the winter months were considered. Therefore, an average value of the NAO index was calculated for the months of December, January, February and March (DJFM).

4 Methods

The analysis of the linear relation between the NAO index and the hydrometeorological variables has been carried out through a cross-correlation analysis for the winter months. The cross correlations were calculated by averaging the NAO index and the hydrometeorological data over the 4-month winter period of December–January–February–March (DJFM).

The knowledge of the cross correlation coefficients allows one to estimate the portion of the variability of the hydrometeorological variables that is explained by the NAO index (e.g., Wilks 1995).

In Southern Italy regional indices were used to investigate the regime of precipitation, river flow and temperature. These were calculated for each administrative region as follows: (1) for each record the normalized deviations from the mean (i.e., deviation from the mean divided by the standard deviation) were calculated; (2) for each year and each administrative region an average index of precipitation, temperature, number of rainy days and discharge was estimated as the yearly mean of the normalized deviations of the records from all stations in the region; (3) the dependence between these regional indices and the NAO was then assessed through a Pearson's lag-zero cross correlation analysis, thereby providing an assessment of the effect of the NAO in each administrative region (4) the same analysis was repeated using average indices for the whole Southern Italy study area in order to globally assess the dependence between the NAO and the considered hydrometeorological variables.

In the Nile Delta area, the analysis is carried out by using the monthly precipitation time series of the gridded database CRU TS 1.2 (Mitchell et al. 2003), developed by the Tyndall Centre for Climate Change Research and the Climate Research Unit (CRU) of the University of East Anglia. The correlation between the winter precipitation in the Nile Delta area and the NAO was also assessed through a Pearson's lag-zero cross correlation analysis.

5 Results and Discussion

The results obtained in Southern Italy are summarized in Table 2 for each administrative region and for the whole Southern Italy study area. Figure 2 shows two scatterplots of NAO index against river discharge index and temperature index for the whole Southern Italy study area. Figures 3 and 4 show the spatial distribution of the Pearson cross-correlation coefficient between NAO index and precipitation index in the Nile Delta and in Southern Italy, respectively. The spatial distribution was derived by applying the ordinary kriging with linear variogram (Kitanidis 1993; Di Baldassarre et al. 2006).

In Southern Italy, both winter precipitation and hydrological records are negatively correlated with the NAO (see Table 2). Hurrell (1995) has shown how the effect of the NAO on the transport and convergence of atmospheric moisture in the Mediterranean basin should lead to drier (wetter) winters during the positive (negative) phases of the NAO. These findings explain the negative cross correlations we have consistently found between NAO and precipitation or river discharge. For Southern Italy such correlations, are all statistically significant at the 99% confidence level.

In the Nile Delta region, the interdependence between the NAO index and winter precipitation is low, but significant (Fig. 3). As expected, the correlation coefficient is higher in coastal areas, where it has values of 0.25–0.30 (Fig. 3). The positive sign of the correlation coefficient is consistent with the values obtained for Eastern Sicilia where the correlation tends to become positive (Fig. 4). This finding is consistent with the fact that, while most of the Mediterranean areas are negatively correlated with the NAO, the southeastern part tends to exhibit a positive correlation (Cullen and deMenocal 2000). It is important to remark that the use of the same interpolation procedure (i.e. ordinary kriging with linear variogram) in Southern Italy and Nile Delta, although justified by the need to make the results comparable, may have led

Table 2 Coefficients of cross correlation (ρ) and explained variance (ρ^2) between the NAO index and the regional indices for winter precipitation, number of rainy days, and river flow

Region	Precipitation		Number of rainy days		Discharge	
	ρ	ρ^2	ρ	ρ^2	ρ	ρ^2
Campania	−0.61	0.37	−0.62	0.39	−0.33	0.11
Calabria	−0.31	0.10	–	–	−0.47	0.22
Basilicata	–	–	–	–	−0.48	0.23
Puglia	−0.39	0.15	–	–	−0.48	0.22
Sicilia	−0.20	0.04	−0.36	0.13	−0.41	0.17
Sardegna	−0.45	0.20	–	–	−0.46	0.21
Whole Southern Italy study area	−0.49	0.24			−0.59	0.34

to a further smoothing of the signal in the Nile Delta region, where gridded data were utilized.

The strongest dependence of precipitation on the NAO is found on the western regions, probably due to a stronger dependence of precipitation on the winter westerlies. This interpretation is supported by the evidence that also in Sardegna a stronger correlation has been found on the west coast, which is exposed to western winds. These results are consistent within each administrative region and across the whole Southern Italy.

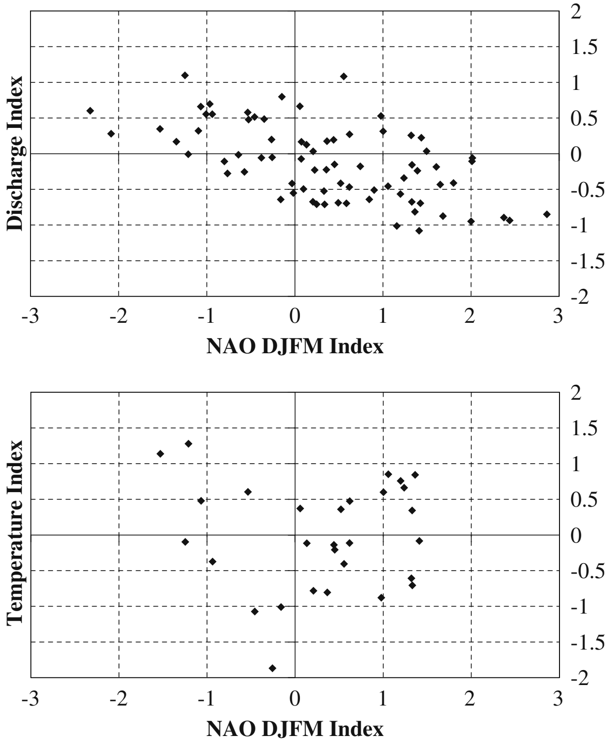

Fig. 2 Scatterplots of NAO index against discharge index (*upper box*) and temperature index (*lower box*) for the whole Southern Italy study area

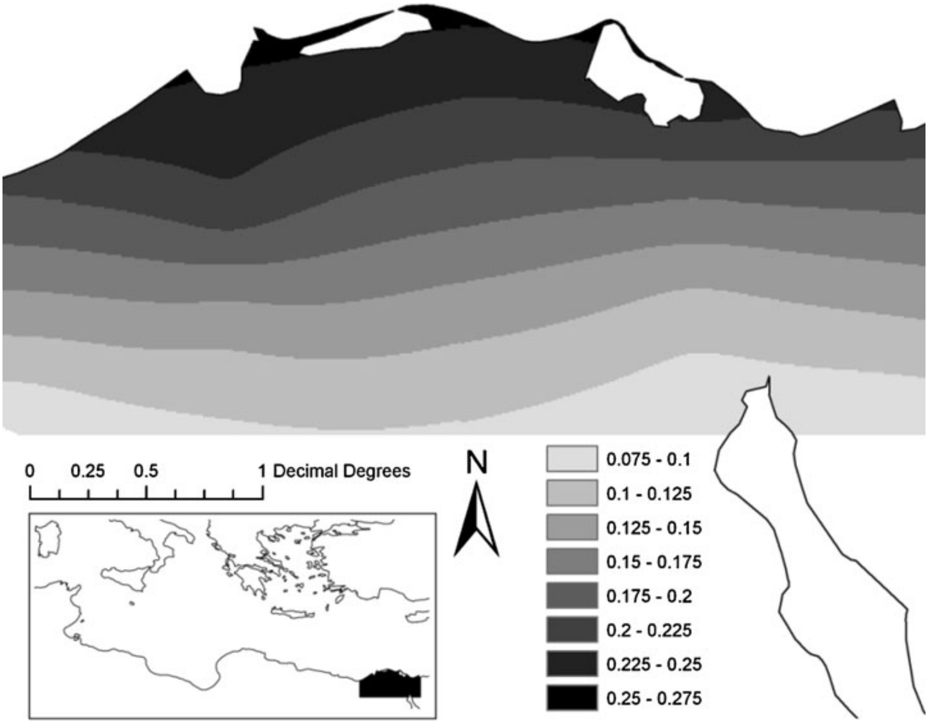

Fig. 3 Nile Delta (Egypt), spatial distribution of the Pearson cross-correlation coefficient between NAO index and winter precipitation (DJFM)

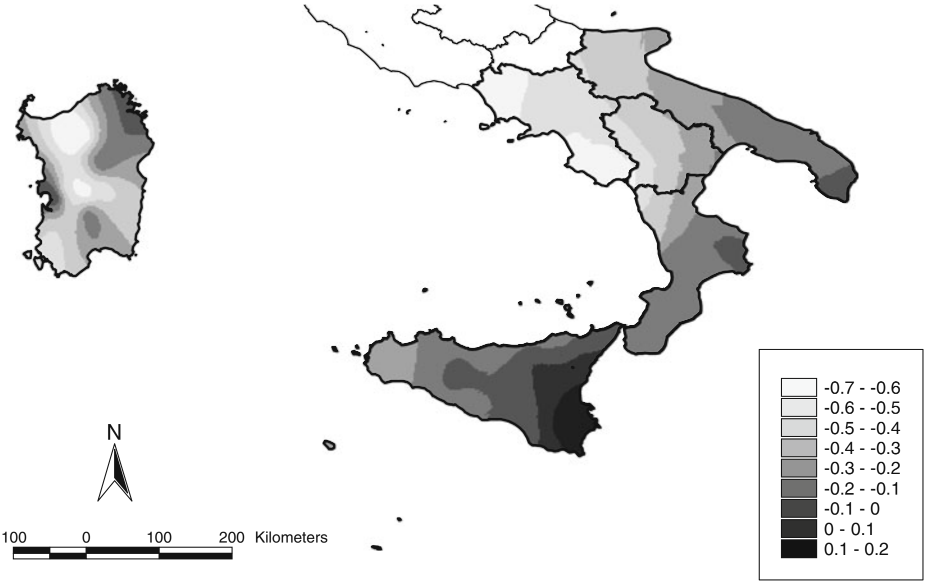

Fig. 4 Spatial distribution of the Pearson cross-correlation coefficient between NAO index and precipitation index for the whole Southern Italy study area, derived by at-site cross correlation data

The square of the correlation coefficient between two time series provides an estimate of the portion of the variance of the hydroclimatic indexes that is explained by a linear regression on the NAO index. On the basis of the results shown in Table 2, the North Atlantic Oscillation was found to explain about 24% of the interannual variability of seasonal precipitation and 34% of the variability of river flows. These results contribute to the understanding of interannual and interdecadal changes in available water resources in these drought-prone regions. In fact, the persistence of the NAO in a positive phase (and with a positive trend) over the last 30 years partly explains the decrease in available water resources observed in the study area in the course of the last three decades. Our study shows how such a decrease is partly explained by large scale patterns of atmospheric circulation in the Northern Hemisphere. However it is still hard to predict how the hydrologic regime in this central sector of the Mediterranean basin will change in the near future (see also Blöschl et al. 2007). In fact, it is still unclear whether the ongoing (positive) trend of the North Atlantic Oscillation is a permanent feature or only a segment of a multidecadal fluctuation of the NAO (e.g., Paeth et al. 1999; Thompson and Wallace 1998).

The monthly records of the number of wet days (available only for part of the study area) are also significantly correlated with the NAO index, suggesting that the phases of the North Atlantic Oscillation influence the rainfall regime in the study region by affecting the number of rainy days and not only the rainstorm depths. Unlike rainfall and river flows, temperature records exhibited only a weak cross correlation with the NAO in agreement with the findings by Cullen and deMenocal (2000).

6 Conclusions

This study aimed at better understanding the relation between the North Atlantic Oscillation (NAO) and hydroclimatic conditions in Mediterranean areas. We focused on two Mediterranean regions: Southern Italy and Nile Delta (Egypt). In both regions rainfall occurs predominantly in wintertime, when the NAO has a stronger impact on the Mediterranean climate.

The study showed that hydroclimatic variables are negatively correlated with the NAO, in most of the Southern Italy and provided a quantification of these effects. The negative correlation was found to be strong in the western regions, such as Sardegna, that are exposed to western winds. This modulation of winter precipitation by the NAO improves our current understanding and ability to predict the interannual variability of precipitation in most of the study region.

In contrast, both Eastern Sicilia and Nile Delta exhibited a low, but significant, positive correlation. This result is consistent with the findings of a larger scale analysis by Cullen and deMenocal (2000) who used shorter time series and a coarser network of rain gauges.. Although Mediterranean areas are mostly negatively correlated with the NAO, the southeastern rim tends to exhibit a positive correlation.

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