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Potential links between the North Atlantic Oscillation and decreasing precipitation and runoff on a Mediterranean area

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ABSTRACT

In the Mediterranean region, the reduction in precipitation and warmer temperatures is generating a desertification process, with dramatic consequences for both agriculture and the sustainability of water resources. On the island of Sardinia (Italy), the decrease in runoff impacts the management of water resources, resulting in water supply restrictions even for domestic consumption. In the 10 Sardinian basins with a longer database (at least 40 complete years of data, including data from the past 10 years), runoff decreased drastically over the 1975–2010 period, with mean yearly runoff reduced by more than 40% compared to the previous 1922–1974 period. Trends in yearly runoff are negative, with Mann-Kendall τ values ranging from −0.39 to −0.2. Decreasing winter precipitation over the 1975–2010 period everywhere on Sardinia island has led to these decreases in runoff, as most yearly runoff in the Sardinian basins (70% on average) is produced by winter precipitation due to the seasonality typical of the Mediterranean climate regime. The trend in winter precipitation is not homogenous; the negative trend is higher (around −0.25) on the west Sardinian coast, becoming lower across the island toward the east coast (around −0.14). Winter precipitation is highly correlated with the North Atlantic Oscillation (NAO), a weather phenomenon in the North Atlantic Ocean that controls the direction and strength of westerly winds and storm tracks into Europe. High negative correlations (up to −0.45) between winter NAO index and winter precipitation are estimated along the west coast. Meanwhile, these correlations decrease east across the island toward the high mountain in the center of Sardinia, reaching the lowest values along the east coast (about −0.25). The generally decreasing correlation between winter NAO index and winter precipitation in the longitudinal direction (from the North Atlantic dipole to the east) here accelerates due to local-scale orographic effects that overlap the large-scale NAO impact on the winter precipitation regime, thus softening the precipitation reduction due to the NAO. Such local topographic effects that may attenuate large-scale climate change effects must be considered in water resource planning and management alongside such climate change effects related to large-scale circulations, such as NAO.

1. Introduction

In the Mediterranean regions, current drier conditions stem from a reduction in precipitation and warmer temperatures, which are generating a desertification process that has consequences for both agriculture and the sustainability of water resources (Brunetti et al., 2002; Ventura et al., 2002; Klein Tank and Können, 2003; Ceballos et al., 2004; Vicente-Serrano and López-Moreno, 2006; García-Ruiz et al., 2011; López-Moreno et al., 2011a, 2011b; Vicente-Serrano et al., 2011; Martinez-Fernandez et al., 2013; Altin and Barak, 2014; Boithias et al., 2014). Future climate change projections predict further reductions in rain and a temperature increase (Cayan et al., 2008; Giorgi and Lionello, 2008; May, 2008, Mariotti et al., 2008; Mastrandrea and Luers, 2012; Ozturk et al., 2015).

Mediterranean regions serve as reference laboratories for the investigation of the impact of global change impact on hydrological process due to the high spatio-temporal variability of their environmental conditions, their rich and unique biodiversity (Doblas-Miranda et al., 2015), and particularly to their transitional climate, which is sensitive to changes in general atmospheric circulation (Giorgi and Lionello, 2008). Using a regional climate change index analysis, Giorgi (2006) identified the Mediterranean Sea region as one of the most prominent “hot spots” in the world, highly sensitive to climate change. In the Mediterranean Sea regions, negative trends in yearly runoff have been widely observed across various time periods: in Southern France from 1965 to 2004 (Lespinas et al., 2010), in the Italian Tiber River from 1922 to 2010

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(Romano et al., 2011), and on the Iberian peninsula from 1950 to 1999 (López-Moreno and Vicente-Serrano, 2007), 1945–2005 (Lorenzo-Lacruz et al., 2012), and 1966–2005 (Martinez-Fernandez et al., 2013). For Iberian rivers, Lorenzo-Lacruz et al. (2012) also detected significant negative trends in winter and spring flows, highlighting the importance of investigating runoff seasonality, which impacts the water resource management strategies used in the Mediterranean climate.

Also, in Sardinia (Italy), an island in the Mediterranean Sea, runoff decreased over the past three decades, thus nullifying the water resource management plans developed in 1987 using hydrologic data up to 1975 (Dessì et al., 1987). The extreme consequences of this recent decrease in runoff have been water supply restrictions even for domestic consumption in the main cities of Cagliari and Sassari (Statzu and Strazzera, 2009). The position of the island of Sardinia in the center of the western Mediterranean Sea basin and its low urbanization and human activity make Sardinia a perfect reference laboratory for Mediterranean hydrologic studies (e.g., Montaldo et al., 2008; Montaldo et al., 2013; Piras et al., 2014). Sardinian water resources are predominately surface water (Vinelli, 1926), mainly collected and regulated through an extended and well-monitored reservoir system (54 main dams) that has been developed since the early 1900s. At the same time, hydrologic data started to be collected from 1922 extensively, so a large hydrologic database is available that provides an interesting opportunity to evaluate historical runoff trends on an almost uncontaminated, large, and central Mediterranean island. Furthermore, topographic (an elevation of 1834 m a.s.l. reached in the center of the island), physiographic, and climate variabilities of the Sardinian basins may impact runoff (differences in floods between the western and eastern basins have been already recognized by Lazzari, 1968, and Deidda et al., 2000). Thus the Sardinian case study is very attractive for evaluating the homogeneity of the potential decrease in runoff across the island and searching for possible causes.

In this sense, decreasing rain is the main recognized reason for the decrease in Mediterranean runoff (Garcia-Ruiz et al., 2011), and negative trends in yearly precipitation have been commonly observed throughout the Mediterranean region, using data from 1880 to 1992 (Esteban-Parra et al., 1998), from 1951 to 1995 (Piervitali et al., 1998), from 1833 to 1996 (Buffoni et al., 1999), from 1951 to 1996 (Brunetti et al., 2001), from 1880 to 2002 (Brunetti et al., 2004), from 1923 to 2000 (Piccarreta et al., 2004), from 1950 to 2000 (Norrant-Romand and Douguedroit, 2006), from 1955 to 2004 (Bartolini et al., 2008), from 1821 to 2003 (Polemio and Casarano, 2008), from 1951 to 2000 (De Luis et al., 2009; Gonzalez-Hidalgo et al., 2009), from 1916 to 2000 (Caloiero et al., 2011), and from 1900 to 2010 (Philandras et al., 2011). Furthermore, contrasting trends in seasonal rainfall, a positive trend in spring and negative trends in autumn and winter have been estimated in Mediterranean Sea regions using data from 1952 to 1999 (Ventura et al., 2002), from 1900 to 1996 (Yue and Hashimo, 2003), from 1955 to 2001 (Feidas et al., 2004), from 1897 to 2001 (Founda et al., 2004), from 1923 to 2000 (Piccarreta et al., 2004), from 1958 to 2000 (Maheras et al., 2006), from 1970 to 1990 (Mohsin and Gough, 2010), from 1950 to 2005 (Lopez-Moreno et al., 2011b), from 1959 to 2008 (Gocic and Trajkovic, 2013). This may asymmetrically impact seasonal and yearly runoff. With its strong seasonality, the Mediterranean climate is characterized as having dry summer months (from June to September) that contrast with wet seasons, which are the main producers of runoff. Hence, although precipitation may increase in dry months, decreasing precipitation in wet months may impact yearly runoff. Indeed, Mediterranean climates are characterized by high values (≥2; Sankarasubramanian et al., 2001; Chiew, 2006) of the precipitation elasticity of streamflow ($\varepsilon_p = \frac{dQ}{Q} / \frac{dPr}{Pr}$. th Q the discharge and Pr the precipitation). This parameter evaluates the sensitivity of streamflow to changes in climate (Schaake and Chunzhen, 1989; Andréassian et al., 2016), and these high values mean that runoff changes in Mediterranean climates are larger than changes in precipitation. In searching for the causes of the potential decrease in runoff, we investigate the role of seasonal precipitation in generating runoff, evaluating yearly and seasonal precipitation trends across the island using the dense and wide network of rain stations in Sardinia.

One potential reason for the decreasing trends in precipitation and runoff is the influence of large-scale weather phenomena, such as the North Atlantic Oscillation (NAO; Hurrell, 1995; Hoerling et al., 2001), in the Mediterranean Sea region. Research on the causes of the decreasing trend in precipitation provides the attractive possibility of identifying a physical control, such as NAO, which can improve future predictability of precipitation and runoff tendencies (Scaife et al., 2014; Smith et al., 2016). The NAO connection with hydrological variables has been recognized both for the entire Mediterranean basin (Hurrell, 1995; Hurrell and Van Loon, 1997; Wibig, 1999; Trigo and Davies, 2000; Castro-Diez et al., 2002; Trigo et al., 2002; Krichak and Alpert, 2005; Lionello et al., 2006; Nissen et al., 2010; Lopez-Moreno et al., 2011a; Nissen et al., 2014; Norrant-Romand and Douguedroit, 2014) and for specific areas in the region (Quadrelli et al., 2001; Goodess and Jones, 2002; Martin-Vide and Lopez-Bustins, 2006; Vicente-Serrano and Lopez-Moreno, 2006; Lopez-Bustins et al., 2008).

Hurrell (1995) estimated a general, longitudinal, and decreasing trend in the correlation between winter precipitation and winter NAO index ($\rho_{P,NAO}$) across the Mediterranean basin from west to east (e.g., $\rho_{P,NAO}$ of −0.64 at Madrid and −0.37 at Milan). Hurrell (1995) also estimated a $\rho_{P,NAO}$ of −0.48 in the center of the Mediterranean Sea basin, but this estimate considered just one station: Ajaccio, Corsica. This island is close to northern Sardinia, but the estimate did not consider Sardinian rain stations. Brunetti et al. (2001) estimated an average $\rho_{P,NAO}$ of −0.37 for the main Italian islands (Sicily and Sardinia), but this estimate considered just three Sardinian rain stations located on the southern and northern Sardinian coasts. The general connection of Sardinian climate to large-scale circulation structures, especially westward via the North Atlantic, has been recognized previously (Delitala et al., 2000). The extended and dense Sardinian precipitation database allows deep evaluation of $\rho_{P,NAO}$ and the influence of NAO on precipitation trends, as well as their spatial variability across the island, in this typical, representative Mediterranean area. Sardinia is also characterized by topographic variability, which typically affects precipitation patterns (e.g., Basist et al., 1994; Duran et al., 2013) and may affect the relationship between precipitation and NAO. In this sense, Millán et al. (2005) examined the effect of topography on the correlation between NAO and Atlantic frontal precipitation for a small area of the eastern Iberia Peninsula, the Valencia region, highlighting a decreased in $\rho_{P,NAO}$ during winter on the coast ($\rho_{P,NAO}$ = −0.34) compared to the mountainous inland ($\rho_{P,NAO}$ = −0.61). Analysis of $\rho_{P,NAO}$ spatial variability across the island also allows evaluation of the topographic effects.

In summary, we address the following objectives:

1) To evaluate the extent and spatial homogeneity of runoff trends over the 1922–2010 period across the island of Sardinia;
2) To evaluate the role of seasonal precipitation in runoff generation, and to evaluate annual and seasonal precipitation trends and their spatial variability across the island;
3) To investigate the impact of the NAO on precipitation-regime trends across Sardinia, also considering topographic effects.