**Reworked coccoliths as runoff proxy for the last 400 years: the case of Gaeta Gulf (central Tyrrhenian Sea, Central Italy)**

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**Abstract**

We present the results of a high resolution study carried out on a shallow water sediment core, recovered in the central Tyrrhenian Sea to reconstruct the runoff story of the catchment basin of Volturno and Garigliano rivers (Gulf of Gaeta, Italy), over the past ~400years. We compared the abundance distribution pattern of Reworked Coccoliths to the surface runoff model simulation for the Volturno and Garigliano rivers hydrographic basins, the Global Historical Climatology Network index, the Palmer drought severity index, the Tevere river discharge anomaly, the summer average rainfall of the Southern Italy and the North Atlantic Oscillation reconstructed signal. This comparison suggested that the biotic signal of the Reworked Coccoliths may be used to detect climatic events from local to “global” scale. The calcareous nannofossil assemblages as well as their diversity index are modulated by oscillation in solar activity, where minima in solar activity correspond to minima calcareous nannofossil diversity and *viceversa*. In particular, the antiphase correlation between the abundance of Reworked Coccoliths and the North Atlantic Oscillation index, which modulates the winter precipitation, suggests that this biotic index could be used as a reliable proxy to reconstruct the variations in the hydrographic basin runoff of the Volturno and Garigliano rivers. In addition, power spectral and wavelet analysis carried out on both signals documented the occurrence of climatic cycles of the duration of about 95yr. From 1900 AD upwards, a turnover in the periodicity from 95yr climatic cycles to 22-26 yr cycles occurred in the Reworked Coccoliths signal, suggesting a strong control of solar forcing (Hale cycle) over the last century.

**1. Introduction**

The study of historical records, aimed towards a better understanding of the Earth’s climatic system and a more accurate prediction of its future evolution, is one of the most important priorities of the scientific community (e.g., Clark et al., 1999; Nakicenovic and Swart, 2000). Despite conflicting opinions regarding the reliability of paleoclimatic “proxies” and the consistency of results obtained from simulation models, applied for the reconstruction of past climate, the study of time series remains a valid analytical tool for the study of the Earth’s dynamic processes especially in conditions different than those of the present and has proven to be crucial in the determination of the reliability of medium and long term predictions models (i.e., Hansen et al., 1988; Hoffert and Covey, 1992; Karl and Trenberth, 1999; Nakicenovic and Swart, 2000; Webb et al., 1998). Within this framework the marine environment offers the unique opportunity to monitor the past climate changes (e.g., Bradley et al., 2003; Jones et al., 2009, 2001). One of the main issue for the scientific community deals with the reconstruction of past significant hydrological events in the marine areas that ultimately control the chemistry of the seawater, the nutrient supply, the food availability and the overall marine ecosystem.

The Mediterranean area is a transition zone between the continental inﬂuences of Europe, Asia, and the north-African desert, and the interaction of the Atlantic Ocean and the Mediterranean Sea (Harding et al., 2009). The Mediterranean climate is strongly influenced by its complex orography and its location within the boundary between subtropical and mid-latitude atmospheric patterns (Lionello et al., 2006; Trigo et al., 2006). Atmospheric circulation patterns of the northern hemisphere, influence climate variability in the Mediterranean region (Combourieu Nebout et al., 2002; Fletcher et al., 2012; Jalut et al., 2009; Roberts et al., 2012). Particularly, the North Atlantic Oscillation (NAO) is one of the dominant atmospheric circulation patterns in the North Atlantic sector, with considerable influences on winter temperature/precipitation throughout the Eurasian continent and eastern North America (Greatbatch, 2000). In Italy, the NAO index modulates the winter precipitations (Benito et al., 2015; Brunetti et al., 2002; Caloiero et al., 2011; López-Moreno et al., 2011; Tomozeiu et al., 2002). Positive NAO conditions fostered warm and dry winters, the opposite occurse with negative NAO index (Benito et al., 2015; López-Moreno et al., 2011; and references within). Due to this geographical configuration, the Mediterranean represents a unique laboratory to study the interaction between continental and marine environments. In particular, the sedimentary record of continental shelf areas represent a natural repository for monitoring, in addition to the past short-term climate oscillations, the past hydrological events whose controlling mechanisms are difficult to predict and to model (i.e., Budillon et al., 2005; Di Bella et al., 2014; Goudeau et al., 2015; Grauel et al., 2013a, 2013b; Incarbona et al., 2010a; Lirer et al., 2014; Oldfield et al., 2003; Piva et al., 2008; Taricco et al., 2009; Vallefuoco et al., 2012). Recently, Benito et al. (2015) proposed a wide review of the Holocene flooding events in the Mediterranean region suggesting that a centennial-to-multi-centennial seesaw pattern, associated to a bipolar hydroclimatic conditions, existed in the Mediterranean during the Holocene. Anyway, none of the datasets reported in this review was derived from marine coastal environments, where river ﬂow regime strongly controls the marine ecosystem evolution (Boesch et al., 2001; Cloern, 2001; Humborg et al., 2008; Paerl et al., 2014; Rabalais et al., 2001). Further studies using fossil archives are thus needed to document quantitatively the riverine freshwater inputs and to foresee their possible future trend in order to assess their impact on marine ecosystem.

An exhaustive data analysis of the Mediterranean river discharge is strongly impaired by the lack of data, especially in the south-eastern parts of the basin. This issue, together with the necessities of climate change and impact studies, has fostered the development of alternative methods for estimating large-scale budgets for present and future climate conditions. Some methods are based on empirical relations between runoff, precipitation, and temperature fields (Biondi et al., 2002; Brunetti et al., 2006; Gou et al., 2007; Gray et al., 2011; Mariotti et al., 2008; Sun et al., 2013; Wirth et al., 2013), while other methodologies focused on the surface integration of the runoff fields produced by climate models or on the development of macroscale hydrological models (Alberico et al., 2014).

Within this framework, the identification of paleoclimatic “proxies” useful to document the past hydrological events is very important. Coccolithophores are calcifying unicellular planktonic algae, whose distribution is controlled by environmental parameters within the photic zone of the oceans (e.g. temperature, salinity, sunlight). The variation in abundance of selected taxa can be used as an excellent proxy for recognizing climate changes. Their exoskeletons, composed of tiny calcareous platelets (coccoliths), are found to very abundant in the fossil record: their long evolutionary story (Late Triassic - present day), high evolutionary turnover, and phenomenal abundance in marine sediments make them ideal fossils for high-resolution biostratigraphic studies as well as for paleoclimatic reconstructions (Bown, 1998; and reference within). The reworked specimens generally bias the biostratigraphic signal. However, in shelf-dominated and river-dominated areas, the Reworked Coccoliths (RC) can provide useful information about land-ocean dynamic, sediment transport (Bonomo et al., 2014; Ferreira and Cachão, 2005; Ferreira et al., 2008), and allow to account for the continental terrigenous fluxes which are useful for paleoclimatic studies and to reconstruct large scale runoff oscillation (Incarbona et al., 2010; Sprovieri et al., 2006).

Here, we present the results of a high resolution study carried out on a sediment core, recovered at 93m depth in the Gulf of Gaeta (GoG) (central Tyrrhenian Sea). The distribution pattern of reworked coccoliths is compared with the 5-year running average of the Surface Runoff model simulation (UTMEA CLIM group - EU project CIRCE) of the Volturno and Garigliano river hydrographic basins, the National Climatic Data Center Global Historical Climatology Network V2 precipitation anomalies (GHCN) (Mariotti et al., 2008), the Palmer drought severity index (PDSI) (Mariotti et al., 2008), the percentage ratios of the summer average rainfall (Caloiero et al., 2011), the Tevere river discharge anomalies (Mariotti et al., 2008) and the NAO reconstructed signal (Trouet et al., 2009). This research aims to reconstruct the runoff story of the catchment basin of the Volturno and Garigliano rivers (GoG) over the past ~400 years using RC.

**2. Study area**

The Tyrrhenian Sea is the deepest major basin in the western Mediterranean Sea (Astraldi et al., 1994). The circulation is overall cyclonic triggered by the Modiﬁed Atlantic Water (MAW), located in the upper 100–200 m of the water column, entering off the northern Sicilian coast and establishing a northward current along the western Italian coast (Fig. 1a) (Artale et al., 1994; Krivosheya and Ovchinnikov, 1973; Millot, 1987; Pierini and Simioli, 1998). According to this circulation pattern the GoG has a cyclonic vortex that interacts with the superﬁcial (down to 10 m depth) and the intermediate (from 10 to 100 m water depth) layers. This pattern is more characteristic during the winter, when a NW water ﬂow dominates. In the summer, although it preserves its cyclonic character, it also shows smaller cells and reduced dynamics, with an S and SE direction of the water movements (Fig. 1b). Moreover, according to De Pippo et al. (2003) two zones with two different circulation regimes are present: a coastal zone (<50 m depth) with closed cyclonic and anticyclonic circulations, and an offshore zone (>120 m depth) inﬂuenced by a mainly northern ﬂow.

The study area is characterized by the presence of two major rivers, the Volturno and Garigliano (Fig. 1b). These rivers are the two longest of southern Italy (175 km and 38 km) with an estimated mean discharge of 80 m3s−1 and 120 m3s−1 and a catchment basin of 5550 km2 and 5020 km2, respectively (Iermano et al., 2012). The littoral zone is also conditioned by two minor rivers, the Regi Lagni and Agnena channels with a catchment basin of about 1095 km and of 209 km2, respectively. The marine area in front of the Volturno river mouth consists of a wide shallow continental platform, gently deep toward the sea, which surface sediments are represented by silt to subordinate fine to medium-grained sands in the area close to the coast (<20 m depth).

The catchment basins contain mainly Cretaceous, Paleogene and Neogene sedimentary rocks and alternate recent volcanic and alluvial deposits (Bonardi et al., 1988).

**3. Materials and methods**

3.1Core SW104-C5

The sedimentary sequence was collected with a SW104 gravity corer system, which preserves the water-sediment interface and allowed the recovery of 108 cm of undisturbed and uncompressed homogeneous brown-gray hemipelagic sediments interlayered by a tephra layer (between 60 and 61 cm). Sedimentary core SW104- C5 (long.13°47’02,714’’E; lat.40°58’24,917’’N) was recovered in GoG in front of the Volturno river mouth at 93 meter below sea level (Fig. 1b).

3.2Calcareous Nannofossils

Counts of calcareous nannofossils were carried out on 108 samples using a transmitted light microscope at 1000× magnification. Rippled smear slides were prepared, without any chemical treatment, sieving or centrifuging. Counts of about 300 specimens were performed on the entire assemblage (Negri and Giunta, 2001; and reference whithin). The abundance of *Florisphaera profunda* was evaluated in a separate count, versus 300 nannofossils (after Beaufort et al., 1997; Castradori, 1993; Matsuoka and Okada, 1989; McIntyre and Molfino, 1996). Separate counts were also made to evaluate the abundance of reworked specimens, which include taxa from different stratigraphic intervals (Mesozoic, early Cenozoic – e.g. Eiffellithaceae, Watznaueriaceae, Kamptneriaceae, *Nannoconus* spp., Sphenolithaceae, Discoasteraceae, *C. macintyrei*, *H. walbersdorfensis*) and Cenozoic long-range taxa showing poor preservation (etching and/or regrowth).

The taxonomic groups were recognized following the taxonomy proposed by Jordan et al. (2004) and Young et al. (2003) (Tab. 1). Gephyrocapsids were identified to species level when larger than 3μm. Specimens smaller than 3μm were merged into the small *Gephyrocapsa* group; *G. muellerae* also includes rare specimens of *G. caribbeanica*; Small placoliths includes specimens of *Reticulofenestra* spp. (<3μm), *Emiliania huxleyi* with dissolved T-shape elements and *Gephyrocapsa* spp. (<3μm) with broken bridge; *Helicosphaera carteri* also includes *H. hyalina*. *Thoracosphaera heimii*, a calcareous dinoflagellate (Jordan and Kleijne, 1994; Tangen et al., 1982), was included in the nannofossil counts since it occurs in the same preparations and provides directly comparable ecological data. In order to obtain paleoenvironmental information from the study core, taxa were subdivided into four groups based on coccosphere functional morphology which might reﬂect different ecological adaptations (Di Stefano and Incarbona, 2004; A. Incarbona et al., 2010; Young, 1994a) (Tab. 1).

The Placoliths bearing group (Pb) includes *E. huxleyi*, small *Gephyrocapsa*, *G. muellerae, G. caribbeanica,* *G. oceanica* and Small Placoliths. The Miscellaneous group (Ms) includes *Helicosphaera* spp., *Syracosphaera histrica*, *Pontosphaera* spp., *Calcidiscus leptoporus*, *Pleurochrysis* spp., *Braarudosphaera* spp. and all the other taxa. The Upper Photic Zone group (UPZ) includes *S. pulchra*, *Umbellosphaera* *tenuis*, *Discosphaera tubifera*, *Rhabdosphaera* spp., *Umbilicosphaera* spp., *Oolithotus fragilis*, *Calciosolenia* spp., *Holodiscolithus*, *Ceratolithus* spp. and the dinoﬂagellate *T. heimii* (Tangen et al., 1982). Lower Photic Zone group (LPZ) includes mainly *F. profunda* and extremely rare *Gladiolithus flabellatus*. All data were smoothed, applying a 3 points running average.

In SW104-C5 core Shannon-H diversity index curve was calculated from percentage assemblage counting data using PAST version 3.10 (Hammer et al., 2001). This index is a quantitative measure that reflects both how many different taxa are present, and how evenly the individuals are distributed among those taxa. The value of this diversity index increases when either the number of taxa or the evenness increases. For any given number of taxa, the value of diversity index is maximized when all taxa are equally abundant.

3.3Age Model

The chronology of the uppermost 60 cmbsf (centimetre below sea floor) of core SW104-C5 was developed on the 210Pb activity-profile, which exponentially declines in depth (Fig. 2) (Margaritelli et al., 2015, Unpublished results), thus suggesting a constant sedimentation accumulation during the last 100 years (mean sedimentation rate of 0.46 cm/yr). This sedimentation rate estimate is supported by 137Cs activities, which show a evident trend to back 34.5 cmbsf (Fig. 2) (Margaritelli et al., 2015, Unpublished results). The peaks recorded at 30.5 cmbsf and at 23.5 cmbsf, associated to 1954 AD (first nuclear explosion) and to 1963 AD (maximum 137Cs fallout), respectively, indicate a mean sedimentation rate of 0.48 cm/yr. The evaluation of sedimentation rate obtained for the last century, is also reinforced by the identification of a tephra layer at 60-61 cmbsf, which is related to the Vesuvius volcanic eruption occurred in 1906 AD (Margaritelli et al., 2015, Unpublished results). Downwards the construction of age-depth profile is based on the recognition of planktonic foraminifer *Globorotalia truncatulinoides* acme interval (Margaritelli et al., 2015, Unpublished results). The maximum abundance peak of *G. truncatulinoides*is recorded at 90 cmbsf, has been dated at 1718 AD by Lirer et al. (2014) in Gulf of Salerno. Finally, the constructed age model allowed us to calibrate the age of the base core at 1640 AD.

3.4 Signals analysis

The analysis of the non-stationary (frequency changes along time) and non-linear signals, to search characteristic periodicities, was performed by applying the Empirical Mode Decomposition algorithm (EMD) of Huang et al. (1998) in order to decompose multi-component signals into a series of amplitude and frequency modulation (AM-FM) waves, each with slowly varying amplitude and phase.

Major advantage of EMD is that the basis functions are derived from the signal itself, hence the analysis is adaptive in contrast to the traditional methods where the basis functions are ﬁxed as sine and cosine for Fourier transform like methods and the mother wavelet functions for wavelet analysis. This decomposition technique is derived from the simple assumption that any complicated signal can be decomposed into a finite and often small number of components called “Intrinsic Mode Functions” (IMF) (Huang et al., 1998) - each of them representing an embedded characteristic simple oscillation on a separated time-scale.

The signals and the IMF components are analysed without interpolation keeping the original unevenly sampling intervals, with:

* “REDFIT”, an evolution of the Lomb-Scargle periodogram (Lomb, 1976; Scargle, 1982; Schulz and Mudelsee, 2002).

The spectral analysis is a powerful tool to separate the variance of a signal into contributions associated at frequencies range *0 < f < fNyq*. A property of modified periodogram *PX(w)* is defined so that if the time series *X(ti)* is purely white noise, then the power in *PX(w)* follows an exponential probability distribution function. This distribution provides a convenient estimate of the “false alarm probability” that says if a given peak is a true periodicity, or whether it is the result of randomly distributed noise. The “false alarm probability” works good only if the noise contained in the signal is “white”, generally, stratigraphic/paleoclimatic signals are characterized by “red-noise” that in the periodogram is showed by continuous decrease of spectral amplitude with increasing frequency (Schulz and Mudelsee, 2002; Schulz and Stattegger, 1997).

To adapt the distribution function to red-noise signals a solution is the utilization of a first-order autoregressive AR(1) process (Hasselmann, 1976), this solution was implemented by Schulz and Mudelsee (2002) in the “REDFIT” software that estimates the AR(1) parameters directly from unevenly spaced signal. Comparison of the modified periodogram of our signal with the spectrum of the AR(1) model allows to test the hypothesis that the analysed signal is consistent with a red-noise AR(1) model. When this test is checked, it is possible: i) to correct our signal Lombe-Scargle spectrum because it is biased, in particular spectral amplitudes at the high frequency end of the spectrum are often over-estimated and ii) to estimate the confidence levels because now the PDF (Partial Discharge Frequency) of the spectrum, at each frequency, follows a 2 distribution.

* Foster's (1996) weighted wavelet Z-transform (WWZ). Wavelet analysis examines the frequency distribution of a non-stationary signal using a set of fully scalable modulated windows that have compact support in time (i.e., decays to zero quickly) and are band-limited in the frequency domain. These window functions resemble tiny waves that grow and decay in short periods of time and hence have the name “wavelets” (Grossmann and Morlet, 1984).

To analyze non-stationary and irregularly sampled signals, we need an extension of the classic wavelet formalism. Foster (1996), who defines the WWZ, developed such extension as a suitable weighted projection method re-orthogonalizing the three basic functions (real and imaginary part of the Morlet wavelet and a constant) by rotating the matrix of their scalar products. He furthermore introduces statistical F-tests to distinguish between periodic components and a noisy background signal.

3.5 Wavelet filtering (Decomposition and reconstruction)

To compare the dominant periodicities recorded in the RC datum with the same order periodicities documented in the reference global signal, we applied a bandpass filter to these signals, using the wavelet multi-level decomposition and reconstruction technique, because it is invertible and thus suitable for filtering data. There are many different names for this procedure, including fast wavelet transform, fast orthogonal wavelet transform, multiresolution algorithm, and pyramid algorithm. In particular, we used the multiresolution analysis (MRA) algorithm to decompose a signal into scales with different time and frequency resolution organized according to a hierarchical scheme (Mallat, 1989). To apply a bandpass filter to the decomposed signal, we removed all information out the choice frequencies window by setting all values of the approximation coefficients, belonging to a range of scales comparable with the frequencies window, to zeros. The signal is subsequently reconstructed iteratively convolving the approximation coefficients with the low-pass reconstruction filter, and convolving the detail coefficients with the high-pass reconstruction filter and summing the results. The reconstruction filters are the time-inverses of the decomposition filters and therefore provide a zero-phase-lag reconstruction.

**4. Result and Discussion**

4.1 Calcareous Nannofossils

The quantitative analysis shows that the Pb group is always dominant, with abundance never lower than ~84% (Fig. 3). This result reﬂects the proximity of the coast and the relatively high level of productivity of the studied area, due to the Volturno and Garigliano river discharge. The dominant species of this group is *E. huxleyi* (Fig. 3), which is consistent with living coccolithophore data from the same area (Bonomo et al., 2014) and Holocene records from Mediterranean Sea (Bárcena et al., 2004; Buccheri et al., 2002; Flores et al., 1997; Knappertsbusch, 1993; Lirer et al., 2013; Malinverno et al., 2003; Ziveri et al., 2000). This taxon is a cosmopolitan, eutrophic species, more abundant in late spring through summer, and its presence is considered as a tracer of turbid, cold, and nutrient enriched waters ( Incarbona et al., 2010a; and reference within).

The abundance pattern of *F. profunda*, virtually the only species representative of the LPZ group, shows very low abundance values never exceeding ~2%. This taxon is almost continuously present from 1920 AD to Present, inside the onset of Industrial Age (IA) and Modern Warm Period (MWP) (Fig. 3). Below these intervals, *F. profunda* shows a scattered distribution pattern most likely due to the occurrence of two concauses: an increased influx in suspend material, which in turn implies a reduction in light penetration, and unfavourable climatic conditions during the Little Ice Age (LIA). This pattern was documented also in the Gulf of Salerno (south Tyrrhenian Sea) by Vallefuoco et al. (2012) and Incarbona et al. (2010) during the Dalton and Damon solar minima events. According to authors, *F. profunda* is the main representative of the lower photic zone group, dwelling under the summer thermocline (Kinkel et al., 2000; Molfino and McIntyre, 1990; Winter et al., 1994; Young, 1994b). In fact, the highest cell densities have been recovered from water samples during periods of maximum insolation (i.e. seasonal stratification), with minimum standing stocks (i.e. oligotrophic conditions) in the upper part of the water column (Bonomo et al., 2012; Cortés et al., 2001; Haidar and Thierstein, 2001; Malinverno et al., 2003). Furthermore, light intensity is responsible for 53% of *F. profunda* cell density variance (Cortés et al., 2001), this suggests that past changes in water column turbidity also control the abundance fluctuations of this species.

The UPZ group never exceeds the ~14% of the total assemblage, and shows a gradual increasing trend from bottom core to Present (Fig. 3). UPZ taxa are K-strategists, specialized to live in warm subtropical surface waters with a minimum amount of nutrients (Andruleit et al., 2003; Baumann et al., 2005; Boeckel and Baumann, 2004; Okada and McIntyre, 1979; Roth and Coulbourn, 1982; Takahashi and Okada, 2000). The distribution patterns of the two most abundant components of this group, *S. pulchra* and *Rhabdosphaera* spp.,show an increasing trend between 1890 and 1940 AD. This time interval fits into the onset of the IA and MWP (Fig. 3).

During the last 400 years, Ms group displays low abundance values, which never exceed ~5% of the total assemblage, and shows a distribution pattern resembling that observed for UPZ and LPZ groups, with the same increasing step between 1890 and 1940 AD (Fig. 3). The Ms group comprises taxa that live without any speciﬁc depth and within a wide range of ecological preferences; nevertheless in SW104-C5 core this group mirrors the profiles of UPZ and LPZ groups. This similarity can be explained by two concomitant factors: the discharge fluxes of the Volturno and Garigliano rivers, inducing high concentrations of suspended material, and the increasing trend of Solar Irradiance Reconstruction (Lean, 2000) that characterizes the LIA-MWP transition. Due to these two concurrent factors, the Shannon-H index shows the same progressive increasing trend than that of LPZ, UPZ and Ms groups with a sharp inflexion around the 1890-1900 AD (Fig. 3-4). Moreover, a robust similarity is unequivocally recognizable between the Shannon-H index and the Solar Irradiance Reconstruction during the last 400 years. The Shannon-H index profile evidences two marked decreases in calcareous nannofossil diversity during the Maunder and Dalton minima (Fig. 4). It means a decrease in calcareous nannofossil diversity during cold events.

4.2 Reworked Coccoliths

Reworking can theoretically happen to any fossil. This simply means that fossils have been removed from their original sedimentary layer and redeposited in a different younger layer. For paleontological studies, the occurrence of reworked specimens is usually considered as a disturbing factor for paleoenvironmental or biostratigraphic interpretations. Conversely, reworked microfossils, such as calcareous nannofossils, can be used as a useful parameter in paleoclimatic reconstruction providing valuable information on runoff variations. This allows for a better understanding of the climatic forcings, acting on the continental areas adjacent to the studied site (Ferreira et al., 2008; Incarbona et al., 2010; Incarbona et al., 2008).

The SW104-C5 core, due to the proximity of the Volturno River mouth (12 km) and the GoG morphology, is an ideal key-site to “use” the reworking signal for a high-resolution reconstruction of the Volturno and Garigliano hydrographic basin dynamic in relation to the last 400yr Mediterranean climatic oscillations. Reworked Coccoliths are very abundant along SW104-C5 core (Min. 32%; Max. 79%; Mean 57%) and consisting of Cretaceous, Paleogene and Neogene taxa, clearly reflect the stratigraphy of the Volturno and Garigliano rivers hydrographic basins. In detail, from bottom core (1640 AD) to 1715 AD, correlated to Maunder minimum, reworked taxa show mean values between 50 and 65 % (Fig. 5). Upwards, an increasing trend culminates at Dalton minimum with the highest values (70-79%) recorded in the SW104-C5 core (Fig. 5). After 1880 AD, the abundance pattern of reworked taxa index shows a general decrease, reaching a plateau mean value of about 60% up to 1940 AD (Fig. 5).

The visual comparison between NAO index and the RC signal shows a general anti-related trend in the first and last 100 years. In fact some maxima in RC correspond to negative values in the NAO index (Fig. 5), so confirming the Atlantic forcings as a general driver of precipitation variation on central Mediterranean area (Griffies and Bryan, 1997; Knight et al., 2006; Mariotti and Dell’Aquila, 2012; Marullo et al., 2011). Afterwards 1940 AD up to top core, RC show an abrupt change in their abundance amplitude and frequency (from 32% to 65%) (Fig. 5). This pattern prevents a direct correlation with NAO index for the last half century. Conversely, the visual comparison for the last 50 years between surface runoff reconstruction model (mean values - Circe project), Tevere river (central Italy) discharge fluctuations (Mariotti et al., 2008), GHCN index, PDSI and summer average rainfall with RC data, show a robust correlation for the last decades (Fig. 5). In particular, the sharp decreases in the RC abundance, recorded at about 1945-1950 AD (D1), 1970 AD (D2) and 1995-2000 AD (D3), are well documented also in the others proxy records (Fig. 5). These three periods could be associated to strong dry phases with low rainfall, especially during summer, as documented for the southern Italy by Caloiero et al. (2011). In addition, two of these drought events have been recognized and reported by several authors (Briffa et al., 1994; Lloyd-Hughes and Saunders, 2002; Spinoni et al., 2015; and reference within) from regional to “global” scale. In detail, the D1 drought was a European to North America continent event recorded by several proxies (e.g. GHCN, PDSI, tree rings) and for the first time by RC abundance fluctuations in marine fossil archives. The D3 event has been recognized in the Southern to Southern-Eastern European (Pal, 2004; Spinoni et al., 2015, 2013) and can be thus considered as regional drought period.

In order to analyse in detail the NAO and RC signals, IMF analysis has been carried out to identify the main components (characteristic simple oscillation on a separated time-scale) occurring in these signals (Fig. 6). In particular, IFM4 and IFM6 are the two main components of RC and NAO signal, respectively, recording comparable distinct long-term trend frequency cycles (Fig. 6).

Power spectral analysis performed on RC signal (IFM4) and NAO index (IFM6) show main peaks, above the 95% of C.I., centered at ~94 yr and ~95 yr, respectively (Fig. 7). In addition, wavelet analysis carried out on NAO indexes (Fig. 7) indicates that the periodicity of 95 yr is clearly present on the entire studied time interval, as documented by many authors (Schlesinger and Ramankutty, 1994; Enfield et al., 2001; Velasco and Mendoza 2008; Frankcombe et al., 2010; Knudsen et al., 2011; Marullo et al., 2011). Conversely, the periodicity of 94 yr, recorded in the RC signal, is documented from 1637 to 1900 AD (Fig. 7). The comparison of the filtered raw data in ~95 yr long-term frequency band shows that the biotic signal is in antiphase with reference target curve, where maxima in RC correspond to negative values in NAO signal (Fig. 8). A slightly mismatch of about 10/15 years is documented in the lower part of the study record, probably related to the age model.

From 1900 AD upwards, the power spectral and wavelet analysis carried out on IFM3 of RC shows a periodicity variable between 21 and 26 yrs. This periodicity interval is well comparable with the well-known Hale solar cycle of 22 yr (i.e., Mursula et al., 2001). In addition in the IFM5 of RC is also documented a strong periodicity centered at 45 yr (Fig. 8) that can be considered a multiple of the Hale cycles. This turnover in periodicity from about 95 yr to 22/45yr is also clearly visible in the RC raw data signature where from 1900AD up to present day is documented an important change in the amplitude and frequency oscillation (Fig. 5).

**Conclusion**

The SW104-C5 core is a key-site for very high-resolution studies to document the continental-marine paleoclimate dynamics through the reconstruction of surface runoff oscillations over the last 400 years, using the calcareous nannofossil reworked signal. In particular, the calcareous nannofossil assemblages as well as their diversity index (Shannon-H index) are strongly related to the oscillations in solar activity, where minima in solar activity correspond to minima calcareous nannofossil diversity and *viceversa*. The transition from the LIA to the MWP is clearly documented through abundance fluctuations of LPZ, Ms and UPZ groups and Shannon-H index also. Conversely, changes in abundance of RC signal reflect the hydrographic basin runoff variations of Volturno and Garigliano rivers, showing a clear correlation with the NAO index, the Circe surface runoff reconstruction model, the GHCN index, PDSI index, Tevere river discharge and summer average rainfall of Southern Italy. Power spectral and wavelet analysis carried out on RC highlights the occurrence of climatic cycles of about 95 years as documented in the NAO index. These data suggest a antiphase correlation of the RC with the NAO index which modulates the winter precipitation (i.e., Brunetti et al., 2002; Caloiero et al., 2011). From 1900 AD upwards, the occurrence of climatic cycles of 22-26 yr in the RC signal suggests a strong control of solar forcing over the last century climate. Finally, the global scale drought events of 1950 AD and of 1995-2000 AD have been documented in marine fossil archives for the first time.

Our data point out that this shallow water site, facing to a river mouth, can be used to reconstruct the surface runoff variations for a single river basin using abundance fluctuations of RC. However, this statement needs to be confirmed by further studies in other rivers mouth sites, in order to make the RC a reliable high-resolution runoff proxy in climatic provisional models.

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