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Key Points:
- Modern Analogue Technique and Artificial Neural Network SST reconstructions are tested on planktonic foraminifera of the last 500 years
- The atmosphere/ocean interplay governs different water column configurations in neighboring mesoscale gyres at multidecadal scale

Supporting Information:
- Supporting Information S1

Correspondence to:
A. Incarbona,
alessandro.incarbona@unipa.it

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Sea Surface Temperatures and Paleoenvironmental Variability in the Central Mediterranean During Historical Times Reconstructed Using Planktonic Foraminifera

Alessandro Incarbona[1], Lukas Jonkers[2], Serena Ferraro[3], Rodolfo Sprovieri[1], and Giorgio Tranchida[4]

[1]Dipartimento di Scienze della Terra e del Mare, Università degli Studi di Palermo, Palermo, Italy, [2]MARUM—Centre for marine environmental research, Bremen University, Bremen, Germany, [3]Dipartimento di Scienze della Terra, della Vita e dell'Ambiente, Campus Scientifico Località Crocicchia, Università degli Studi di Urbino "Carlo Bo", Urbino, Italy, [4]Consiglio Nazionale delle Ricerche, Istituto per l'Ambiente Marino Costiero, Sezione Capo Granitola, Trapani, Italy

Abstract The ongoing anthropogenic-induced warming assessment requires a robust background from regional sea surface temperature (SST) reconstructions. Planktonic foraminifera have yielded valuable insights into late Quaternary SST dynamics, but the techniques to estimate SST from fossil assemblages have only rarely been used in very recent sedimentary records (the last 2,000 years). Here we use two transfer function methods, modern analog technique and artificial neural networks, to reconstruct SST variability in two cores from the Central Mediterranean Sea that span the last five centuries. Both cores show similar and considerable changes in the planktonic foraminifera assemblages. However, the inferred mean annual SSTs only varied in a narrow range, in agreement with instrumental data that go back to 1850 CE. Our reconstructions extend this time frame and indicate that SST variability did not exceed 1.5 °C over the past three centuries. Rather than temperature, we suggest that the changes in the assemblages reflect switches between sea surface winter/spring productivity and a deep winter mixed layer, due to the atmosphere/ocean interplay that governs different productivity modes in neighboring mesoscale gyres.

1. Introduction

Late Holocene sea surface temperature (SST) estimates are a basic requisite to assess natural climatic trends and the ongoing anthropogenic-induced warming (Abram et al., 2016; McGregor et al., 2015). Planktonic foraminifera assemblages were exploited as one of the first paleothermometers used in paleoceanographic reconstructions, more than 40 years ago (McIntyre et al., 1976). Since then, transfer function techniques have been refined, improving the quality and reliability of results (Guiot & de Vernal, 2007). In the Mediterranean Sea, Modern Analogue (MAT) and Artificial Neural Network (ANN) Techniques were broadly employed to investigate temperature changes across late Quaternary glacial/interglacial cycles, with special emphasis on last glacial Dansgaard-Oeschger oscillations and the transition from the last glacial period to the Holocene (Hayes et al., 2005; Kallel et al., 1997; Pérez-Folgado et al., 2003, 2004; Siani et al., 2010).

Holocene and late Holocene planktonic foraminifera paleoenvironmental reconstructions in the Mediterranean Sea were especially focused on the ecological response to change associated with the deposition of the most recent organic-rich layer in the eastern basin (sapropel S1, between about 10 and 6 ka, Grant et al., 2016; De Lange et al., 2008) and to synchronous environmental modifications in the western and central areas (Capotondi et al., 1999; De Rijk et al., 2000; Mojtahid et al., 2015; Principato et al., 2006; Sbaffi et al., 2001; Sprovieri et al., 2003; Triantaphyllou et al., 2009, 2016). Planktonic foraminifera species in the central-western Mediterranean show similar trends and variations in the last 2 kyr, as can be seen in local ecobiozones (Capotondi et al., 1999; Lirer et al., 2013; Margaritelli et al., 2016; Margaritelli et al., 2018; Sprovieri et al., 2003; Vallefuoco et al., 2012).

This work aims to assess the limits and applicability of SST reconstructions based on planktonic foraminifera species in the central Mediterranean Sea in the recent past. We apply MAT and ANN on species assemblages from two cores from the Sicily Channel that span the last 450 years. The radionuclide chronology of the two cores (Incarbona et al., 2016) meets strict quality control criteria used in a compilation of high-resolution sedimentary SST archives of the last 2,000 years (McGregor et al., 2015). The short time interval makes us confident that calibration assumptions, for instance, no changes in the ecological properties of the species and stability in the thermal structure of the upper water column (Guiot & de Vernal, 2007; Jonkers & Kučera, 2017; Telford et al., 2013), were respected. Instrumental Kaplan SST since 1856 CE (Kaplan et al., 1998) and alkenone and Mg/Ca-based SST estimates already acquired at the same St 342 and 407 sites (Incarbona et al., 2016) provide independent evidence to be compared with planktonic foraminifera MAT and ANN results. Finally, the investigated area, characterized by mesoscale oceanographic variability (Robinson et al., 1999), experiences very recent changes of surface water salinity and productivity associated with modifications of the Mediterranean thermohaline circulation and the influence of multidecadal atmospheric patterns (Incarbona et al., 2010, 2016), thus being an ideal natural laboratory for environmental variations that are reflected in planktonic foraminifera assemblages in historical times.

2. Regional Setting

2.1. Oceanographic and Atmospheric Framework

The Mediterranean is an elongated and semienclosed sea, with an antiestuarine circulation pattern forced by the negative hydrological balance with the Atlantic Ocean (Robinson & Golnaraghi, 1994). The Mediterranean conveyor belt reproduces global ocean processes of dense water formation and thermohaline circulation in relation to climate (Bethoux et al., 1999). Surface waters coming from the Atlantic Ocean, called Modified Atlantic Water (MAW), occupy the first 100–200 m of the water column. In the Sicily Channel, MAW is split into two streams (Béranger et al., 2004; Robinson et al., 1999). The Atlantic Tunisian Current follows the African coast and flows eastward as a coastal current. The northern branch, called the Atlantic Ionian Stream, feeds the Mid-Mediterranean Jet that flows eastward into the central Levantine basin up to Cyprus (Pinardi & Masetti, 2000; POEM group, 1992; Figure 1).

Five semipermanent mesoscale summer features are associated with Atlantic Ionian Stream meanders, mainly in response to topographical effects, but also to atmospheric forcings and internal dynamics: the Adventure Bank Vortex, the Maltese Crest Channel (MCC) anticyclonic gyre, the Ionian Shelfbreak Vortex cyclonic gyre in the Sicily Channel, the Messina Rise Vortex, and temperature and salinity fronts of the Ionian slope in the Ionian Sea (Figure 1; Béranger et al., 2004; Lermusiaux & Robinson, 2001; Onken, 2003). St 342 is located within the MCC western edge, close to the ABV (Figure 1). St 407 is located within the MCC eastern edge, close to the Ionian Shelfbreak Vortex cyclonic gyre (Figure 1). These features vary in size and strength and interact with each other (Béranger et al., 2004; Lermusiaux & Robinson, 2001). A clear SST signature of cyclonic and anticyclonic gyres in the Sicily Channel is shortly visible as mesoscale features reach their maximum strength (Lermusiaux & Robinson, 2001), but this is obscured by the general eastward warming trend in longer CTD surveys (Bonanno et al., 2014; Sorgente et al., 2010).

Levantine Intermediate Water (LIW) forms between Rhodes and Cyprus in winter as a process of surface cooling on water masses which underwent a severe salt enrichment (Malanotte-Rizzoli & Hecht, 1988; POEM group, 1992). LIW occupies a depth between 150–200 and 600 m and enters the Sicily Channel through the sills south of Malta, occasionally together with a thin thickness of the uppermost layer of Eastern Mediterranean Deep Water (Gasparini et al., 2005; Lermusiaux & Robinson, 2001). Models and observations show that Sicily Channel circulation is seasonally and interannually modulated by the density gradient between the Tyrrhenian and Ionian Seas that may also play a role in driving South Sicily coastal upwelling intensity (Béranger et al., 2004; Jouini et al., 2016).

Seasonal atmospheric variations in the Mediterranean/European region are controlled by the transition between the subtropical high-pressure belt over North Africa and westerlies over Central and Western Europe. The northward and southward displacements of this transition lead to drought and penetration of Atlantic depressions, respectively, in summer and winter (Rohling et al., 2015). The Mediterranean region is under the influence of the North Atlantic Oscillation (NAO). During positive NAO-index phases, westerlies blow over the western parts of northern Europe, while dry conditions are experienced in southern Europe and northern Africa. The situation is reversed during negative NAO-index phases (Comas-Bru & McDermott, 2014). Other indices, such as the Mediterranean Oscillation Index, are important for describing local rainfall patterns but are usually linked to large-scale atmospheric circulation dynamics, primarily to

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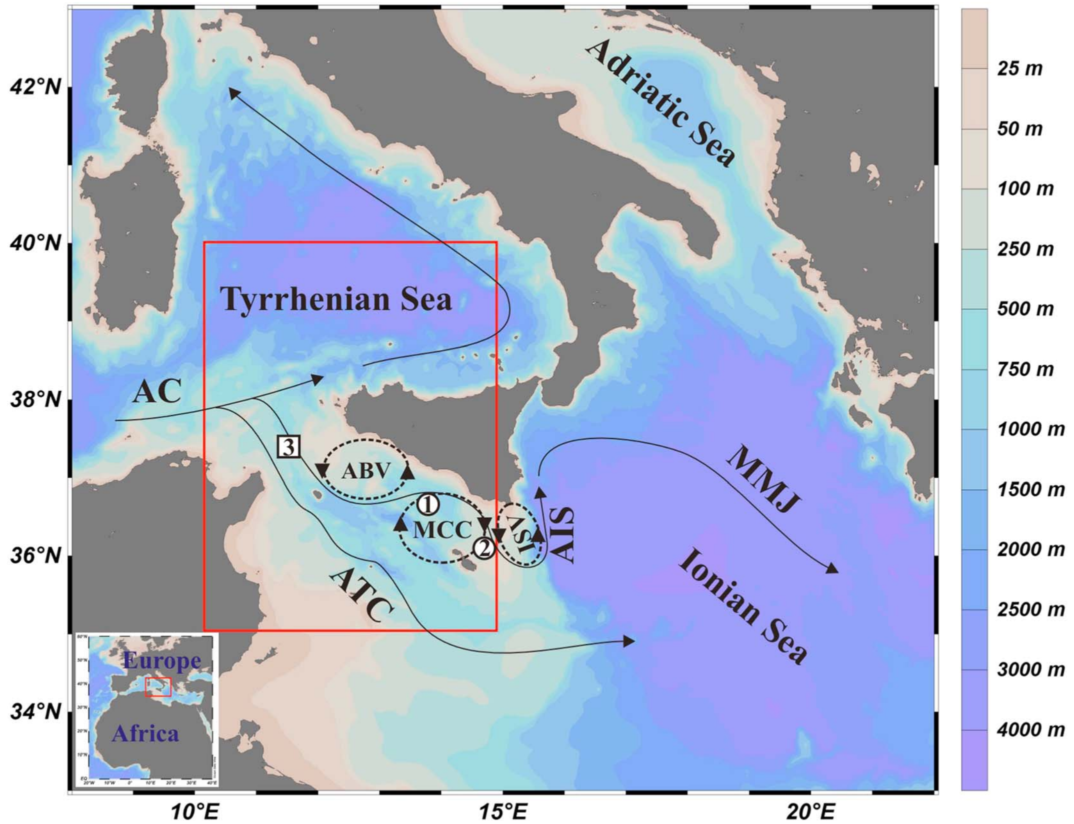

Figure 1. Bathymetric map of the Sicily Channel and location of cores St 342 and 407. Black arrows illustrate the path of Modified Atlantic Water across the Sicily Channel (modified from Pinardi & Masetti, 2000). Dashed black arrows illustrate the location and flow of mesoscale anticyclonic and cyclonic gyres in the southern Sicily offshore (modified from Robinson et al., 1999): Adventure Bank Vortex (ABV); Maltese Crest Channel (MCC); Ionian Shelfbreak Vortex (ISV). The red square depicts the extent of Kaplan sea surface temperature anomalies cell. Circles: (1) location of St 342 core; (2) location of St 407 core. Square: (3) location of station 8 water samples collected during VICOMED I and VICOMED II (Pujol & Grazzini, 1995). AC = Algerian Current; ATC = Atlantic-Tunisian Current; AIS = Atlantic-Ionian Stream; MMJ = Mid-Mediterranean Jet. Below the inset map of the whole Mediterranean Sea.

the NAO (Lionello, 2012). Mediterranean SSTs of the last 150 years are also significantly correlated with multidecadal Atlantic indices (NAO and Atlantic multidecadal oscillation [AMO]) for time intervals longer than 40 years (Marullo et al., 2011). The AMO index used in Marullo et al. (2011) is defined by detrended SST anomalies averaged over the North Atlantic from 0° to 70°N (Enfield et al., 2001). The AMO index used below for comparison with planktonic foraminifera assemblages is a tree ring-based reconstruction (Gray et al., 2004).

2.2. Productivity and Living Planktonic Foraminifera Surveys

The trophic conditions of the Mediterranean Sea are among the poorest in the world's oceans. The antiestuarine circulation pattern contributes to their maintenance, since the inflow of nutrient-depleted surface water and the outflow of nutrient-enriched intermediate water at the Strait of Gibraltar (Béthoux, 1979; Sarmiento et al., 1988). Primary production follows the seasonal cycle: Winter convection, and less frequent frontal zones or coastal upwelling, brings nutrients into the photic zone inducing a mesotrophic regime (Klein & Coste, 1984). LIW is the carrier of nutrients providing the source for fertilization of the upper part of the water column (Krom et al., 2010). An oligotrophic regime, characterized by a much lower level of production, occurs in summer, when a stable stratification, due to the deepening of the summer thermocline, takes place (Allen et al., 2002; Klein & Coste, 1984).

Cluster analysis based on satellite surface chlorophyll observations defines the northern Sicily Channel as a "no bloom" area, with a main primary productivity peak centered between December and March

(D'Ortenzio & D'Alcalà, 2009). More recently, Rinaldi et al. (2014) focused on Sicily Channel primary productivity modes, examining a 19-year-long time series of chlorophyll concentration by satellite estimates. They conclude that approximately 80% of variance is explained by the advection of chlorophyll- and nutrient-enriched Atlantic Water from the North African coast that enters the Sicily Channel in late fall/early winter and fuels phytoplankton blooming in late winter/early spring. Chlorophyll concentration by satellite estimates in both studies does not show any clear link with the Sicily Channel mesoscale features (D'Ortenzio & Ribera d'Alcalà, 2009; Rinaldi et al., 2014).

Living planktonic foraminifera surveys and sediment trap studies also document seasonally variable conditions throughout the Mediterranean Sea (Hernández-Almeida et al., 2011; Pujol & Grazzini, 1995; Rigual-Hernández et al., 2012). The only available data for the Sicily Channel are from a few stations at the western entrance of MAW and within the Adventure Bank (Mallo et al., 2017; Pujol & Grazzini, 1995). Water samples were recovered across the top 350 m during Vicomed I (September–October 1986) and Vicomed II (February–March 1988) cruises (Pujol & Grazzini, 1995; Figure 1). Ten species and 3,579 specimens/1,000 m^3 were found during Vicomed I, when the assemblage was strongly dominated by *Globigerinoides ruber* pink (88.1%), followed by *Globigerinoides trilobus* (7.4%) and *Globigerinoides ruber* white (2.3%). A few specimens (<1%) of *Orbulina universa*, *Globigerinella siphonifera*, *Globigerinita glutinata*, *Globorotalia inflata*, *Globorotalia truncatulinoides*, and *Neogloboquadrina incompta* were also found. A total of 2,268 specimens × 1,000 m^3 of water was found during Vicomed II, and the assemblage was dominated by *G. inflata* (35.0%), *G. truncatulinoides* (27.4%), and *Globigerina bulloides* (25.0%). Minor amounts of *N. incompta* (4.8%), *G. siphonifera* (2.8%), *G. glutinata* (2.2%), *O. universa* (1.6%), and *G. ruber* white (1.0%) were also present during this winter survey.

3. Material and Methods

Box-cores St 342 (36° 42′ N, 13° 55′ E, 858.2-m depth) and St 407 (36° 23′ N, 14° 27′ E, 345.4-m depth) were recovered off the southern Sicily coast (Figure 1). Sediments are made up of marl with 35–40% of clay (Tranchida et al., 2010). The chronology is based on ^{210}Pb profiles using a constant flux-constant sedimentation model (Incarbona et al., 2016). The average sedimentation rate is 90.2 cm/kyr (mean sampling resolution of 11.1 year) for St 342 and 57.4 cm/kyr (mean sampling resolution of 17.4 year) for St 407.

A total of 23 and 24 samples (every 1 cm) for, respectively, St 342 and 407 was prepared for planktonic foraminifera analysis. Samples were washed using a 63-μm mesh sieve and were oven-dried at 40 °C. Quantitative planktonic foraminifera analysis was carried out on split aliquots containing over 400 specimens on average from the fraction >150 μm. Specimens of 12 species were identified, counted, and normalized to percentage values following taxonomic concepts by Hemleben et al. (1989) and Schiebel and Hemleben (2017). The *Globigerinoides ruber* white group includes *Globigerinoides elongatus* and *Globigerinoides conglobatus*. The *Globigerinoides sacculifer* group includes *Globigerinoides trilobus* and *Globigerinoides quadrilobatus*. The *Globigerina bulloides* group includes *Globigerina falconensis*. These species were lumped together because of their similar ecological preferences (Schiebel & Hemleben, 2017). *Globigerinoides ruber* white and pink varieties both thrive in warm and oligotrophic water, with a distinct preference of the latter species for summer months (Pujol & Grazzini, 1995; Rigual-Hernández et al., 2012; Schiebel & Hemleben, 2017; Žarić et al., 2005). *Globigerinoides sacculifer* also thrives in warm and oligotrophic water but also prefers less salty surface water (Bijma et al., 1990; Pujol & Grazzini, 1995; Rigual-Hernández et al., 2012; Schiebel & Hemleben, 2017; Žarić et al., 2005). *Globigerina bulloides* is a taxon typical of cold and productive surface water (Pujol & Grazzini, 1995; Rigual-Hernández et al., 2012; Schiebel & Hemleben, 2017). *Neogloboquadrina incompta* profits from a deep chlorophyll maximum (Fairbanks & Wiebe, 1980; Hemleben et al., 1989; Pujol & Grazzini, 1995; Rigual-Hernández et al., 2012). *Globorotalia inflata* is abundant from subtropical to subpolar latitudes. This species has often been found associated with hydrologic fronts and eddies and in coastal topographically driven upwelling areas (Pujol & Grazzini, 1995; Schiebel & Hemleben, 2017). *Globorotalia truncatulinoides* is among the deepest dwelling living planktonic foraminifera species and may indicate the occurrence of a deep winter mixed layer (Pujol & Grazzini, 1995; Schiebel & Hemleben, 2017). *Globigerinella siphonifera* is common and abundant in tropical and subtropical oceans (Schiebel & Hemleben, 2017). *Orbulina universa* is abundant from tropical to temperate waters and tolerates a wide range of water salinity and temperature (Bijma et al., 1990; Schiebel & Hemleben, 2017).

Two methods were used to infer SST from the planktonic foraminifera assemblages: MAT and ANN (Guiot & de Vernal, 2007; Malmgren & Nordlund, 1997). These represent fundamentally different ways to relate the faunal assemblage with SST, and comparison of their results can inform about the reconstruction robustness. For both methods, we used the Mediterranean training set of Hayes et al. (2005) and annual mean temperature in the upper 10 m of the ocean based on the World Ocean Atlas 1998 climatology (http://www.nodc.noaa.gov/oc5/woa98.html).

SSTs based on the MAT technique (Hutson, 1980; Prell, 1985) were estimated as the weighted mean of measured temperatures at stations of the best 10 modern analogs, using PaleoAnalogs version 3.0 software. The mean degree of similarity between the sample and the best 10 modern analogs is quantified using the square chord distance (dissimilarity index [DI]). Values of DI < 0.2 are considered to be of good quality (Kallel et al., 1997; Pérez-Folgado et al., 2003; Siani et al., 2010). MAT annual prediction errors span from 0.84 and 1.67 °C across the world's oceans (Kucera et al., 2005). A specific estimate for the Mediterranean Sea is still missing, but it is 1.27 °C in the North Atlantic (Kucera et al., 2005), which is arguably the closest ocean bioprovince.

The ANN-based estimates were obtained using previously trained networks for the Mediterranean Sea (Kucera et al., 2005). The estimate error of prediction for annual mean temperatures is 0.91 °C (Kucera et al., 2005). We report here the average temperature obtained from the output of the 10 best networks.

A successful reconstruction based on assemblage data not only requires that the modern assemblages in the training set respond to the environmental variable that is to be reconstructed but also that this variable shaped the down-core assemblages (Telford & Birks, 2005, 2011). SST is indeed the best predictor of modern planktonic foraminifera assemblages (Morey et al., 2005), but in order to assess to what extent this also holds for the down-core data, we conducted a principal component (PC) analysis of the down-core data and compared the reconstructed temperatures with the loadings of the first PC. This analysis assumes that the main trend in the assemblages (as indicated by the first PC) reflects the dominant environmental forcing that shaped the assemblages. In a reliable reconstruction, the estimated temperatures should thus be correlated to the PC scores. The PC analysis was carried out by the "R version 2.5.2" software (https://www.r-project.org/), "Vegan: Community Ecology Package" (https://cran.r-project.org/web/packages/vegan/index.html).

To further evaluate the reconstructions, instrumental SST data were acquired by Kaplan SST V2 (Kaplan et al., 1998), as monthly anomalies since 1852 CE. They refer to the area between 10°E and 15°E and 35°N and 40°N, that also include the southern Tyrrhenian Sea and Sicily Channel entrance (Figure 1).

4. Results

4.1. Planktonic Foraminifera Assemblages

Planktonic foraminifera assemblages from St 342 and St 407 cores include 12 species that were previously collected during Vicomed I and II surveys (Pujol & Grazzini, 1995), except for *Neogloboquadrina dutertrei* and *Globoturborotalita rubescens* that are very rare in sediment samples.

Despite the very short time interval under investigation and presumably little changes in water column dynamics, the species reveal large abundance variations and trends in both St 342 and St 407, well beyond the 95% confidence level errors associated with counting (Figures 2 and 3). *Globorotalia inflata* is the dominant species (18.4–50.0% and 27.4–47.4%, on average 31.7% and 38.4%, respectively, for St 342 and St 407) followed by *G. ruber* (14.8–44.3% and 23.7–36.7%, on average 26.3% and 29.5%, respectively, for St 342 and St 407), by *G. bulloides* (4.2–35.2% and 5.1–24.5%, on average 20.8% and 13.2%, respectively, for St 342 and St 407), and by *G. truncatulinoides* (1.6–21.3% and 5.9–13.7%, on average 12.3% and 8.9%, respectively, for St 342 and St 407). Other selected species are much less abundant, <5% on average (Figure 3). As highlighted in percentage ranges and in Figures 2 and 3, planktonic foraminifera abundances are usually more variable in St 342. Interestingly, the same species sometimes shows abundance fluctuations of opposite signs between the two sites, especially evident in *G. inflata* and *G. bulloides* distribution patterns (Figure 2). Warm water species, like *G. ruber* and *G. sacculifer*, are generally more abundant in St 407, while *G. bulloides* is more abundant in St 342 where a few specimens of *N. incompta* where also found (Figures 2 and 3).

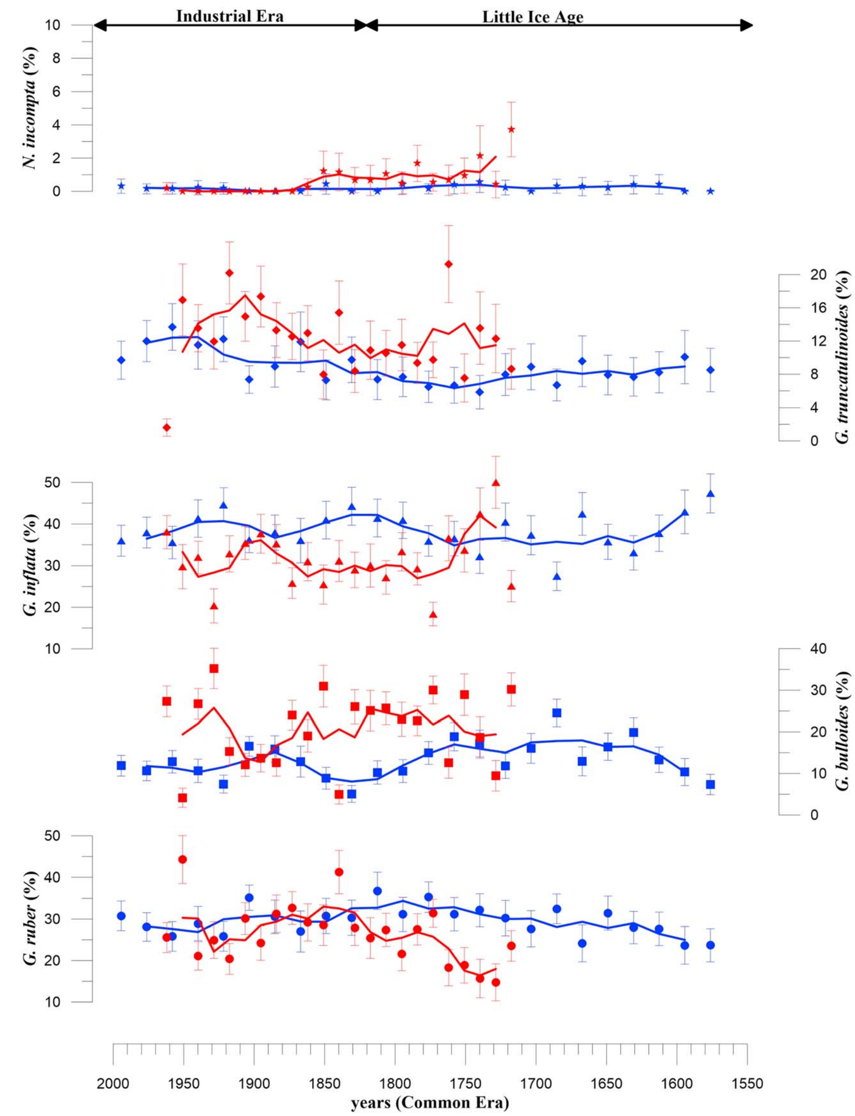

Figure 2. Downcore variations of planktonic foraminifera species over the last five centuries in cores St 342 and 407. Red and blue symbols, respectively, show percentage values of planktonic foraminifera species in St 342 and St 407, with the 95% confidence level of the counts. Red and blue lines show the 3-pt running average of planktonic foraminifera species data in St 342 and St 407, respectively. The Little Ice Age duration is based on estimates by Luterbacher et al. (2012) and Margaritelli et al. (2016).

4.2. Planktonic Foraminifera SST Estimates and Multivariate Statistics

SST estimates obtained by the MAT at St 342 range between 18.52 and 19.62 °C (18.96 °C on average), the average standard deviation is ±0.67 °C, and the DI is 0.066 on average, in any case always <0.2 (Figure 4). The temperatures obtained using ANN are very similar and range between 18.53 and 19.54 °C (19.89 °C on average, Figure 4). Estimated SST ranges are even narrower for St 407 (Figure 4). MAT-based values range between 18.87 and 19.36 °C (19.16 °C on average) with a mean standard deviation of ±0.76 °C. The DI is 0.070 on average and always <0.2 (Figure 4). ANN-based estimates are slightly higher and range between 19.20 and 19.77 °C (19.37 °C on average; Figure 4).

The first PCs of cores 342 and 407 explain 44% and 43% of the variance in the fauna. In both cores, this component appears to dominantly reflect the relative abundance of *G. bulloides* (not shown). The temperature reconstructions of core 342 are strongly correlated with the loadings of the first PC axis (Figure 5). For

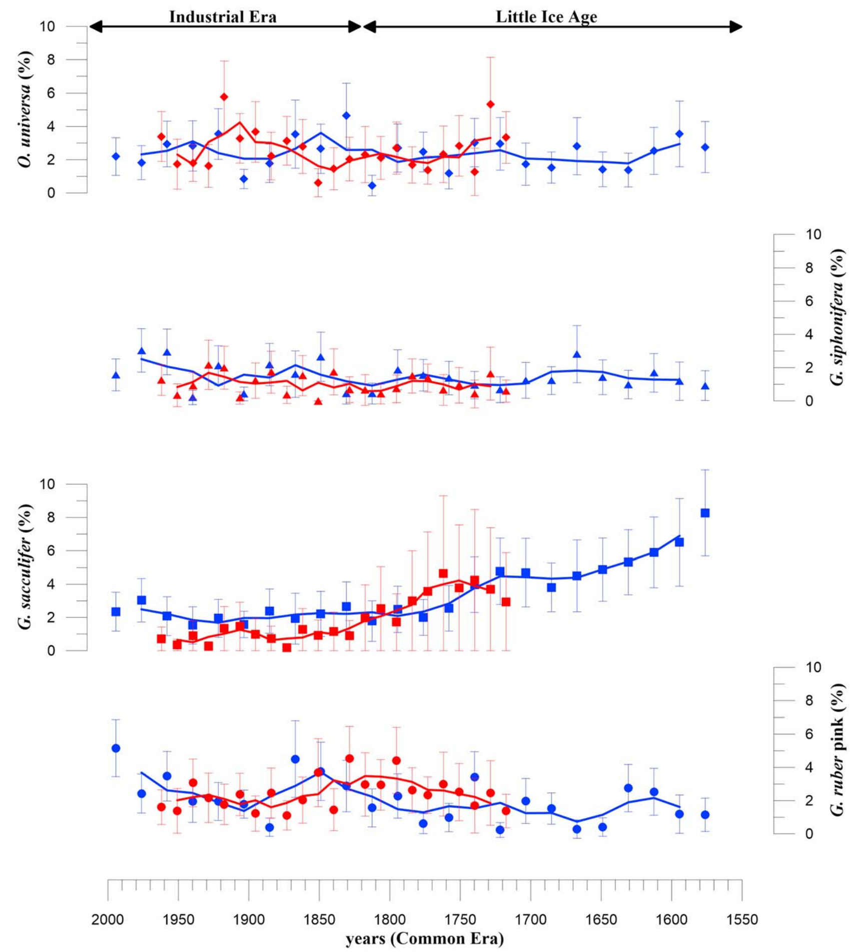

Figure 3. Downcore variations of planktonic foraminifera species over the last five centuries in cores St 342 and 407. Red and blue symbols, respectively, show percentage values of planktonic foraminifera species in St 342 and St 407, with 95% confidence interval of the counts indicated by the error bars. Red and blue lines, respectively, show 3-pt running average of planktonic foraminifera species data in St 342 and St 407. The Little Ice Age duration is based on estimates by Luterbacher et al. (2012) and Margaritelli et al. (2016).

core 407, the correlation is less clear using the ANN-based SST estimates and virtually absent for the MAT-based SSTs (Figure 5).

5. Discussion

5.1. Planktonic Foraminifera SST Reconstructions

The reconstructions based on planktonic foraminifera assemblages suggest that mean annual SSTs in the Sicily Channel remained close to their present-day values of ~19 °C over the last 450 years. A comparison between MAT- and ANN-based SST estimates and the PC scores of the first axis shows a significant correlation for St 342, suggesting that, despite the fact that the reconstructed temperature variability is of comparable magnitude as the reconstruction error, the inferred temperatures correspond to the main trend in the data (Figure 5). The magnitude of MAT and ANN SST variability at St 342 is also comparable to variability in instrumental data smoothed to the same decadal resolution of the reconstructions (Figure 6). Together, this suggests that at this site, the foraminifera assemblages may provide a reasonable estimate of long-term average SST variability, offering the chance to extend the instrumental record by about two centuries. However, given the uncertainty in the reconstructions, all we can conclude is that mean annual SSTs at this site did not vary by more than 1.5°.

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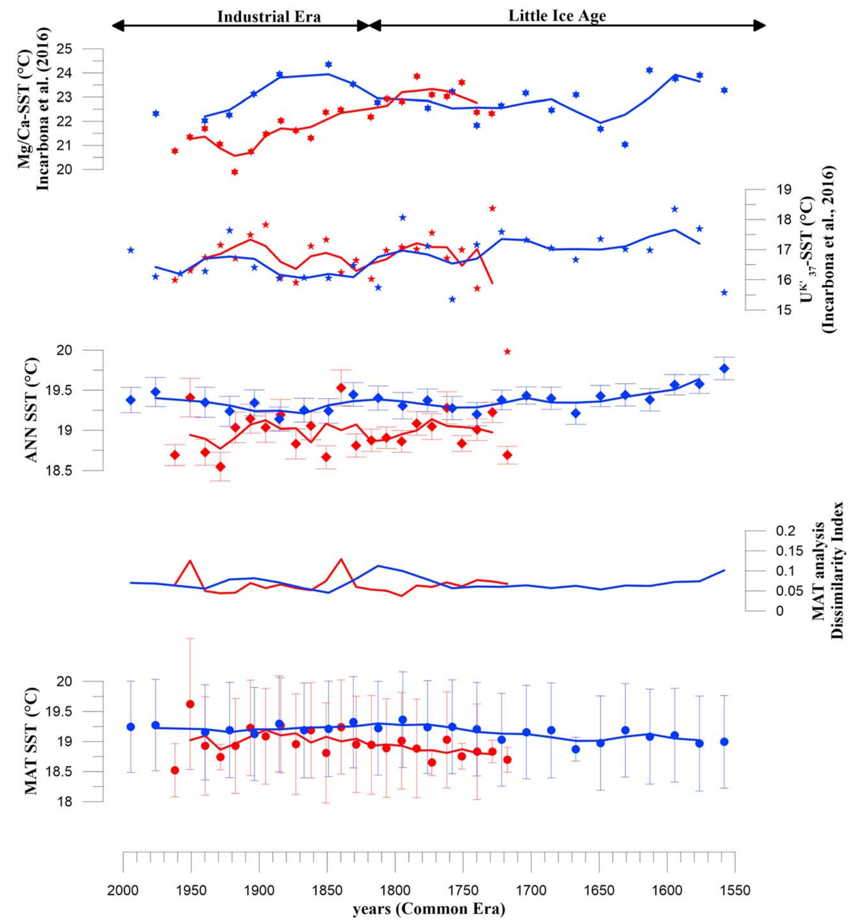

Figure 4. Downcore variations of SST estimates in the Sicily Channel. Red and blue symbols, respectively, show SST values in St 342 and St 407. Standard deviation estimates are shown for MAT and ANN techniques. Red and blue lines, respectively, show 3-pt running average of SST values in St 342 and St 407, except for dissimilarity Index of MAT where averaging was not carried out. The Little Ice Age duration is based on estimates by Luterbacher et al. (2012) and Margaritelli et al. (2016). SST = sea surface temperature; MAT = Modern Analogue Technique; ANN = Artificial Neural Network.

At site St 407, no or only a weak correlation between the first PC axis and reconstructed SST is observed for MAT and ANN (Figure 5), and neither technique yielded reconstructions with a temperature variability in the range of the instrumental data (Figure 6). This indicates that at this site, assemblage-based SST reconstructions for the last five centuries are even more challenging. This regional variability, even between sites that are a few tens of kilometers from each other, illustrates the difficulty with reconstructing fine-scale temperature dynamics from planktonic foraminifera assemblages. A possible explanation deals with water column variability in the mesoscale gyres that will be described in the next section.

The mean annual temperatures estimated from the planktonic foraminifera assemblages fall in between previous SST reconstructions based on the same cores (Incarbona et al., 2016). SSTs inferred from *G. ruber* Mg/Ca are 1.5° to 4.5° warmer, and temperatures estimates based on the alkenone unsaturation ratio are generally lower by 1.0° to 5.0° (Figure 4). We infer from this that *G. ruber*-based SST estimates are biased toward the summer months, which is in agreement with water sample and sediment trap data (Hernández-Almeida et al., 2011; Pujol & Grazzini, 1995). Similarly, we infer that in the Sicily Channel, $U^{K'}37$-based temperatures carry a winter signal. Whereas some studies have suggested that $U^{K'}37$ temperatures reflect annual mean conditions (Conte et al., 2006), we argue that the alkenone-producing coccolithophores are more abundant during the winter half year and that the $U^{K'}37$ temperatures are weighted toward winter conditions. We note that the Mediterranean Sea is characterized by many different productivity

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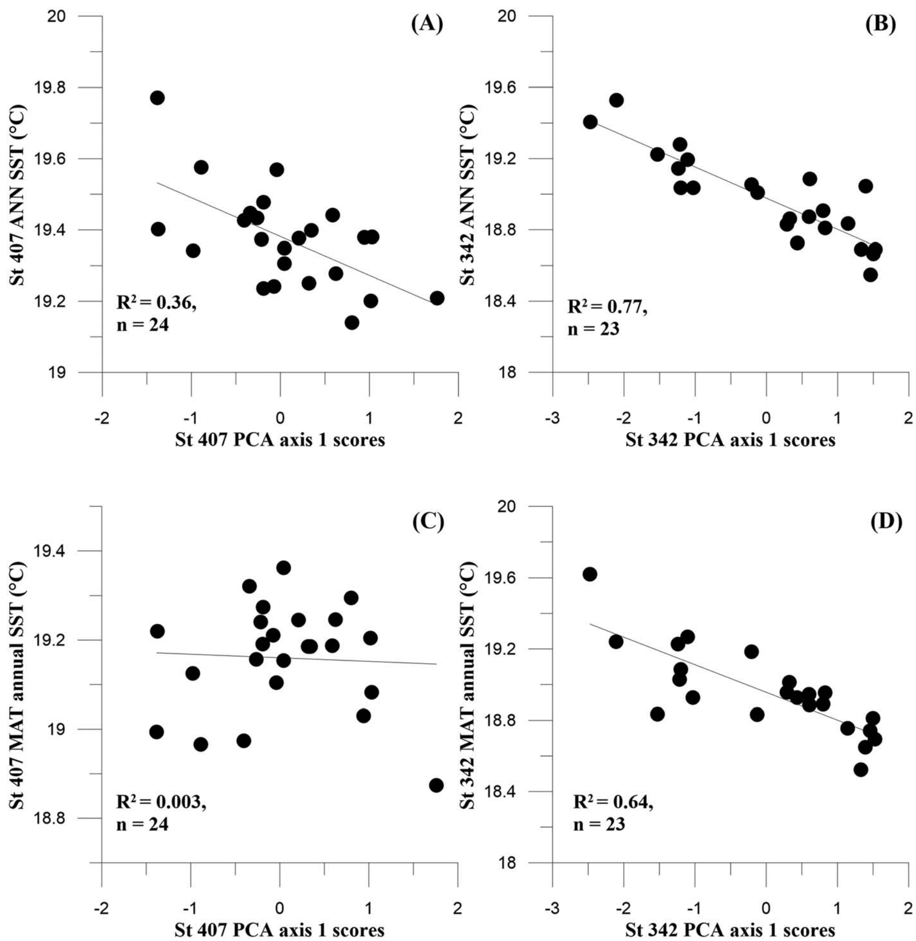

Figure 5. Scatter plots of MAT and ANN SST estimates versus PCA axis 1 scores, in both St 342 and St 407. Correlation index results are also shown. SST = sea surface temperature; MAT = Modern Analogue Technique; ANN = Artificial Neural Network.

regimes that vary on short spatial scales (D'Ortenzio & D'Alcalà, 2009) but support higher abundances of *Emiliania huxleyi* in Sicily Channel during winter blooming (Knappertsbusch, 1993; Ziveri et al., 2000). This is further supported by a recent review that reports the highest correlation between the $U^{K'}37$ index and November–May SST in the Mediterranean Sea (Tierney & Tingley, 2018).

In contrast to the assemblage-based mean annual SST estimates, the Mg/Ca and $U^{K'}37$-based SST estimates show temporal variability considerably above the analytical and calibration uncertainties (Figure 4). A comparison between Kaplan seasonal instrumental and St 342 Mg/Ca and alkenone SSTs has been carried out to shed light on the wider oscillations of these paleothermometers than in planktonic foraminifera transfer functions. The 2.5 °C oscillation in Mg/Ca SSTs is in agreement with summer/autumn instrumental data smoothed at the resolution of the sediment data over the 1860–1960 CE interval (Figure 6). Similarly, the 2 °C alkenone-derived winter SST variability is in quantitative agreement with the smoothed instrumental winter/spring temperature data (not shown in figure). The consistence in the magnitude of variability between the temperature estimates supports our interpretation of the seasonality of the proxies in the Sicily Channel.

5.2. Paleoenvironmental Reconstruction

The planktonic foraminifera assemblages at St 342 and 407 are compatible with data of the top ecobiozone from central-western Mediterranean sites, highlighted by the dominance of *G. ruber*, *G. bulloides* and *G. inflata* and the low abundance of *G. sacculifer* and *N. incompta* (Capotondi et al., 1999; Lirer et al.,

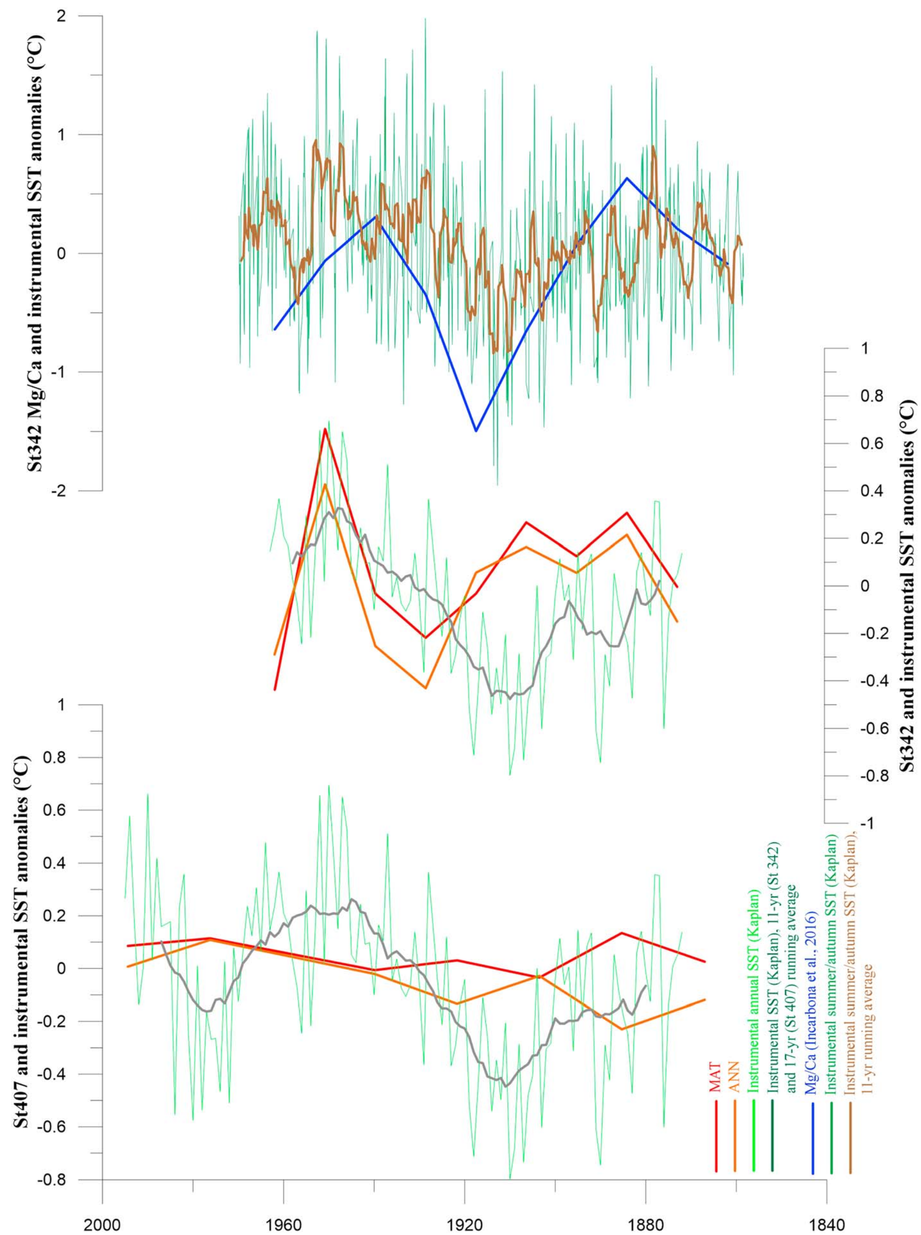

Figure 6. Comparison between planktonic foraminifera SST estimates, expressed as anomaly, Kaplan instrumental SST anomaly of the area shown in Figure 1 and *G. ruber* Mg/Ca from St 342 (Incarbona et al., 2016). From the left, MAT and ANN SSTs from St 407, Kaplan annual temperatures. MAT and ANN SSTs from St 342, Kaplan annual temperatures. *Globigerinoides ruber* Mg/Ca from St 342 (Incarbona et al., 2016) and Kaplan summer/autumn temperatures. The Kaplan instrumental anomaly is calculated with respect to 1856–2017 CE. The anomaly for St 342 planktonic foraminifera and geochemical records is calculated with respect to 1862–1962 CE. The anomaly for St 407 planktonic foraminifera and geochemical records is calculated with respect to 1867–1994 CE. SST = sea surface temperature; MAT = Modern Analogue Technique; ANN = Artificial Neural Network.

2013; Margaritelli et al., 2016; Sbaffi et al., 2001; Sprovieri et al., 2003; Vallefuoco et al., 2012). Moreover, some of the peaks that characterize Tyrrhenian Sea and Menorca Basin historical records (Lirer et al., 2014; Margaritelli et al., 2016; Margaritelli et al., 2018) also occur in the Sicily Channel, such as the *G. truncatulinoides* peak in coincidence of the Maunder minimum and the *G. ruber* peak at ~1950 CE (Figure 2). The latter is only visible in St 342 (Figure 2), highlighting local variability even in sedimentary records that are a few kilometers far each other.

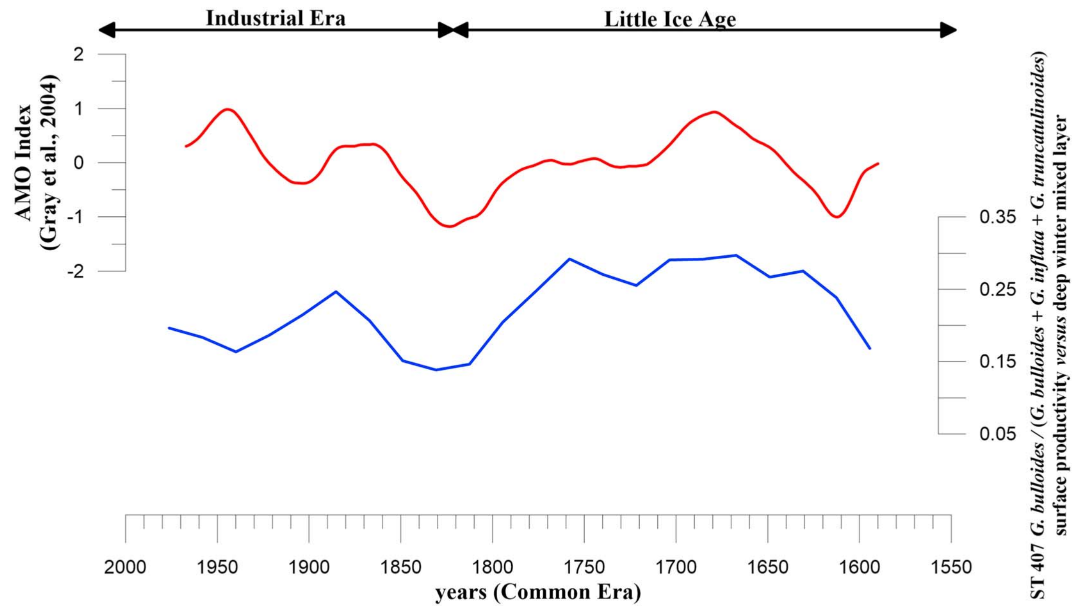

Figure 7. Comparison between *G. bulloides* and (*G. inflata* + *G. truncatulinoides*) ratio at St 407, expressed as a 3-pt running average, and AMO Index variations (Gray et al., 2004), expressed as a 37-pt running average, over the last five centuries. The Little Ice Age duration is based on estimates by Luterbacher et al. (2012) and Margaritelli et al. (2016). AMO = Atlantic multidecadal oscillation.

The higher abundance of *G. bulloides*, the occurrence of specimens of *N. incompta*, and the lower abundance of *G. ruber* indicate cooler and more productive surface and subsurface waters in St 342, with respect to St 407 (Figure 2). This interpretation is supported by both ANN and MAT SSTs that are consistently lower at St 342 (Figure 4), as well as by CTD oceanographic surveys that highlight a clear West-East SST gradient within the Sicily Channel (Bonanno et al., 2014; Sorgente et al., 2010). A significant coastal upwelling activity has been reported from south off Sicily (Bonanno et al., 2014; Piccioni et al., 1988; Raffa et al., 2017; Robinson et al., 1999). This phenomenon is induced by Northwesterly winds, always starts from the westernmost part of South Sicily, within the Adventure Bank Vortex, and then moves eastward the Sicilian coast but very rarely affects the Ionian Shelfbreak Vortex area because the Gulf of Gela seems to be a topographical barrier to upwelling extension (Piccioni et al., 1988; Raffa et al., 2017). These surveys on Sicily coastal upwelling support our finding of colder and more productive water in the anticyclonic gyre of St 342 that may be invested by part of the upwelling plume, differently from St 407 location. Our results are further supported by long time series satellite observation, highlighting that about 80% of the chlorophyll variability is explained by Atlantic water advection, producing a clear productivity eastward gradient in the southern Sicily offshore (Rinaldi et al., 2014).

Less clear is the possible role of the Sicily Channel anticyclonic and cyclonic gyres. Mesoscale eddies affect the biogeochemical and physical properties of the photic zone that control phytoplankton blooming, as evident in the vertical pumping of nutrients observed within cyclonic gyres (Falkowski et al., 1991). Different mesoscale features have been later identified, and different mechanisms have been proposed to explain phytoplankton dynamics (McGillicuddy et al., 2007; Stramma et al., 2013). Recent reports from tropical and subtropical oceans highlight the absence of a straightforward link between primary production and cyclonic or anticyclonic vorticity (Dufois et al., 2016; Frenger et al., 2018). Following long-term chlorophyll concentration in the Sicily Channel from satellite observation (D'Ortenzio & Ribera d'Alcalà, 2009; Rinaldi et al., 2014), we conclude that mesoscale features activity had little or no role in explaining higher productivity in the St 342 than in the St 407.

One of the most intriguing points is the repeated and opposite abundance variation in different species visible at the same time at St 342 and 407, notably *G. inflata* and *G. bulloides* (Figure 2). They concern different sedimentary records and cannot be explained by closed-sum effect. Increased and decreased abundance of *G. bulloides* versus (*G. bulloides* + *G. inflata* + *G. truncatulinoides*) would, respectively, witness the switch between sea surface winter/spring surface productivity and a deep winter mixed layer or hydrological fronts (Pujol & Grazzini, 1995; Rigual-Hernández et al., 2012; Schiebel & Hemleben, 2017). The ratio between *G. bulloides* and (*G. inflata* + *G. truncatulinoides*) displays an excellent visual match with oscillations in the AMO pattern (Gray et al., 2004; Figure 7). The impact of the North Atlantic SST variability on the Mediterranean and European region is well-established and drives different temperature, precipitation, and atmospheric patterns (Marullo et al., 2011; Zampieri et al., 2017).

The AMO negative mode is a major atmospheric configuration to foster heat and buoyancy loss in Mediterranean deep water formation sites (Marullo et al., 2011; Romanski et al., 2012; Tsimplis & Josey, 2001; Zervakis et al., 2004).

It is evident that North Atlantic SST and ocean circulation variations would affect the neighboring St 342 and 407 sites producing the same ecological change in the water column, unless the mesoscale activity is taken into account. Independently from the precise identification of the atmospheric circulation regime in the Mediterranean region (Peings & Magnusdottir, 2013; Zampieri et al., 2017), we suggest that the AMO pattern does affect Sicily Channel water column configuration. The AMO positive mode seems to foster surface productivity and *G. bulloides* proliferation in the St 407, while a deep winter mixed layer was established in the St 342. We conclude that multidecadal oscillations govern water column stabilization and winter vertical mixing in the two sites, by modifying the shape and size of Sicily Channel cyclonic and anticyclonic gyres. This phenomenon represents an interesting model of different plankton productivity modes of opposite sign in mesoscale gyres, due to the atmosphere/ocean interplay.

6. Conclusion

We have carried out the study of planktonic foraminifera assemblages in two Sicily Channel sedimentary cores over historical times to reconstruct SSTs by ANN and MAT techniques. Results were compared to instrumental (Kaplan) and coregistered (alkenone and *G. ruber* Mg/Ca) SST proxies. A significant correlation with PCA scores of the first axis suggests that temperature covaries with fauna changes at St 342. However, the estimate error of prediction (Kucera et al., 2005) is of the same magnitude or even overcomes the range of ANN and MAT SST oscillations (<1.5 °C). We conclude that planktonic foraminifera SST reconstructions may be not appropriate to gather small magnitude variations, here recorded in historical times.

Planktonic foraminifera assemblages from St 342 and St 407 cores include 12 species that were previously collected in Sicily Channel water samples (Pujol & Grazzini, 1995). The higher abundance of *G. bulloides*, the occurrence of specimens of *N. incompta*, and the lower abundance of *G. ruber* indicate cooler and more productive surface and subsurface waters in the St 342, with respect to the St 407. Winter convective mixing and a deeper mixed layer, together with the occurrence of upwelling plumes and the entrance of nutrient-rich water from the western side of the Sicily Channel, provides a likely explanation for this configuration. Finally, repeated and opposite abundance variation in different species is visible at the same time at St 342 and 407 and testifies the switch between sea surface winter/spring productivity and a deep winter mixed layer, in connection with North Atlantic SST. This phenomenon represents an interesting model of different plankton productivity modes of opposite sign in mesoscale gyres, due to the atmosphere/ocean interplay in response to multidecadal oscillations.

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