Clim. Past Discuss., 6, 817–866, 2010
www.clim-past-discuss.net/6/817/2010/
doi:10.5194/cpd-6-817-2010

Climate of the Past Discussions

Calcareous nannofossil assemblages from the Central Mediterranean Sea over the last four centuries: the impact of the little ice age

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Received: 22 April 2010 – Accepted: 29 April 2010 – Published: 17 May 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

We present decadal-scale calcareous nannofossil data from four short cores (Station 272, 37°17′ N, 12°48′ E, 226 m depth; St 342, 36°42′ N, 13°55′ E, 858.2 m depth; St 407, 36°23′ N, 14°27′ E, 345.4 m depth; C90-1M, 40°36′ N, 14°42′ E, 103.4 mdepth) recovered in the central Mediterranean Sea (northern Sicily Channel and Tyrrhenian Sea), which, on the basis of ^{210}Pb activity span the last 200–350 years. Assemblages are dominated by placoliths, mostly *Emiliania huxleyi*, while, at least in the Sicily Channel sediments, *Florisphaera profunda* was an important part of the coccolithophore community.

The paleoenvironmental reconstruction, based on ecological preference of species and groups, suggests that the Tyrrhenian core C90-1M maintained higher productivity levels over recent centuries, with respect to the Sicily Channel sites, possibly because of more pronounced winter phytoplankton blooms, in agreement with modern primary productivity variations over the last ten years.

The lowermost part of the record of one of the cores from the Sicily Channel, Station 407, which extends down to 1650 AD, is characterized by drastic changes in productivity. Specifically, below 1850 AD, the decrease in abundance of *F. profunda* and the increase of placoliths, suggest increased productivity. The chronology of this change is related to the main phase of the Little Ice Age, which might have impacted the hydrography of the southern coast of Sicily and promoted vertical mixing in the water column. The comparison with climatic forcings points out the importance of stronger and prolonged northerlies, together with decreased solar irradiance. The identification of the LIA in the northern Sicily Channel cover the Bond cycle BO that was missing in a previous study of Holocene climatic anomalies in the Sicily Channel.

Finally, we suggest that major abundance changes in reworked nannofossil specimens, recorded in the Tyrrhenian core C90-1M, might be linked to variations in terrigenous supply from land. Paradoxically, higher amounts of reworking correspond to dry periods. We argue that soil and rock vulnerability is enhanced during times of

prolonged drought and vegetation cover loss.

1 Introduction

Coccolithophores are unicellular, flagellate, phytoplanktonic organisms, belonging to the phylum Haptophyta. They are attracting the attention of researchers, because of their role in the climate system and their sensitivity to ocean acidification in response to rising atmospheric CO_2 (Westbroek et al., 1993; Rost and Riebesell, 2004; Barker et al., 2006; Rickaby et al., 2007; Fabry, 2008; Iglesias-Rodriguez et al., 2008; Langer et al., 2009).

The term calcareous nannofossils is used for remains that are calcite plates in some way analogous to today's coccoliths of coccolithophores. They are found in the sedimentary archive since the late Triassic (Bown, 1998), and after pioneering studies on water samples and surface sediments (McIntyre and Bé, 1967; McIntyre et al., 1970; Okada and Honjo, 1973; Geitzneauer et al., 1977) have been widely used in paleoceanographic reconstructions (e.g. Molfino and McIntyre, 1990; Flores et al., 1997; Bollmann et al., 1998; Giraudeau et al., 2000; Colmenero-Hidalgo et al., 2004; Stoll et al., 2007).

A recent work demonstrated the pervasive occurrence of a 1500-yr climate periodicity, first recognized in the North Atlantic Ocean (Bond et al., 1997, 2001) even in Holocene Mediterranean sediments (Incarbona et al., 2008a). *Florisphaera profunda* abundance fluctuations of about 10–15% were interpreted as due to the deepening/shoaling of the nutricline within the photic zone and related to different productivity levels, given that the distribution of this species on the Sicily Channel sea floor showed a significant correlation to productivity changes as provided by satellite imagery. Unfortunately, the youngest of these cycles, the Bond cycle B0 corresponding to the Little Ice Age (LIA), was not recovered at this studied site (Site 963), possibly because of disturbance in the recovery of sedimentary material.

Here we show calcareous nannofossil data of four cores and box-cores from the central Mediterranean Sea (Fig. 1), characterised by exceptionally high sedimentation rates and which span the last 200–350 years. They were retrieved in oceanographically sensitive areas of the northern Sicily Channel, within semi-permanent features due to surface current meandering, and in a coastal site of the Tyrrhenian Sea, in front of the mouth of the Sele river. We put to test the impact of the LIA on the marine environment utilizing calcareous nannofossil ecological proxies. Furthermore, we aim to test if there is any signature of recent oceanographic changes, including the Eastern Mediterranean Transient (EMT), which involved the eastern basin in the late 1980's and propagated westwards, (Schroeder et al., 2006; 2008) and of 20th century global warming.

2 Material and methods

Box-cores Station (St) 272 (37°17′ N, 12°48′ E, 226 m depth), 342 (36°42′ N, 13°55′ E, 858.2 m depth) and 407 (36°23′ N, 14°27′ E, 345.4 m depth) were recovered in the northern Sicily Channel (Fig. 1) by a USGS-modified NEL box-corer sampler. They were retrieved in the course of Bansic01, Bansic02 and Bansic03 oceanographic cruises, after investigation by a 3.5 kHz Sub Bottom Profiler. The sedimentary material is comprised of marls with a variable content of clay, about 70% in St 272, 35% in St 342 and 40% in St 407 (Tranchida, 2006).

The gravity core C90-1M (40°36′ N, 14°42′ E) was recovered from the shelf break of the northern Salerno Bay (Fig. 1) in June 2006, by the SW 104 drill-system of the ISMAR-CNR at a depth of 103.4 m. It is a 106 cm thick sequence of marls punctuated by a tephra layer between 55 and 66 cm below sea floor (cm bsf).

Box-cores St 272 (29 cm thick), 342 (23 cm thick) and St 407 (25 cm thick), as well as the upper 40 cm of core C90-1M, were sampled every 1-cm. Calcareous nannofossil analysis was carried out by a polarized microscope at about 1000×magnification. Rippled smear slides were prepared following a standard procedure (Bown and Young, 1998). A total of 500 specimens within the entire assemblage, plus a variable number of *F. profunda* platelets, were analysed. In two cases, for St 342 and 407, we considered the relative abundance of *F. profunda* per 1000 coccoliths, in order to reduce the standard error associated to the counting.

Quantitative data were collected on more than 20 taxonomic units, generally following the taxonomic concepts on living coccolithophores of Young et al. (2003). Gephyrocapsids were identified to a species level when they are at least 3 µm long, whereas smaller specimens were grouped into small *Gephyrocapsa*. Small placolihs include *Reticulofenestra* spp. and likely very small specimens of *Emiliania huxleyi* or specimens with slight diagenetic problems, that are dissolved T-shaped elements. Finally, *Florisphaera profunda* includes rare specimens of *Gladiolithus flabellatus*.

Taxa were grouped into "placoliths", "miscellaneous group", "upper photic zone (UPZ) group" and "lower photic zone (LPZ) group". Placoliths include *E. huxleyi*, small placoliths, small *Gephyrocapsa*, *Gephyrocapsa muellerae* and *Gephyrocapsa oceanica*. Miscellaneous group includes *Helicosphaera* spp., *Coccolithus pelagicus*, *Syracosphaera histrica*, *Pontosphaera* spp., *Calcidiscus leptoporus*, *Pleurochrysis* spp., *Braarudosphaera* spp. and specimens of all the other species ("others" in Table 1, Supplementary Material http://www.clim-past-discuss.net/6/817/2010/cpd-6-817-2010-supplement.zip). UPZ group includes *Syracosphaera pulchra*, *Umbellosphaera* spp., *Discosphaera tubifera*, *Rhabdosphaera* spp., *Umbilicosphaera* spp., *Oolithotus fragilis*, *Calciosolenia* spp., holodiscolithus, *Ceratolithus* spp. and the dinoflagellate *Thoracosphaera heimii* (Tangen et al., 1982). Finally, given the rarity of *Gladiolithus flabellatus* and given that *Algirosphaera robusta* was not found in any sample, *F. profunda* is the main species of the 'lower photic zone (LPZ) group.

Oxygen isotope analysis was carried out on 5–10 specimens of the planktonic foraminifera species *Globigerinoides ruber* white. Samples were measured by an automated continuous flow carbonate preparation GasBench II device (Spötl and Vennemann, 2003) and a ThermoElectron Delta Plus XP mass spectrometer at the IAMC-CNR (Naples) isotope geochemistry laboratory. Acidification of samples was per-formed at 50 °C. An internal standard (Carrara Marble with $\delta^{18}O = -2.43‰$ versus Vienna Pee Dee Belemnite – VPDB) was analyzed every six samples, whereas the NBS19 international standard was measured every 30 samples. Average standard deviations of oxygen isotope analyses was estimated at 0.08‰, on the basis of ∼100 repeated samples. All isotope data are reported in per mil (‰) relative to the VPDB standard.

Net Primary Production data, expressed in milligrams of carbon per square meter per day ($mgC \times m^{-2} \times d^{-1}$), are available on request as global 2160×4320 hdf files with an approximate resolution of about 9×9 square kilometers, and were downloaded from the web site http://web.science.oregonstate.edu/ocean.productivity/index.php. They refer to products generated using the standard algorithm for the Vertically Generalized Production Model (VGPM) (Behrenfeld and Falkowski, 1997). The VGPM is a "chlorophyll-based" model that estimates the net primary production from chlorophyll using a temperature-dependent description of chlorophyll-specific photosynthetic efficiency. For the VGPM, net primary production is a function of chlorophyll, available light, and the photosynthetic efficiency. Specifically, input data were SeaWiFS Photosynthetically Active Radiation (PAR), SeaWiFS Chl-a and AVHRR SST prior to year 2002, day 185, and SeaWiFS PAR, SeaWiFS Chl-a, and MODIS SST afterwards. Clouds were filled using a gap-filling software developed at Oregon State University, whereas estimates of photic zone depth were obtained from a model developed by Morel and Berthon (1989) and based on chlorophyll concentration. A cumulative global climatology field was first obtained by averaging the downloaded monthly climatological averages, calculated using available data between September 1997 and April 2007. From this 2160·4320 image, information from the pixels closest to the location of the sediment sample sites was extracted with the aim of further analysis.

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3 Chronology

The C90-1M core chronology is based on ^{210}Pb and ^{137}Cs radiometric dating (Vallefuoco, 2008). The ^{210}Pb activity-depth profile in core C90-1 m shows an exponential decline with depth suggesting a constant sediment accumulation over the last century. The application of dating models is not straightforward because there is no simple mechanism that describes the delivery of sedimentary material and ^{210}Pb to the bottom. Furthermore, the effects of mixing might add complexity to the process of profile formation. In fact, the application of simple dating models in the presence of mixing would provide overestimated sedimentation rates. Nevertheless, the excess ^{210}Pb profile shows no evidence of a superficial mixed layer. Consequently, the sediment accumulation rate was calculated for the first 40 centimetres below sea floor (cm bsf) by applying a Constant Flux–Constant Sedimentation model (Robbins, 1978) to the activity–depth profile of excess ^{210}Pb. A mean sediment accumulation rate of 0.20 cm/yr (sampling resolution of 4.8 yr) was obtained with an age of 1802 AD at 40.5 cm bsf (Fig. 2). The measured ^{137}Cs activities are low compared to those measured in the Northern Adriatic sediments (Frignani et al., 2004), but show a clear trend detectable down to 15 cm (Fig. 2). Assuming that the following peaks at 11.5 cm bsf and at 7.5 cm bsf can be associated to caesium activity onsets dated 1954 AD and to the caesium fallout dated at 1963 AD, respectively, and that 2006.5 AD represents the year of core recovery, the resulting mean sedimentation rate is 0.18 cm/yr. These values are in good agreement with those obtained from the ^{210}Pb activity-depth profile. The preservation of a clear curve trend of ^{137}Cs activity suggests that the sedimentation rate has been mostly constant for the last 50 years.

The chronology of Sicily Channel box-cores St 272, 342 and 407 (Fig. 3) has been determined by the ^{210}Pb activity (Di Leonardo et al., 2006; Tranchida, 2006). The age of sediments was determined by a constant rate of supply model (Oldfield and Appleby, 1984), which considers the flow of ^{210}Pb from the water column towards the sea floor as constant, independently from the sedimentation rate (Dickinson et al., 1996; Ligero et al., 2002). On this basis sediment accumulation rates were estimated as 0.19 cm/yr (sampling resolution of 5.3 yr) for St 272, 0.094 cm/kyr (sampling resolution of 10.6 yr) for St 342 and 0.067 cm/yr (sampling resolution of 14.9 yr) for St 407.

4 Oceanography and climatology of the study area

4.1 Oceanographic circulation

The Mediterranean is an elongated and semi-enclosed sea, with an anti-estuarine circulation pattern forced by the negative hydrological balance and the density gradient with the Atlantic Ocean (Robinson and Golnaraghi, 1994).

Surface waters, called Modified Atlantic Water (MAW), enter from the Atlantic Ocean and occupy the first 100–200 m of the water column. At the entrance of the Sicily Strait, they separate into two branches (Millot, 1987): 2/3 of these water masses enter the Sicily Channel; the remainder flows into the Tyrrhenian Sea and follows the northern coast of Sicily (Bethoux, 1980) (Fig. 1). Mesoscale turbulence phenomena occur during the flow along northern Sicily and the Italian peninsula (Marullo et al., 1994; Millot, 1999). Into the Sicily Channel, MAW is again split into two streams, southeast of Pantelleria (Robinson et al., 1999; Béranger et al., 2004). The Atlantic Tunisian Current follows the 200 m isobath, reaching the African coast and flowing eastwards as a coastal current (Onken et al., 2003; Béranger et al., 2004). The northern branch, called the Atlantic Ionian Stream (AIS), contributes to the MAW transport into the eastern Mediterranean off the southern coast of Sicily. Three semi-permanent mesoscale summer features are associated with AIS meanders, the Adventure Bank Vortex (ABV), the Maltese Channel Crest (MCC) and the Ionian Shelfbreak Vortex (ISV) (Fig. 1), mainly in response to topographical effects (Lermusiaux and Robinson, 2001; Béranger et al., 2004).

Levantine Intermediate Water (LIW) forms in the eastern basin in February-March as a process of surface cooling on water masses which underwent a severe salt enrich-

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ment (Ovchinnikov, 1984; Malanotte-Rizzoli and Hecht, 1988). LIW is not able to reach the sea-bottom and occupies a depth between 150–200 and 600 m. It is prevalent and ubiquitous throughout the eastern basin and enters the Sicily Channel through the sills south of Malta (Fig. 1), together with a thin uppermost layer of Eastern Mediterranean Deep Water (EMDW) (Lermusiaux and Robinson, 2001; Gasparini et al., 2005). LIW exits the Sicily Channel as a flow cascading down to about 2000 m into the Tyrrhenian Sea. It is composed of an upper part of LIW *sensu stricto* and a lower part of Tyrrhenian Dense Water which is the result of the mixing between EMDW and Tyrrhenian resident water. The circuit of LIW in the Tyrrhenian Sea is anticlockwise along the slope (Fig. 1) and it flows out along the slope of Sardinia.

Since 1910, observations on the Eastern Mediterranean indicate that the Adriatic Sea was the main source of EMDW and the Aegean Sea played a minor role (Wüst, 1961). Around 1990, oceanographers witnessed an important change called the Eastern Mediterranean Transient (EMT) with a unique high-volume influx of dense waters from the Aegean Sea, which replaced the 20% of EMDW. The process impacted the hydrography and biogeochemistry of the area, such as the production of intermediate waters with different physico-chemical properties and shoaling of the nutricline (Roether et al., 1996; Klein et al., 1999; Lascaratos et al., 1999; Malanotte-Rizzoli et al., 1999). The EMT propagated in the western basin (Schroeder et al., 2006; 2008) where it will probably influence the circulation and ecology. The EMT testifies to the sensitivity of the Mediterranean Sea circulation and biological activity to even minor perturbations.

4.2 Nutrient dynamics

The trophic resources of the Mediterranean Sea are among the poorest in the world's oceans. The anti-estuarine circulation pattern contributes to its maintenance, since, at the Strait of Gibraltar, surface waters coming from the Atlantic Ocean are nutrient depleted, with respect to outflowing waters, mainly constituted by LIW (Bethoux, 1979; Sarmiento et al., 1988).

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The main factor which controls the seasonal change in primary production is linked to the dynamics of the water column. Winter convection, and less frequently frontal zone migration or upwelling, brings nutrients into the photic zone (mesotrophic regime) (Klein and Coste, 1984). LIW is the carrier of nutrients in the upper part of the water column for fertilization (Intergovernmental Oceanographic Commission, 1999). 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 up to about 90 m, takes place (Klein and Coste, 1984; Krom et al., 1992; Crispi et al., 1999; Allen et al., 2002).

The seasonal control on primary productivity is displayed by the time series from September 1997 to December 2007, acquired on the basis of satellite imagery (http://web.science.oregonstate.edu/ocean.productivity/index.php). Winter maxima alternated with late summer minima can be seen in all investigated sites (Fig. 4). The mean value calculated for different stations is 206.8 $gC\times m^{-2}\times a^{-1}$ for St 272, 172.2 $gC\times m^{-2}\times a^{-1}$ for St 342, 163.1 $gC\times m^{-2}\times a^{-1}$ for St 407 and 218.5 $gC\times m^{-2}\times a^{-1}$ for C90-1M. The highest values in core C90-1M, both in the total mean and in the winter peaks, reflect the coastal location of this site. Values in the Sicily Channel box-cores display a west-east reduction gradient which is possibly due to the nutrient availability. In addition, there is a further influence controlled by the coastal proximity and site depths (see Sect. 2).

4.3 Atmospheric pattern

The middle-latitude location of the Mediterranean basin is suitable to provide information on the high- and low-latitude connection in the Northern Hemisphere. Moreover, given its West-East elongate nature, it interacts with different climatic systems.

Most of the Mediterranean region, including the study area, is indirectly under the influence of North Atlantic sea surface temperature (SST), one of the most important factors that drives the atmospheric circulation pattern. Rainy westerlies provide moisture and lower the temperature in winter, whereas the penetration of the Azorean

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high-pressure cell in summer causes a general drought. Even on a longer time-scale, the Mediterranean region is linked to the North Atlantic through the North Atlantic Oscillation (NAO) variability, defined as the normalized winter difference in the sea-level pressure between the Azorean high and the Icelandic low cells (Hurrell, 1995). During periods of high NAO-index, 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 low NAO-index periods. Other indices, such as the Mediterranean Oscillation Index, are important for determining local rainfall patterns, but are linked to large-scale atmospheric circulation dynamics, primarily to the NAO.

5 Results

A total of 116 samples were investigated with a mean counting of 545 specimens per sample (Table 1, Supplementary Material http://www.clim-past-discuss.net/6/817/2010/cpd-6-817-2010-supplement.zip). Assemblages are overwhelmingly dominated by *E. huxleyi*, similar to other Holocene records and living coccolithophore samples from the Mediterranean Sea (Knappertsbusch, 1993; Flores et al., 1997; Ziveri et al., 2000; Buccheri et al., 2002; Malinverno et al., 2003; Barcena et al., 2004; Colmenero-Hidalgo et al., 2004; Di Stefano and Incarbona, 2004; Incarbona et al., 2008b). This species shows relative abundance values of about 60–75% in the northern Sicily Channel (Figs. 5–7) and between about 75% and 90% in the Tyrrhenian Sea coastal site (Fig. 8). However, as already seen at Ocean Drilling Program (ODP) Site 963, most of the specimens of the taxonomic unit “small placoliths”, with variable percentages between 5% and 20% (Figs. 5-8), might belong to this species (Incarbona et al., 2009), further enhancing its dominant role. Gephyrocapsids are always rare and only in St 272, the westernmost station of the Sicily Channel, *G.muellerae* and *Gephyrocapsa oceanica* are slightly more abundant, possibly because of a more intense MAW flux (Knappertsbusch, 1993; Incarbona et al., 2008b,c).

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At least in the Sicily Channel box-cores, *F. profunda* is an important part of the assemblages, with percentage values of about 10–20% (Figs. 5–7). All the other species account for less than 5% and are largely subordinated within the assemblages (Figs. 5–8, Table 1 in Supplementary Material http://www.clim-past-discuss.net/6/817/2010/cpd-6-817-2010-supplement.zip).

6 Discussion

6.1 Paleoproductivity considerations

In order to obtain paleoenvironmental information from the cores, taxa were grouped on the basis of coccosphere functional morphology which might reflect different ecological adaptations (Young, 1994). The standard error associated to the counting, calculated at a 95% confidence level, is shown as a bar in Figs. 9–12, and demonstrates the general stability of environmental conditions over the last 3–4 centuries, with a few exceptions of significant abundance changes in a few taxonomic units.

From the plots it can be seen that placoliths are always dominant, with values never lower than 70% (Figs. 9–12). This group is formed by r-strategist taxa which rapidly exploit the nutrient uptake and, as observed in areas of upwelling (Okada and Honjo, 1973; Roth and Coulbourne, 1982), can be considered as a proxy of high productivity conditions (Young, 1994; Broerse et al., 2000; Flores et al., 2000; De Bernardi et al., 2005; López-Otálvaro et al., 2008). The dominance of this group reflects the proximity of the coast for all investigated sites and the relatively high productivity level.

The abundance of *F. profunda*, the only species representative of the LPZ community, is very low in the coastal site of the Tyrrhenian Sea, and more abundant in the Sicily Channel (Figs. 9–12). We suggest that such a distribution is primarily due to the depth of the cores (about 100 m depth for the recovery of core C90-1M in the Tyrrhenian Sea, and more than 200 m depth for Sicily Channel cores) which potentially causes a vertical zonation in the coccolithophore community (Winter et al., 1994; Young et al., 1994). In fact, as already seen by the distribution of this species from the western Pacific Ocean and the Sicily Channel sea floor (Okada, 1983; Incarbona et al., 2008c), *F. profunda*'s percentage values are directly correlated to the depth of the site.

In Fig. 13, the relative abundance of placoliths is plotted *versus* that of *F. profunda*, as another way to express a ratio which is considered a proxy for paleoproductivity (Flores et al., 2000; López Otálvaro et al., 2008). Samples from the Sicily Channel are confined into a unique field which is distinct from the Tyrrhenian core. Based on the ratio, the Tyrrhenian Sea core C90-1M maintained higher productivity levels over the last two centuries, with respect to Sicily Channel sites. Such a fact might reflect more pronounced winter phytoplankton blooming, according to primary productivity seasonality of the last ten years (Fig. 4).

Samples of Site 342, recovered in the anticyclonic gyre of the MCC, shows the lowest values in the ratio (that is higher values of *F. profunda* and lower ones of placoliths). Samples from the cyclonic gyres (St 272 and 407) ABV and ISV are instead largely similar. Those ones from St 407 are more dispersed, possibly because this Station reaches the oldest sedimentary levels and records the occurrence of climatic anomalies (impact of the LIA, discussed in the following section). In fact, as highlighted in Fig. 13, most of the highest values in the ratio (that is the highest productivity) can be referred to samples older than about 1850 AD. Without LIA samples of St 407, the placoliths/*F. profunda* ratio would depict a West-East productivity decrease that again mirrors what can be observed by satellite imagery over the last ten years (Sect. 4.2, Fig. 4).

The gradient of regression lines is significantly similar among Sicily Channel samples (Fig. 13), with minor differences perhaps due to oceanographic (anticyclonic/cyclonic gyres) and topographic (depth and coast proximity) characteristics. There is a significant difference with the regression line of Tyrrhenian C90-1M samples (Table 2, Supplementary Material http://www.clim-past-discuss.net/6/817/2010/cpd-6-817-2010-supplement.zip). This is because of the coastal setting of core C90-1M, but also reflects the different history, hydrography and nutrient resources of Sicily

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Channel and Tyrrhenian sub-basins.

6.2 Paleoclimatic considerations and the impact of the little ice age

There is evidence for a general, long-term cooling of the high- and mid-latitude regions in the Northern Hemisphere during the Holocene, due to the decline of summer insolation (Wright, 1993; Mayewski et al., 2004; Wanner et al., 2008). This trend culminated in the Little Ice Age, between 1250 AD and 1850 AD but with a main phase usually recognized between 1550 AD and 1850 AD, when many glaciers of the Northern Hemisphere realized their most extensive advance since the Younger Dryas (Grove, 2004; Holzhauser, 2005; Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). Severe LIA winters, with frozen lakes and rivers and icy canals, for instance in Italy, The Netherlands and England, are reported from historical chronicles. Different temperature reconstructions carried out on Northern Hemisphere records suggest drops between 0.5 °C and 1 °C (Matthews and Briffa, 2005; Goosse et al., 2008; Mann et al., 2008; Mann et al., 2009).

The lowermost part of the St 342 and St 407 records show significant decreases in *F. profunda* abundance (Fig. 14), while placoliths increase in abundance, supporting an increase in primary productivity, that coincides with most of the main phase of the LIA for St 407 and possibly with its terminal part for St 342. Applying the formula of Incarbona et al. (2008a) to transform *F. profunda* percentage values into absolute estimates of Net Primary Productivity (NPP), productivity would have decreased by about 35–40 $gC \times m^{-2} \times a^{-1}$ from year 1700 AD (NPP about 213 $gC \times m^{-2} \times a^{-1}$) to year 1855 (NPP about 177 $gC \times m^{-2} \times a^{-1}$). These estimates are compatible with the values found in the ABV area (Fig. 1) throughout the Holocene (Incarbona et al., 2008a). The composite section built for Site 963 and St 407 further suggests that this change can be attributed to part of the Bond cycle B0 and part of the LIA (Fig. 15).

The increase in productivity in the Sicily Channel represents a new evidence of the impact of the LIA in the marine realm. Previous studies on the central sector of the Mediterranean Sea focused on SST decrease. A temperature fall of 2 °C has been deduced along the northern Sicilian coast by geochemical analysis on Vermetid Reefs (Silenzi et al., 2004). A similar temperature drop, accompanied by concomitant heavier values in δ^{18}O of planktonic foraminifera, has been showed in the Gulf of Taranto, western part of the Ionian Sea (Versteegh et al., 2007; Taricco et al., 2009).

In Figure 14, the distribution patterns of *F. profunda* at St 342 and St 407 are plotted together with Northern Hemisphere and global climate proxy records such as temperature, solar irradiance and atmospheric activity (Mayewski et al., 1997; Lean, 2000). *F. profunda* distribution patterns at St 342 and 407 do not show a significant match with Northern Hemisphere temperature (Mann et al., 2008) and with solar irradiance reconstructions (Lean, 2000), apart from the general increasing trend and the decrease in abundance in coincidence of the Dalton Minimum (Fig. 14). No further significant correlation with temperatures can be seen focusing on the regional context of the Italian Peninsula (Brunetti et al., 2004, 2006). However, the spectral analysis of *F. profunda* percentage values in the St 407 sedimentary record highlights a significant periodicity (over 95% confidence level) at 60 yr (Fig. 16). It is a solar periodicity, known as the Yoshimura cycle (Yoshimura, 1979) and seems to be a natural forcing of large scale atmospheric phenomena, such as the NAO over the last four centuries (Velasco and Mendoza, 2008). Significantly, algal blooms in the Adriatic Sea have been recently tied to this cycle (Ferraro and Mazzarella, 1998). Nevertheless, the occurrence of a solar periodicity in the Sicily Channel sedimentary record has to be prudently considered, since the standard error associated to *F. profunda* countings is on average 1.9%, that is just suitable to decipher variation at the 0–75 year band.

Three main episodes of strengthened atmospheric circulation in the Northern Hemisphere, deduced by sea salt Na and non-sea salt K in Greenland ice cores (Mayewski et al., 1997), have been recorded between about 1910–1940 AD, 1790–1830 AD and below 1750 AD (Fig. 14). These intervals correspond to increased productivity in the St 407 core. Remarkable is especially the link at about 1930 AD, that would hardly been explained by other climatic forcings (Fig. 14). As already proposed for Holocene climatic anomalies recognized at ODP Site 963, stronger northern winds might promote vertical mixing in the water column stimulating phytoplankton blooming (Incarbona et al., 2008a). Moreover, the strengthened atmospheric circulation in the Northern Hemisphere might have impacted on the oceanographic circulation of the Mediterranean Sea, enhancing the deepwater production and reinforcing the thermohaline circulation, as recently observed in the Western Basin (Frigola et al., 2007). The AIS follows the topography of southern Sicily coast and generates three mesoscale features (Sect. 4.1). In case of reinforcing of the Mediterranean thermohaline circulation the character of the gyres would be invigorated, independently from their cyclonic/anticyclonic nature. Therefore, the ABV cyclonic gyre of St 407 might have widened and strengthened (increased productivity) at about 1930 AD, while anticyclonic conditions of MCC persisted at St 342, explaining the different response of the two site to the climatic perturbation.

Four significant peaks in abundance of the UPZ group, at about 1810, 1875, 1910 and 1965 AD can be seen in the St 342 box-core (Fig. 14). UPZ taxa are K-strategists, specialized to live in warm subtropical surface waters and to exploit a minimum amount of nutrients (Okada and Mcintyre, 1979; Roth and Coulbourne, 1982; Takahashi and Okada, 2000; Andruleit et al., 2003; Boeckel and Baumann, 2004; Baumann et al., 2005). In the Mediterranean Sea, they are significantly abundant in the upper part of the water column in the presence of a deep late-summer thermocline (Kappertsbusch, 1993) (Fig. 17). On this basis, it should be expected a pronounced control of solar irradiance variations which leads the deepening and strengthening of the summer thermocline. Surprisingly, UPZ peaks decrease in coincidence with relative solar activity minima, even in correspondence with the Dalton Minimum (Fig. 14). We are not able to provide a straightforward explanation for such behaviour, however we note that exceptionally high solar output, for instance with a high number of sunspots, might widen the influence depth of harmful ultraviolet light (Buma et al., 2000; Müller et al., 2008; Guan and Gao, 2010) in the uppermost part of the water column and therefore might reduce the habitat of K-strategist species.

The last decades are characterised by rapid increase of greenhouse gases in the atmosphere and global surface temperature (Fig. 14). Recent studies pointed out

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that coccolithophore PIC production responds to rising atmospheric CO_2 (Fabry, 2008; Iglesias-Rodriguez et al., 2008; Langer et al., 2009). Moreover, as discussed in Sect. 4.1, the Mediterranean Sea has been experiencing a change in hydrography which involves the marine ecosystem. One of the aims of the present work was to test the response of calcareous nannofossil assemblages to the these phenomena.

We do not note any turnover in the assemblages but only minor tendencies in groups. The distribution pattern of placoliths and of *F. profunda* in St 342 and St 407 box-cores shows trends that can be interpreted as a primary productivity reduction, started, respectively at 1910 AD and at 1930 AD (Figs. 10, 11 and 14). This trend is also evident in the Tyrrhenian core C90-1M since about 1980 AD (Fig. 12), whereas an opposite trend supporting an increase in productivity can be deduced for St 272 (Fig. 9). We suspects that coccolithophore trends in the central Mediterranean sediments are likely not a response to global phenomena but rather a local hydrographic response. Given the proximity to the coast of the investigated sites, they might have been affected by human activity, such as public works and pollution. In fact, as discussed in the next section, a dam built in 1934 AD would have greatly affected the flow capacity of the Sele river, whereas high heavy metal concentrations, such as Hg, characterise the northern Sicily Channel sediments since 1950–1970 AD (Di Leonardo et al., 2006). Further investigation, especially focused in less anthropogenic-affected regions, is needed to gather the signal of recent oceanographic-climatic transformations in the Mediterranean environment.

6.3 The meaning of reworked specimens

The relative abundance of calcareous nannofossil reworked specimens in sedimentary records is a complex interplay of factors, among others the response to eustatic sea-level fluctuations, proximity to the coast and primary productivity variations (Sprovieri et al., 2003; Di Stefano and Incarbona, 2004; Incarbona et al., 2008b, 2009, 2010).

The distribution pattern of reworked calcareous nannofossil specimens in cores St 272, St 342, St 407 and C90-1M is shown in Fig. 18. The record of the Tyrrhenian core

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C90-1M is the most remarkable, with wide fluctuations, between about 10 and 50%, over the last two centuries. Many specimens are Mesozoic taxa, coeval with those found in outcrops of the southern Appennines. Since eustatic sea-level fluctuation of the past centuries is limited to a few centimetres (Lambeck et al., 2004a, b; Antonioli et al., 2007) and since primary productivity remained almost unchanged (Fig. 12), calcareous nannofossil reworking changes are expected to be mainly due to variations of the Sele river discharge rates, also considering the proximity of core C90-1M to its mouth. In order to investigate such a possibility, we carried out the oxygen isotope analysis of the planktonic foraminifera species *Globigerinoides ruber*, which is thought to be sensitive to the condition of surface waters and thus suitable to record freshwater lenses and flooding episodes (Rohling et al., 2004).

Even the *G. ruber* δ^{18}O shows wide fluctuations over the last two centuries, with values between 1.1‰ and −1.4‰ (Fig. 18). Calcareous nannofossil reworked specimens and *G. ruber* δ^{18}O values show a significant correlation at site C90-1M, $R=0.47$ $n=38$. Unexpectedly, it is a positive correlation, with peaks in abundance of reworked nannofossils, like the one located between 1855 and 1880 AD, coinciding with the heaviest δ^{18}O (Fig. 18). This could mean that enhanced drought made the soil and rock outcrops highly vulnerable to erosion, loading higher amounts of reworked nannofossils. Interestingly, reworking lowest values are recorded since 1934 AD, when a dam reduced the solid carriage of the Sele river (Fig. 18), highlighting the anthropogenic impact on the sedimentary record of site C90-1M.

The northern Sicily Channel box-cores do not display any significant abundance variation in the reworked nannofossil distribution pattern (Fig. 18), which are mainly Miocene-Pliocene taxa, as expected by rocks exposed in southern Sicily. However, it is noteworthy that the 3 records show a similar increasing upward trend, opposite to that of core C90-1M. We suggest that such a behaviour follows 2 middle-late Holocene trends experienced in Sicily: a long-term trend towards aridification, due to reduced precipitation as witnessed by fossil pollen assemblages and the geochemistry of lake sediments and speleothems (Sadori and Narcisi, 2001; Frisia et al., 2006; Zanchetta et al., 2006; Sadori et al., 2008), started approximately at the end of the African humid period (Gasse, 2000; deMenocal et al., 2000). The Sicily reduction in precipitation also mirrors the Italian Peninsula trend of the last few centuries (Brunetti et al., 2004, 2006); the intensive anthropogenic land-use, already highlighted by palynological studies of two southern Sicilian coastal lakes, started about 2.7 kyr BP, at the time of the first Greek colonization pulses, which caused, and is still causing, the loss of a natural vegetation cover (Noti et al., 2009; Tinner et al., 2009). As discussed above, the loss of vegetation would have enhanced soil erosion.

In conclusion, we suggest that if major factors like eustatic sea-level fluctuations remain quite stable, the relative abundance of reworked calcareous nannofossils can increase when the soil is more vulnerable, for instance in case of prolonged drought and vegetation cover loss.

7 Conclusions

Coccolithophore data on 116 samples have been acquired on 4 small cores spanning the last 2–4 centuries, recovered in the central Mediterranean Sea.

Relative abundances of placoliths plotted *versus* those ones of *Florisphaera profunda* allow evaluation of productivity levels. The coastal and shallow Tyrrhenian Sea core C90-1M seems to have maintained higher primary productivity levels, with respect to Sicily Channel cores. The proxy results are corroborated by productivity variations deduced by satellite imagery of the last ten years. In particular, more pronounced winter phytoplankton blooming is the more likely cause for such a difference.

The lowermost part of the records of St 342 and St 407 show significant decreases in *F. profunda* abundance, while placoliths increase in abundance, supporting an increase in primary productivity. The chronology based on ^{210}Pb activity suggests the productivity increase can be ascribed to the main phase of the LIA, ended about 1850 AD. In particular, productivity would have decreased by about 35–40 $gC \times m^{-2} \times a^{-1}$ from year 1700 AD to year 1855. These estimates are compatible with the values found in the

ABV area throughout the Holocene (Incarbona et al., 2008a), where the last Bond cycle (BO) was missing due to material recovery problems.

We carried out a comparison with climate forcing records to reconstruct the LIA impact on the marine ecosystem in the Sicily Channel. The lower photic-zone dweller *F. profunda* species decreases in abundance in the early 19th century mimicking decreased solar (sunspot) activity during the Dalton minimum, as well as during the Maunder Minimum. This species, at St 407, exhibits a periodicity of 60 yr which might be attributed to the Yoshimura cycle of solar origin. Main episodes of strengthened atmospheric circulation in the Northern Hemisphere, recorded between about 1910–1940 AD, 1790–1830 AD and below 1750 AD, might correspond to main intervals of increased productivity in the Sicily Channel. In fact, strengthened northern winds were a suitable explanation for other Holocene climatic anomalies (Incarbona et al., 2008a) and for a concomitant 2 °C SST decrease indicated by geochemical analysis on Vermetid Reefs along the northern Sicilian coast (Silenzi et al., 2004).

The coastal and shallow Tyrrhenian Sea core C90-1M shows wide abundance changes of reworked nannofossil specimens. The comparison with δ^{18}O of the planktonic foraminifera species *G. ruber*, suggests that the most important reworking pulses occurred during prolonged aridity, probably because enhanced drought and vegetation loss made the soil and rock outcrops more vulnerable to erosion.

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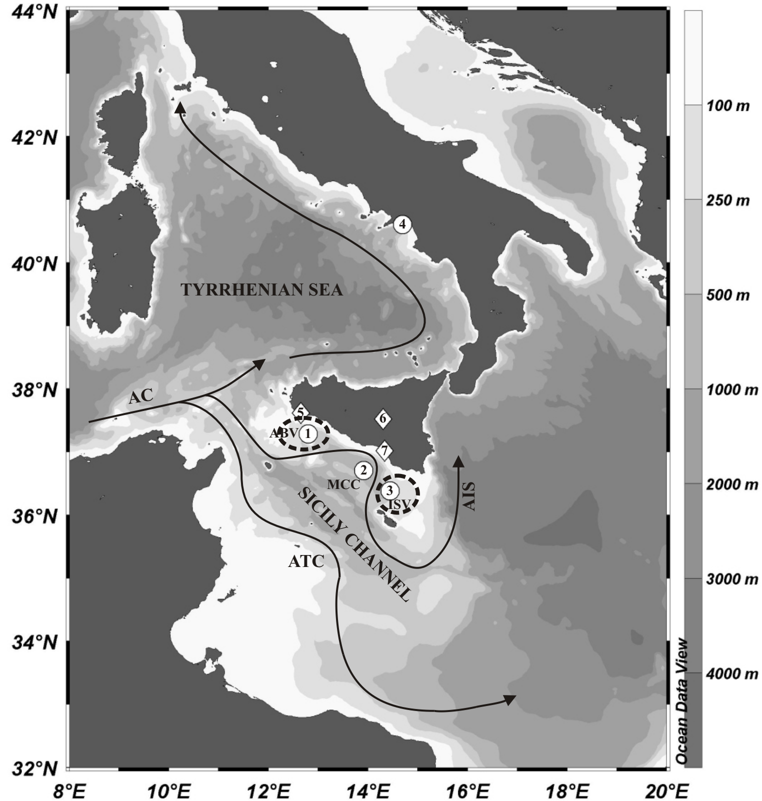

Fig. 1. Bathymetric map of the Mediterranean Sea and core locations. Surface water circulation in winter is illustrated, with major currents and semi-permanent features: AC, Algerian Current; ATC, Atlantic Tunisian Current; AIS, Atlantic Ionian Stream; ABV, Adventure Bank Vortex; MCC, Maltese Crest Channel; ISV, Ionian Shelfbreak Vortex. Circles show: (1) St 272; (2) St 342; (3) St 407; (4) C90-1M. Diamonds refer to palynological studies inform Sicilian lakes and cited in the text: (5) Gorgo Basso coastal lake (Tinner et al., 2009); (6) Pergusa lake (Sadori and Narcisi, 2001; Zanchetta et al., 2006; Sadori et al., 2008); (7) Biviere di Gela coastal lake (Noti et al., 2009).

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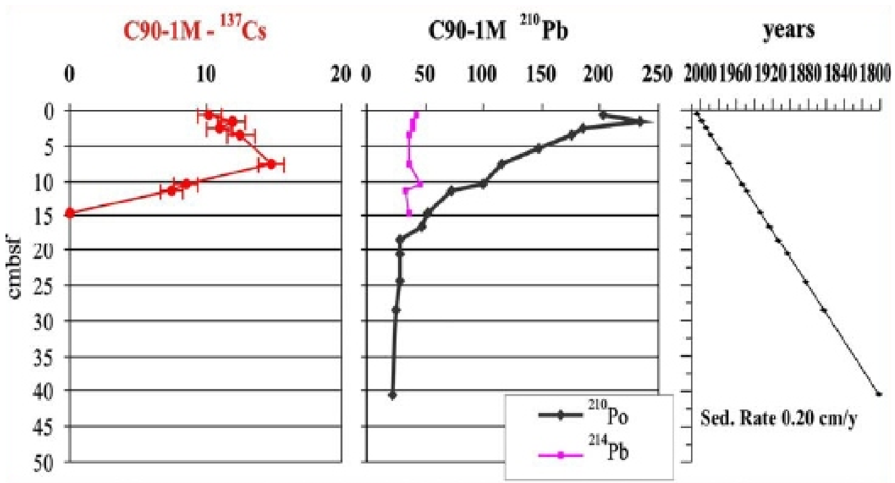

Fig. 2. The ^{210}Pb and ^{137}Cs activity-depth profiles in core C90-1M and the age-depth profile for the first 40 cmbsf (Vallefuoco, 2008).

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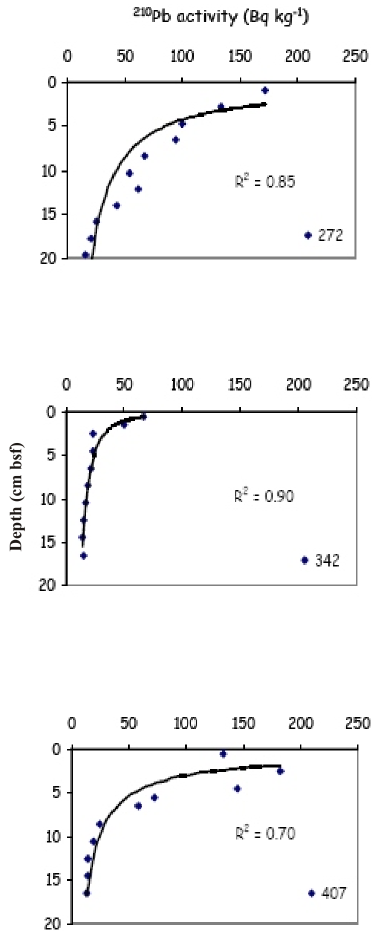

Fig. 3. The ^{210}Pb activity-depth profiles in cores St 272, 342 and 407 (Tranchida, 2007).

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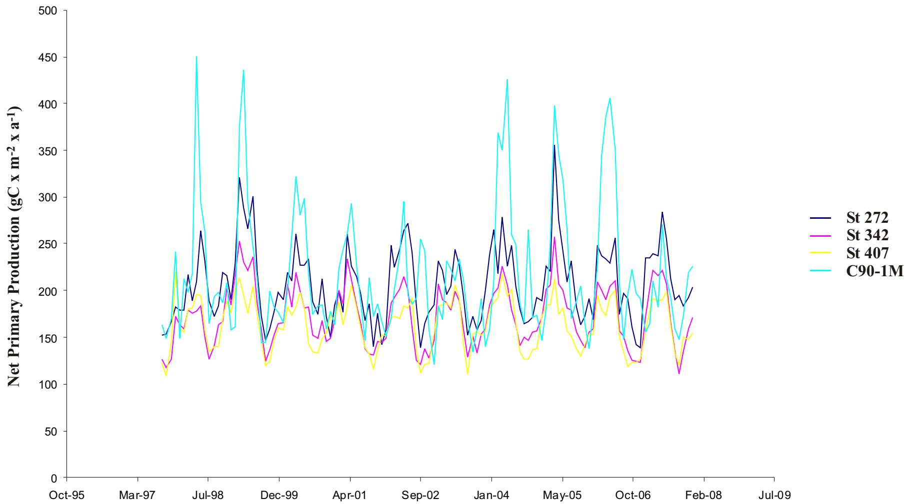

Fig. 4. Net Primary Production data, expressed in milligrams of carbon per square meter per day ($mgC \times m^{-2} \times d^{-1}$), calculated at core locations with an approximate resolution of about 9×9 square kilometers, between September 1997 and April 2007 (http://web.science.oregonstate.edu/ocean.productivity/index.php).

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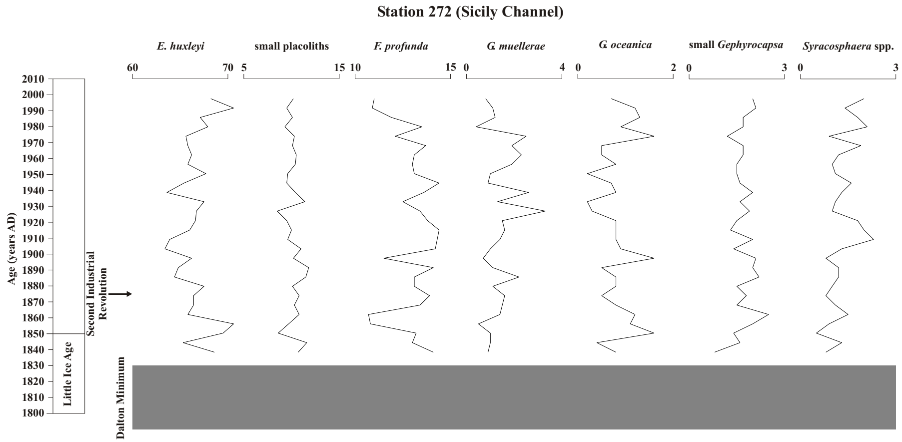

Fig. 5. Distribution patterns of calcareous nannofossils (relative % values) at St 272 (Sicily Channel), plotted *versus* age (years AD). The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton Minimum is also indicated by a gray band, even if no samples come from this horizon.

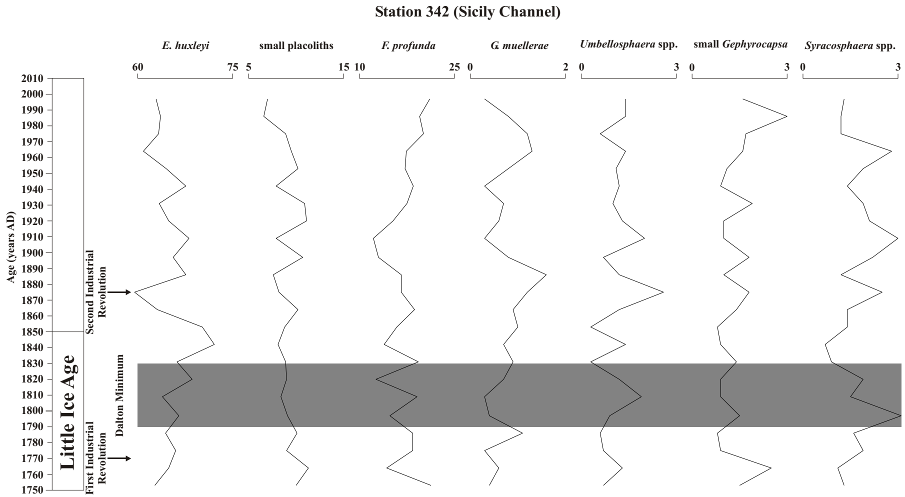

Fig. 6. Distribution patterns of calcareous nannofossils (relative % values) at St 342 (Sicily Channel), plotted *versus* age (years AD). The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton Minimum is also indicated by a gray band.

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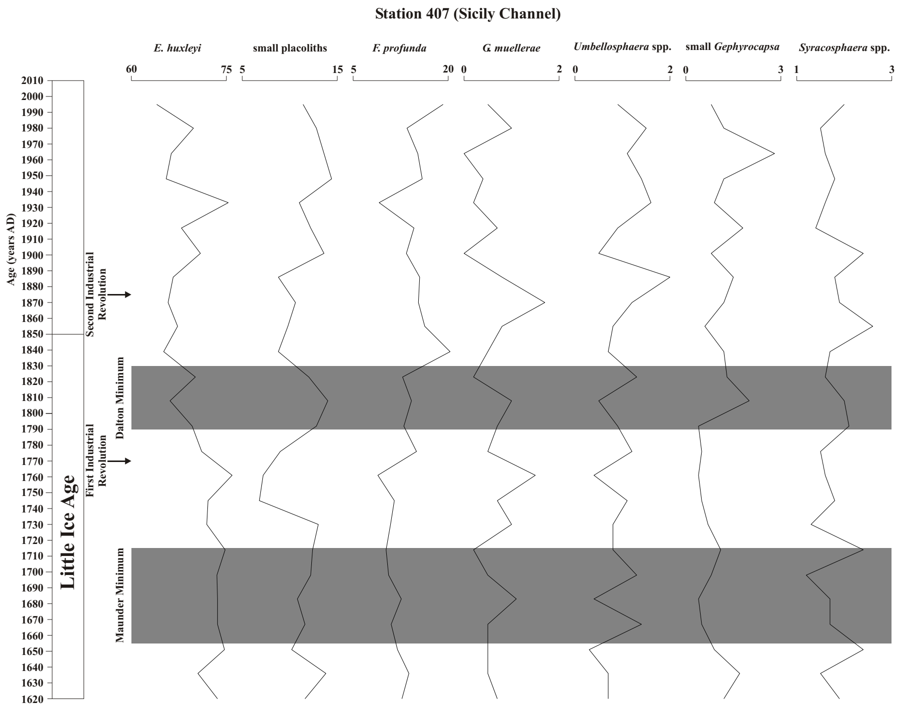

Fig. 7. Distribution patterns of calcareous nannofossils (relative % values) at St 407 (Sicily Channel), plotted *versus* age (years AD). The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton and Maunder Minima are both indicated by gray bands).

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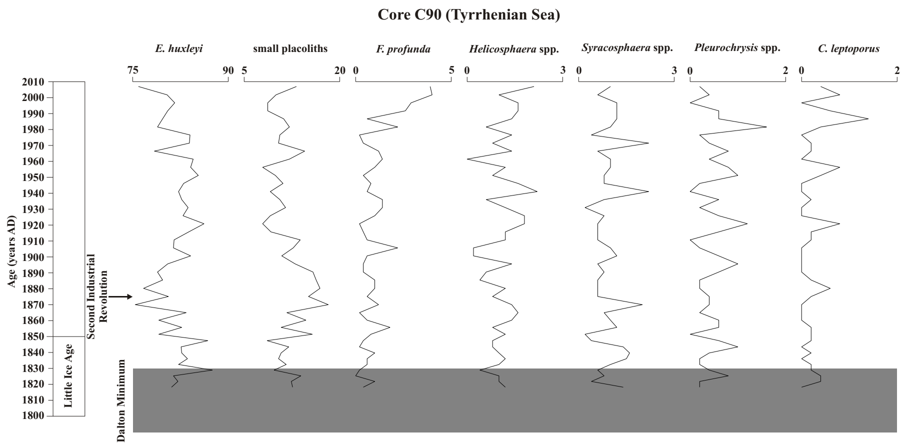

Fig. 8. Distribution patterns of calcareous nannofossils (relative % values) at core C90-1M (Tyrrhenian Sea), plotted *versus* age (years AD). The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton Minimum is also indicated by a gray band.

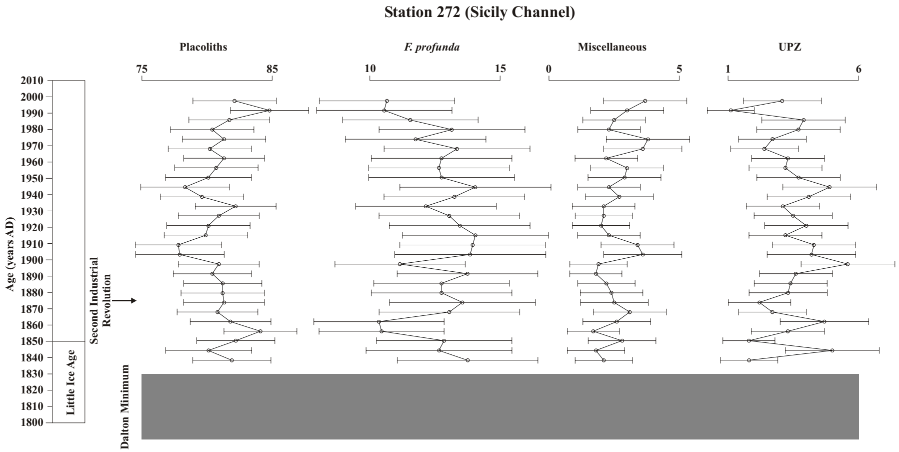

Fig. 9. Distribution patterns of calcareous nannofossil groups (percentage values) at St 272 (Sicily Channel), plotted *versus* age (years AD). The horizontal bars show the error associated to the countings, for a 95% of confidence level. The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton Minimum is also indicated by a gray band, even if no samples come from this horizon.

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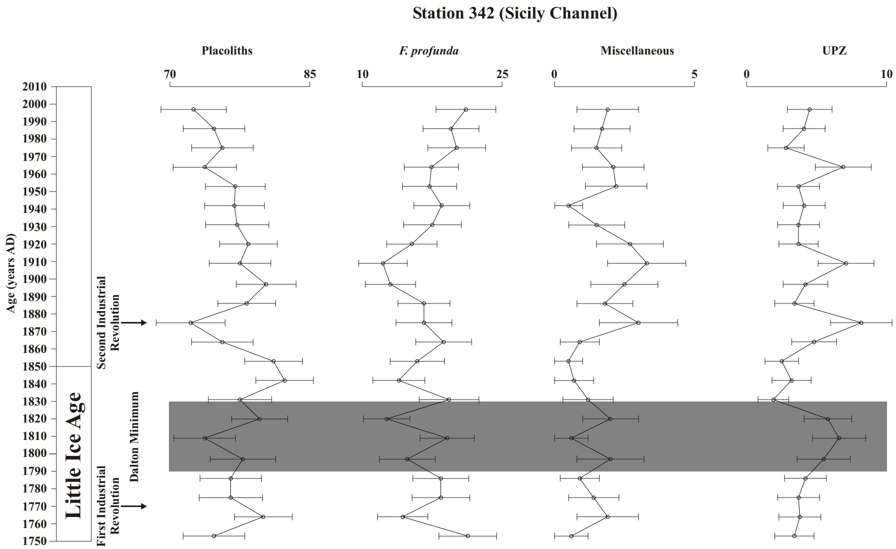

Fig. 10. Distribution patterns of calcareous nannofossil groups (percentage values) at St 342 (Sicily Channel), plotted *versus* age (years AD). The horizontal bars show the error associated to the countings, for a 95% of confidence level. The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton Minimum is also indicated by a gray band.

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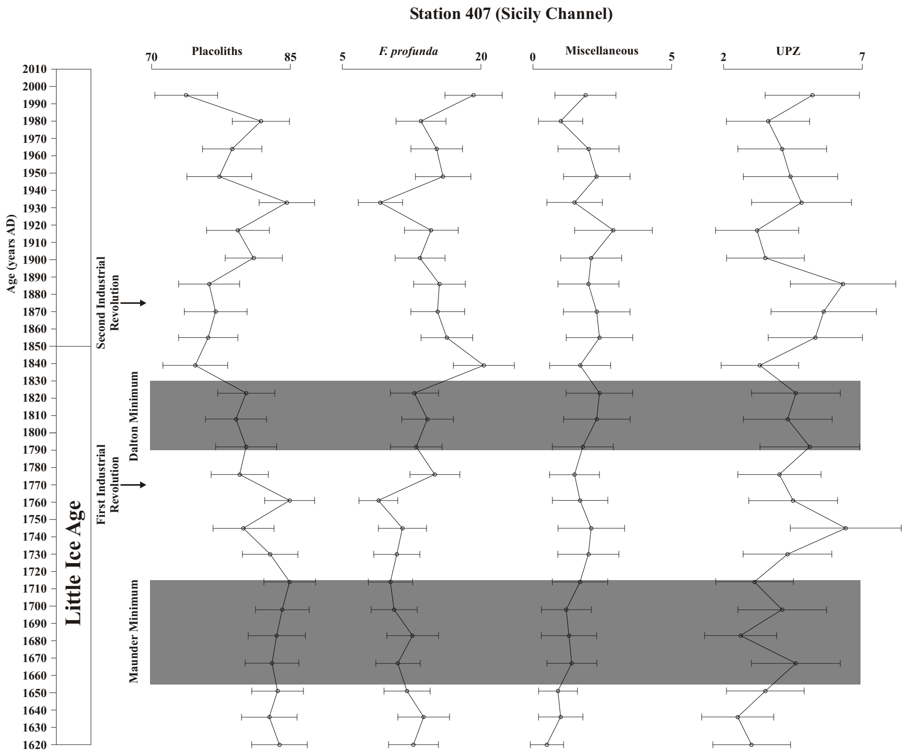

Fig. 11. Distribution patterns of calcareous nannofossil groups (percentage values) at St 407 (Sicily Channel), plotted *versus* age (years AD). The horizontal bars show the error associated to the countings, for a 95% of confidence level. The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton and Maunder Minima are both indicated by gray bands.

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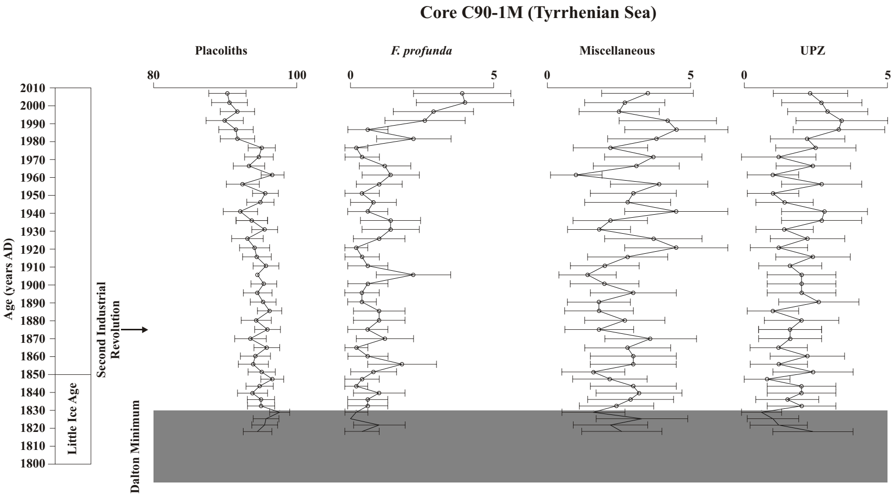

Fig. 12. Distribution patterns of calcareous nannofossil groups (percentage values) in core C90-1M (Tyrrhenian Sea), plotted *versus* age (years AD). The horizontal bars show the error associated to the countings, for a 95% of confidence level. The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton Minimum is also indicated by a gray band.

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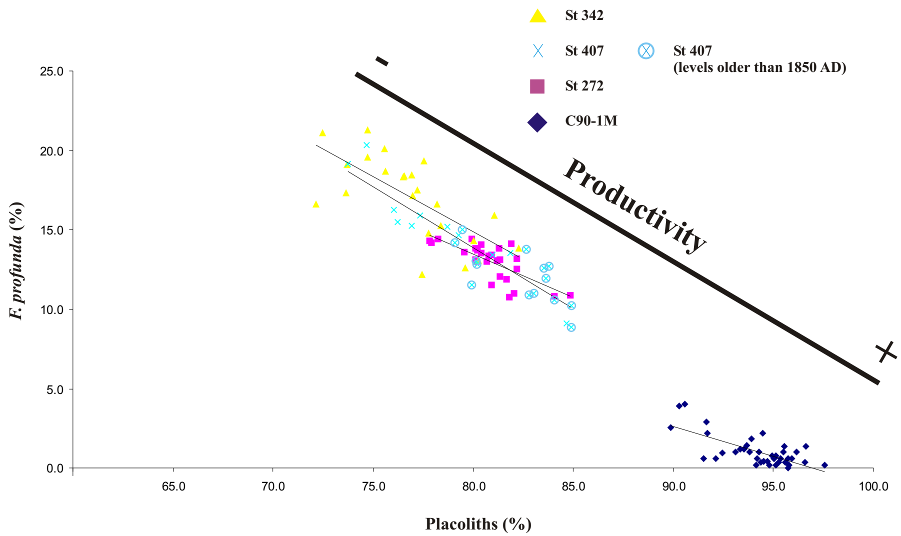

Fig. 13. Placoliths (percentage values) *versus F. profunda* (percentage values) of the investigated data set. This plot can be considered as another way to show a ratio which is used in paleoproductivity reconstructions (Flores et al., 2000; López Otálvaro et al., 2008). Each sample group has its own regression line.

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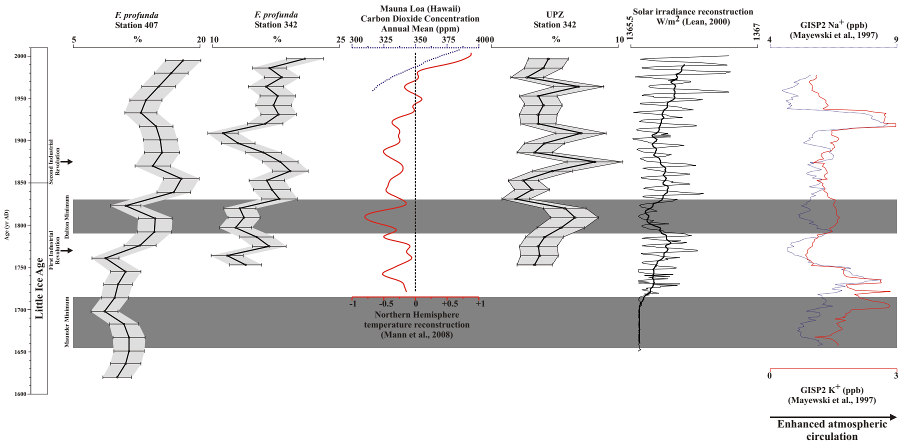

Fig. 14. Downcore variations of *F. profunda* percentage values (counted against 1000 other coccoliths); the gray shadow indicates the error for a 95% confidence level) at St 407 and 342 and of UPZ at St 342, plotted together with climatic proxy records: carbon dioxide at Mauna Loa (Hawaii, annual mean in ppm) from 1959 AD (http://www.ncdc.noaa.gov/paleo/paleo.html); Northern Hemisphere temperature reconstruction (Mann et al., 2008); Solar irradiance reconstruction (W/m^2) since the Maunder Minimum (Lean, 2000); GISP 2 ice core sea salt Na and non-sea-salt K records, expressed in ppb (Mayewski et al., 1997).

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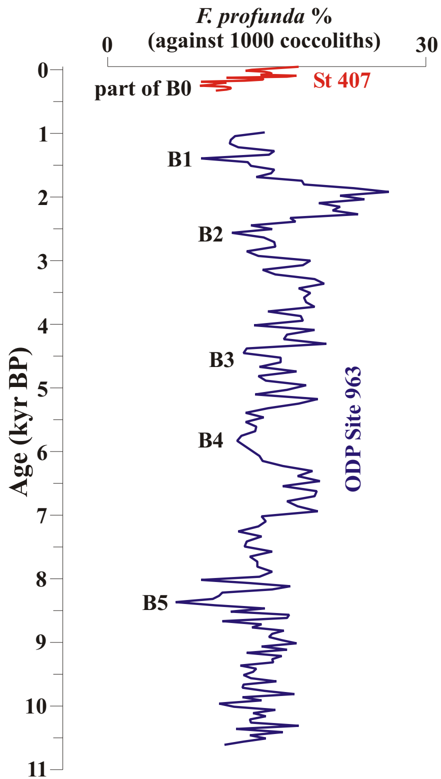

Fig. 15. Composite section of *F. profunda* percentage values between ODP Site 963 (Incarbona et al., 2008a) and St 407 (present study). B0-B7 indicate peaks of ice rafted detritus in the northern North Atlantic, the so called Bond cycles (Bond et al., 1997, 2001), often used as a master record for Holocene climatic anomalies.

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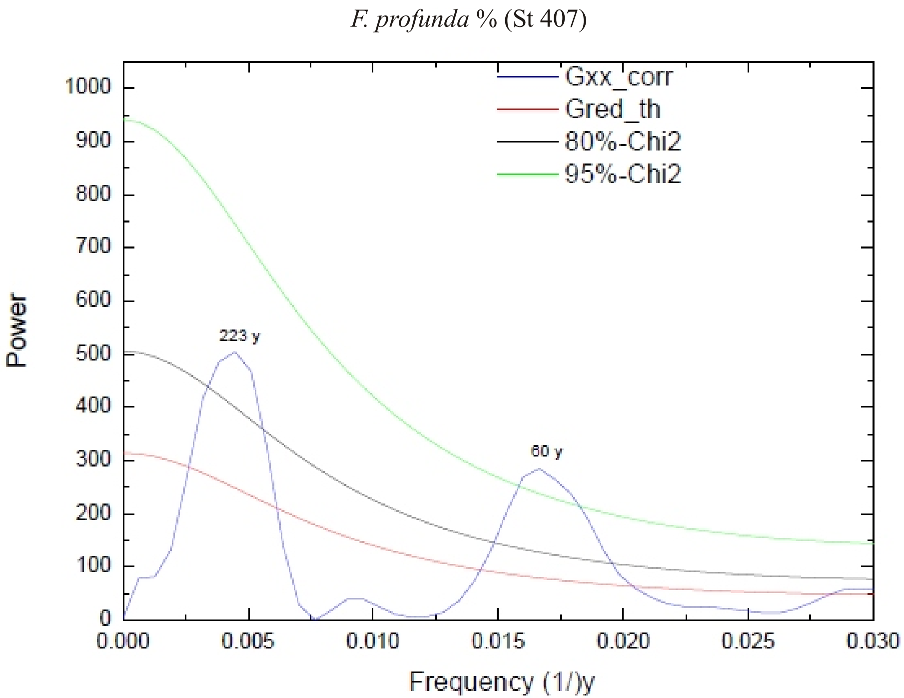

Fig. 16. Bias-corrected power spectrum (REDFIT) of the unevenly sampled *F. profunda* abundance signal at St 407. The green line and the black line, respectively indicate the 95% and the 80% confidence level. The red line indicates the AR(1) theoretical red-noise spectrum.

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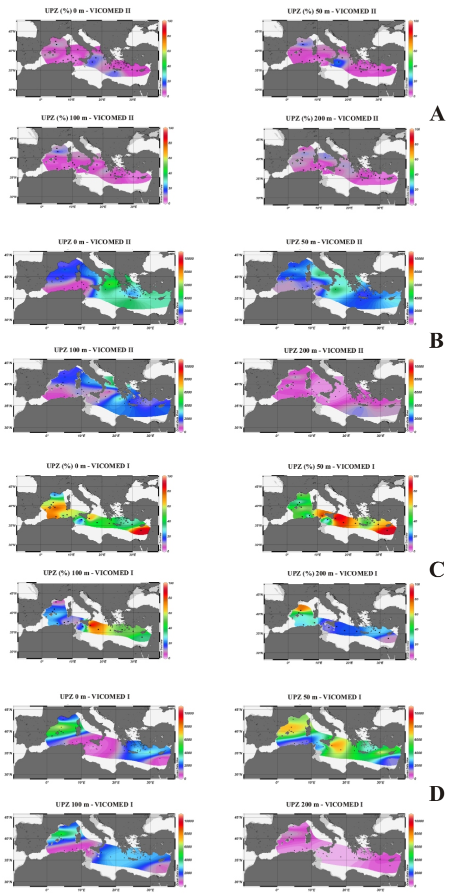

Fig. 17. Distribution map of the relative (%) and absolute abundance of UPZ group taxa across the Mediterranean Sea during cruises VICOMED I (September–October 1986) and VICOMED II (February–March 1988), at 0, 50, 100 and 200 m depth (Knappertsbusch, 1993). **(A)** relative and **(B)** absolute abundance of UPZ group during the winter cruise VICOMED II; **(C)** relative and **(D)** absolute abundance of UPZ group during the late summer cruise VICOMED I.

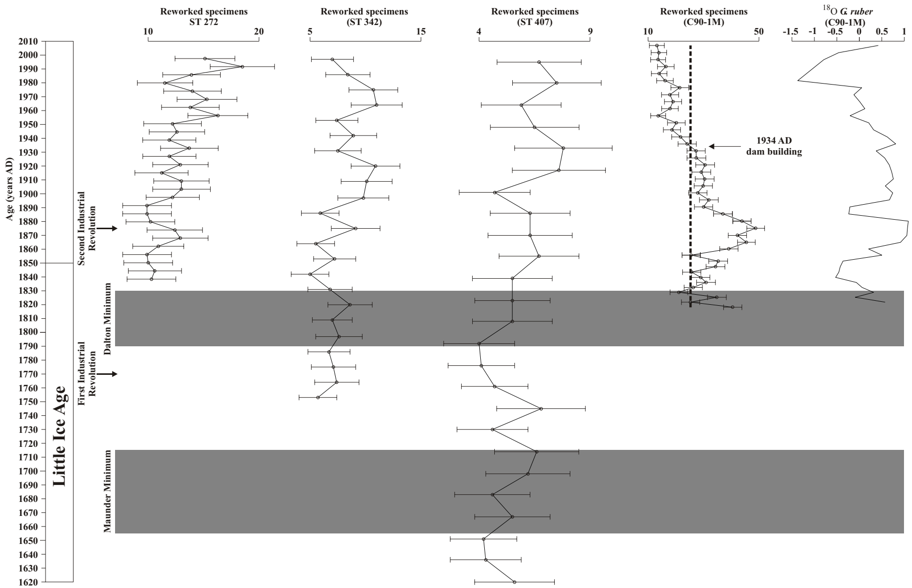

Fig. 18. Downcore variations (percentage values) of reworked calcareous nannofossil specimens at all investigated sites and oxygen isotope values (‰ relative to the VPDB standard) of the planktonic foraminifera species *G. ruber* in the Tyrrhenian Sea core C90-1M. The horizontal bars show the error associated to the countings, for a 95% of confidence level. The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton and Maunder Minima are both indicated by a gray band.

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