Clim. Past, 6, 795–805, 2010
www.clim-past.net/6/795/2010/
doi:10.5194/cp-6-795-2010

Climate of the Past

The Impact of the Little Ice Age on Coccolithophores in the Central Mediterranea Sea

A. Incarbona[1], **P. Ziveri**[2], **E. Di Stefano**[1], **F. Lirer**[3], **G. Mortyn**[2,4], **B. Patti**[5], **N. Pelosi**[3], **M. Sprovieri**[5], **G. Tranchida**[5], **M. Vallefuoco**[3], **S. Albertazzi**[6], **L. G. Bellucci**[6], **A. Bonanno**[5], **S. Bonomo**[7], **P. Censi**[8], **L. Ferraro**[3], **S. Giuliani**[6], **S. Mazzola**[5], **and R. Sprovieri**[1]

[1]Università degli Studi di Palermo, Dipartimento di Geologia e Geodesia, Via Archirafi 22, 90123 Palermo, Italy
[2]Universitat Autònoma de Barcelona, Institute of Environmental Science and Technology, Edifici Cn Campus de la UAB, 08193 Bellaterra (Cerdanyola del Vallès), Barcelona, Spain
[3]Consiglio Nazionale delle Ricerche, Istituto per l'Ambiente Marino Costiero, Calata Porta di Massa, Interno Porto di Napoli, 80133, Naples, Italy
[4]Universitat Autònoma de Barcelona, Department of Geography, 08193 Bellaterra, Spain
[5]Consiglio Nazionale delle Ricerche, Istituto per l'Ambiente Marino Costiero U.O. Capo Granitola, Via del Mare 3, 91021 Torretta Granitola (Campobello di Mazara, Trapani), Italy
[6]Consiglio Nazionale delle Ricerche, Istituto Scienze Marine (Sezione di Geologia Marina), Via Gobetti 101, 40129 Bologna, Italy
[7]Consiglio Nazionale delle Ricerche, Institute of Biomedicine and Molecular Immunology (A. Monroy), Via La Malfa 153, 90146 Palermo, Italy
[8]Università degli Studi di Palermo, Dipartimento di Fisica e Chimica della Terra (CFTA), Via Archirafi 36, 90123 Palermo, Italy

Received: 22 April 2010 – Published in Clim. Past Discuss.: 17 May 2010
Revised: 15 November 2010 – Accepted: 1 December 2010 – Published: 15 December 2010

Abstract. The Little Ice Age (LIA) is the last episode of a series of Holocene climatic anomalies. There is still little knowledge on the response of the marine environment to the pronounced cooling of the LIA and to the transition towards the 20th century global warming. Here we present decadal-scale coccolithophore data from four short cores recovered from the central Mediterranean Sea (northern Sicily Channel and Tyrrhenian Sea), which on the basis of ^{210}Pb activity span the last 200–350 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 northerly winds, together with decreased solar irradiance.

Correspondence to: A. Incarbona
(alessinc@unipa.it)

1 Introduction

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 (LIA), 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, 2009).

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

The LIA is also the last episode of a series of Holocene climatic anomalies that occurred every 1500 years and that were first recognized in the North Atlantic Ocean (Bond et al., 1997, 2001). A recent work reported these anomalies even in Holocene Mediterranean sediments (Incarbona et al., 2008a), but the youngest of these cycles, the Bond cycle B0 corresponding to the LIA, was not recovered at this studied site (Site 963), possibly because of disturbance in the recovery of sedimentary material. Indeed there is a general lack of studies dealing with the marine sedimentary record of the last centuries that may show the response of the marine environment to the pronounced cooling of the LIA and to the transition towards the twentieth century global warming.

Here we discuss the record of coccolithophores, unicellular phytoplanktonic organisms very sensitive to the past and ongoing transformation of the marine environment (Molfino and McIntyre, 1990; Westbroek et al., 1993; Beaufort et al., 1997; Flores et al., 1997; Lototskaya et al., et al., 1998; Colmenero-Hidalgo et al., 2004; Stoll et al., 2007; Fabry, 2008; Iglesias-Rodriguez et al., 2008; Langer et al., 2009). Data were collected in 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 and in a coastal site of the Tyrrhenian Sea. Collected data have several paleoenvironmental/paleoceanographic implications. We verify the occurrence of the LIA in the central Mediterranean sediments and its eventual impact on the marine environment utilizing coccolithophore ecological proxies and we aim to test if there is any signature of turnover in the coccolithophore assemblages of the last century that might be ascribed to the global warming and/or to human activity.

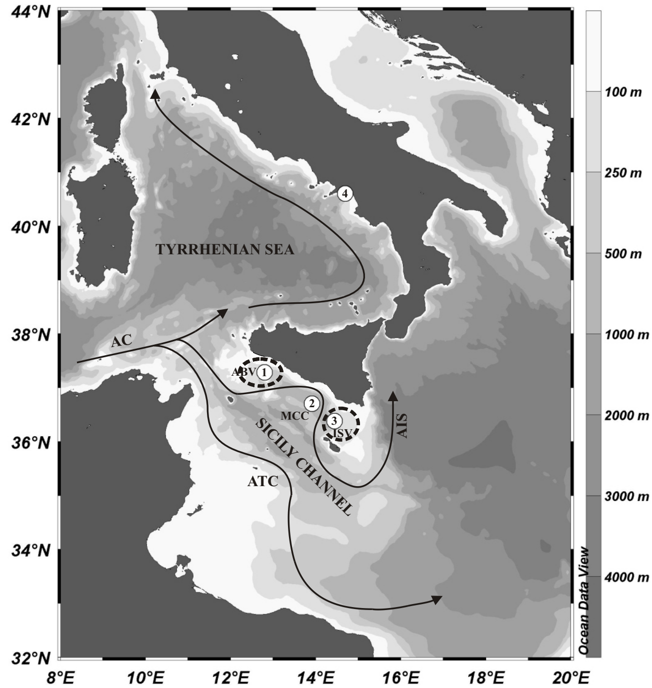

Fig. 1. Bathymetric map of the Mediterranean Sea and core locations. Surface water circulation in winter is illustrated, with major currents and semi-permanent features: AC, Algerian Current; ATC, Atlantic Tunisian Current; AIS, Atlantic Ionian Stream; ABV, Adventure Bank Vortex; MCC, Maltese Crest Channel; ISV, Ionian Shelfbreak Vortex. Circles show: (1) St 272; (2) St 342; (3) St 407; (4) C90-1M.

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 et al., 2010).

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), St 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 X magnification. Rippled smear slides were prepared following a standard procedure (Bown and Young, 1998). More than 500 specimens were counted taking into account about 20 taxonomic units, generally following the taxonomic concepts on living coccolithophores of Young et al. (2003). Taxa were grouped following Di Stefano and Incarbona (2004) and Incarbona et al. (2009): "Placoliths", are r-strategist taxa 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); "Miscellaneous group" taxa comprise those that live without any specific depth and within a wide range of ecological preferences; 'Upper photic zone' (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). Finally, *F. profunda* is the main species of the "lower photic zone" (LPZ) group. This species fluorishes in the lower photic zone and its relative abundance, evaluated versus the rest of the assemblage, is sensitive to modifications in the depth of the nutricline (Molfino and McIntyre, 1990; Beaufort et al., 1997; Flores et al., 2000).

Net Primary Production data, expressed in milligrams of carbon per square meter per day ($mg\,C \times m^{-2} \times d^{-1}$), 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 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). 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.

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 C90-1m shows an exponential decline with depth suggesting a constant sediment accumulation over the last century. 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. 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. Data indicate a mean sedimentation rate of 0.18 cm/yr. This value is 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 has been determined by the ^{210}Pb activity (Di Leonardo et al., 2006; Tranchida et al., 2010). 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 of the study area

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

The Mediterranean anti-estuarine circulation pattern is forced by the negative hydrological balance and by 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): The majority of these waters enter the Sicily Channel; the remainder flows into the Tyrrhenian Sea and follows the northern coast of Sicily (Bethoux, 1980) (Fig. 1). 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 enrichment (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, 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 and it flows out along the slope of Sardinia.

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).

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

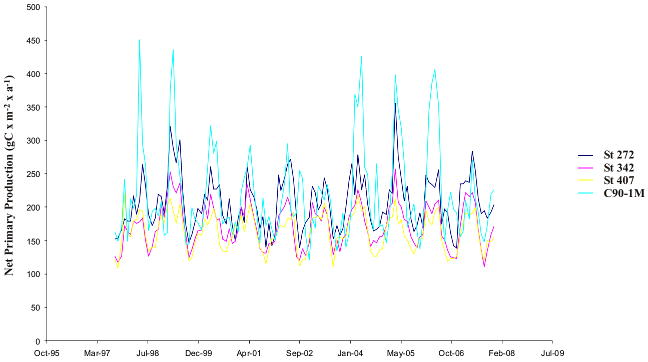

Fig. 2. Net Primary Production data, expressed in milligrams of carbon per square meter per day (mg C$\times$m$^{-2}\times$d^{-1}), calculated at core locations with an approximate resolution of about 9$\times$9 square kilometers, between September 1997 and April 2007 (http://web.science.oregonstate.edu/ocean.productivity/index.php).

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. 2). 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).

5 Results

A total of 116 samples were investigated with a mean counting of 545 specimens per sample. 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. 3–6, and demonstrates that some significant abundance changes in a few taxonomic units occurred over the last 3–4 centuries.

From the analysis it can be seen that placoliths are always dominant, with values never lower than 70% (Figs. 3–6), reflecting the proximity of the coast for all investigated sites and the relatively high productivity level. The dominant species is *E. huxleyi*, similarly 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; Bárcena et al., 2004; Colmenero-Hidalgo et al., 2004; Di Stefano and Incarbona, 2004; Incarbona et al., 2008b). This taxon shows relative abundance values of about 60–75% in the northern Sicily Channel and between about 75% and 90% in the Tyrrhenian Sea coastal site. 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 where it is an important part of the assemblages, with percentage values of about 10–20% (Figs. 3–6). All the other species account for less than 5% and are largely subordinated within the assemblages, even if they can show significant abundance variations once grouped in the Miscellaneous and UPZ group, for instance the four significant peaks in abundance of the UPZ group, at about 1810, 1875, 1910 and 1965 AD in the St 342 box-core (Fig. 4).

6 Paleoclimatic considerations and the impact of the Little Ice Age

The lowermost part of the St 342 and St 407 records show significant decreases in *F. profunda* abundance (Fig. 7), 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 increase in productivity in the Sicily Channel represents 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 drop 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 shown in the Gulf of Taranto, western part of the Ionian Sea (Versteegh et al., 2007; Taricco et al., 2009).

In Fig. 7, 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

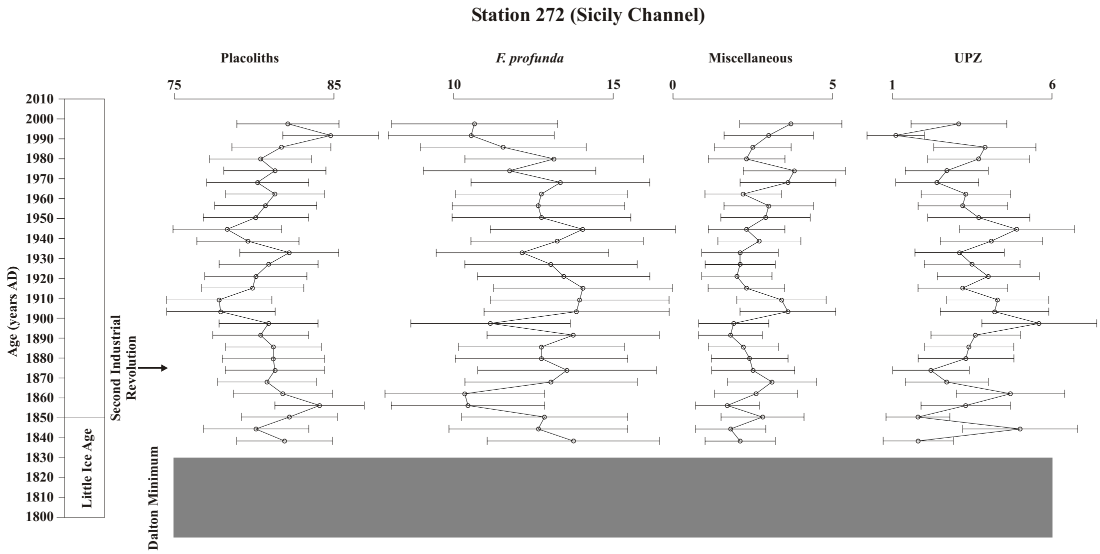

Fig. 3. Distribution patterns of calcareous nannofossil groups (percentage values) at St 272 (Sicily Channel), plotted versus age (years AD). The horizontal bars show the error associated to the countings, for a 95% of confidence level. The top of the Little Ice Age is indicated at 1850 AD, according 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.

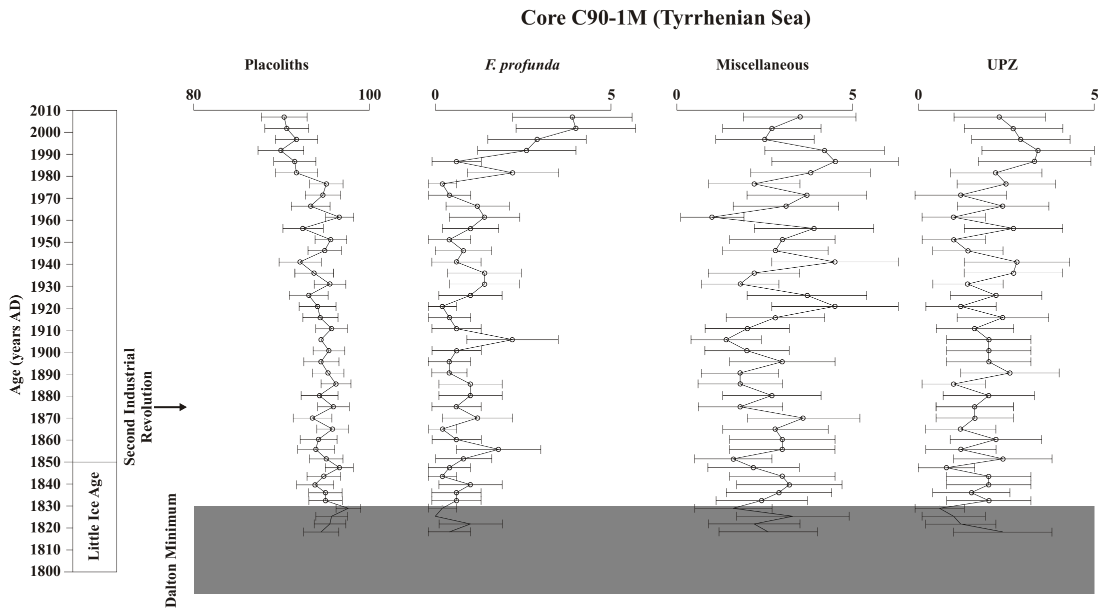

Fig. 4. Distribution patterns of calcareous nannofossil groups (percentage values) in core C90-1M (Tyrrhenian Sea), plotted versus age (years AD). The horizontal bars show the error associated to the countings, for a 95% of confidence level. The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton Minimum is also indicated by a gray band.

increasing trend and the decrease in abundance in coincidence of the Dalton Minimum (Fig. 7). 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. 8). 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

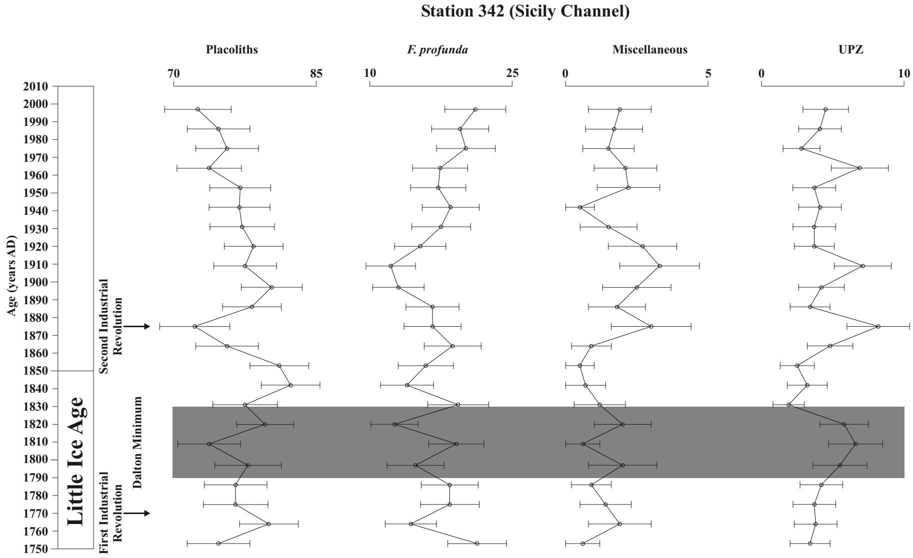

Fig. 5. Distribution patterns of calcareous nannofossil groups (percentage values) at St 342 (Sicily Channel), plotted versus age (years AD). The horizontal bars show the error associated to the countings, for a 95% of confidence level. The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton Minimum is also indicated by a gray band.

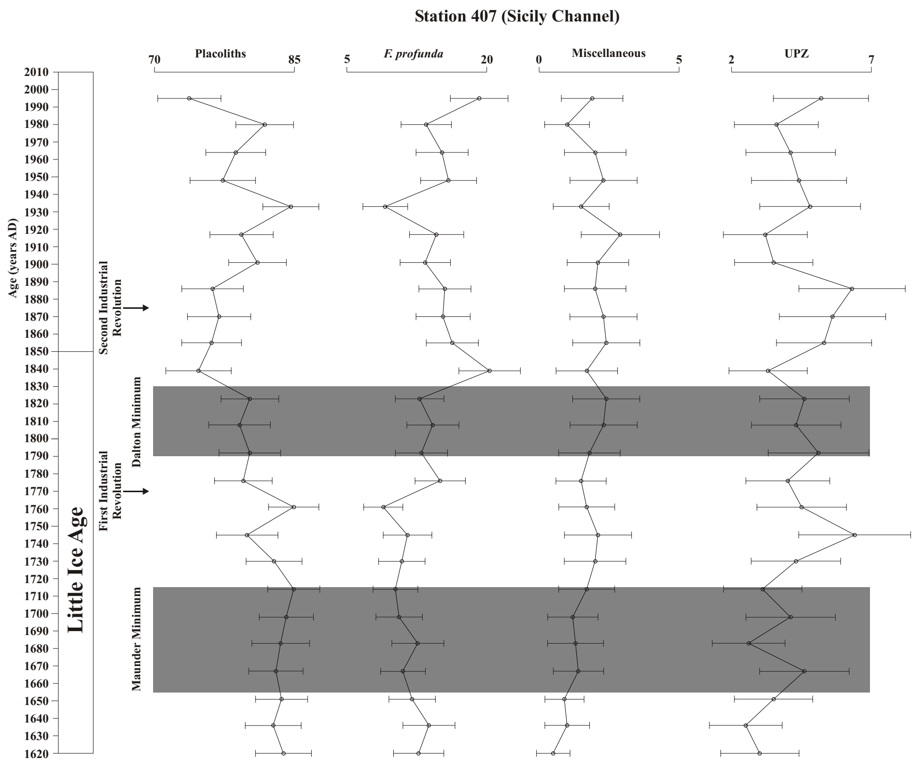

Fig. 6. Distribution patterns of calcareous nannofossil groups (percentage values) at St 407 (Sicily Channel), plotted versus age (years AD). The horizontal bars show the error associated to the countings, for a 95% of confidence level. The top of the Little Ice Age is indicated at 1850 AD, according to (Bradley, 2008; Verschuren and Charman, 2008; Wanner et al., 2008). The Dalton and Maunder Minima are both indicated by gray bands.

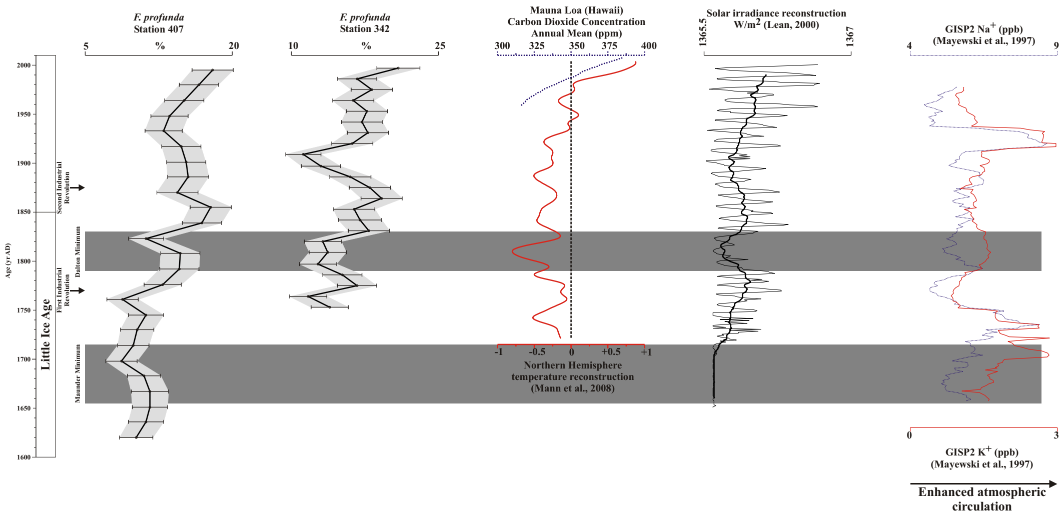

Fig. 7. Downcore variations of *F. profunda* percentage values (counted against 1000 other coccoliths); the gray shadow indicates the error for a 95% confidence level at St 407 and 342, plotted together with climatic proxy records: carbon dioxide at Mauna Loa (Hawaii, annual mean in ppm) from 1959 AD (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).

the last 4 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. 7). These intervals correspond to increased productivity in the St 407 core. The link at about 1930 AD is especially remarkable, since it can hardly be explained by other climatic forcings (Fig. 7). 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

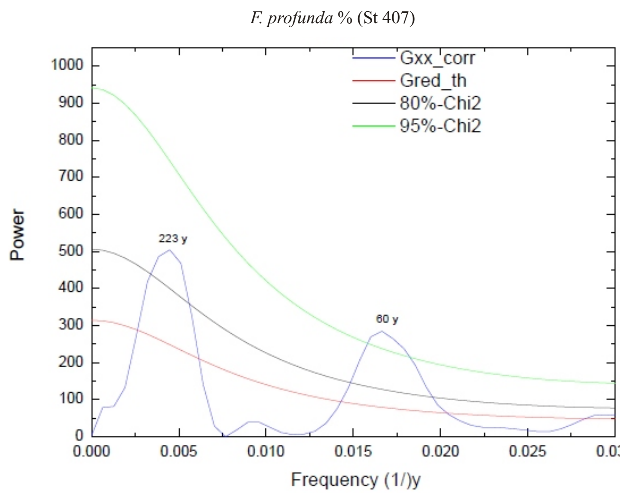

Fig. 8. Bias-corrected power spectrum (REDFIT) of the unevenly sampled *F. profunda* abundance signal at St 407. The green line and the black line respectively indicate the 95% and the 80% confidence level. The red line indicates the AR(1) theoretical red-noise spectrum.

conditions of MCC persisted at St 342, explaining the different response of the 2 sites to the climatic perturbation.

The last decades are characterised by rapid increase of greenhouse gases in the atmosphere and global surface temperature (Fig. 7). Recent studies pointed out that coccolithophore PIC production responds to rising atmospheric CO_2 (Riebesell et al., 2000; 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 coccolithophores, as a key component of the Mediterranean marine ecosystem, to these phenomena.

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, starting respectively at 1910 AD and at 1930 AD (Figs. 4, 5 and 7). This trend is also evident in the Tyrrhenian core C90-1M since about 1980 AD (Fig. 6), whereas an opposite trend supporting an increase in productivity can be deduced for St 272 (Fig. 3). We suspect 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. For instance, 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; Tranchida et al., 2010). Further investigation, especially focused in less anthropogenically-affected regions, is needed to deduce the signal of recent oceanographic-climatic transformations in the Mediterranean environment.

7 Conclusions

We carried out a comparison between decadal-scale coccolithophore data and 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 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 $\text{gC}\times\text{m}^{-2}\times\text{a}^{-1}$ 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).

Acknowledgements. We thank two anonymous referees for their valuable comments and suggestions. This work was financially supported by MIUR ex 60% grants to E. Di Stefano, by the project "Interdecadal Variability of the Mediterranean Ecosystem (MEDECOS)" (CTM2008-04365-E) supported by the MarinERA project of FP6 ERA-NET and by the project VULCOST grants to Bruno D'Argenio.

Edited by: L. Beaufort

References

Allen, J. I., Somerfield, P. J., and Siddorn, J.: Primary and bacterial production in the Mediterranean Sea: a modelling study, J. Mar. Syst., 33–34, 473–495, 2002.

Andruleit, H., Stäger, S., Rogalla, U., and Cepek, P.: Living coccolithophores in the northern Arabian Sea: ecological tolerances and environmental control, Mar. Micropaleontol., 49, 157–181, 2003.

Bárcena, M. A., Flores, J. A., Sierro, F. J., Pérez-Folgado, M., Fabres, J., Calafat, A., and Canals, M.: Planktonic response to main oceanographic changes in the Alboran Sea (Western Mediterranean) as documented in sediment traps and surface sediments, Mar. Micropaleontol., 53, 423–445, 2004.

Baumann, K.-H., Andruleit, H., Böckel, B., Geisen, M., and Kinkel, H.: The significance of extant coccolithophores as indicators of ocean water masses, surface water temperature, and paleoproductivity: a review, Paläontologische Zeitschrift, 79, 93–112, 2005.

Beaufort, L., Lancelot, Y., Camberlin, P., Cayre, O., Vincent, E., Bassinot, F., and Labeyrie, L.: Insolation Cycles as a Major Control of Equatorial Indian Ocean Primary Production, Science, 278, 1451–1454, 1997.

Behrenfeld, M. J. and Falkowski, P. G.: Photosynthetic rates derived from satellite-based chlorophyll concentration, Limnol. Oceanogr., 42, 1–20, 1997.

Béranger, K., Mortier, L., Gasparini, G.-P., Gervasio, L., Astraldi, M., and Crépon, M.: The dynamics of the Sicily Strait: a comprehensive study from observations and models, Deep-Sea Res. Pt. II, 51, 411–440, 2004.

Bethoux, J. P.: Budgets of the Mediterranean Sea. Their dependance on the local climate and on the characteristics of the Atlantic waters, Oceanol. Acta 2, 157–163, 1979.

Bethoux, J. P.: Mean water fluxes across sections in the Mediterranean Sea, evaluated on the basis of water and salt budgets and of observed salinities, Oceanol. Acta, 3, 79–88, 1980.

Boeckel, B. and Baumann, K.-H.: Distribution of coccoliths in surface sediments of the south-eastern South Atlantic Ocean: ecology, preservation and carbonate contribution, Mar. Micropaleontol., 51, 301–320, 2004.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G.: Persistent solar influence on North Atlantic climate during the Holocene, Science, 294, 2130–2136, 2001.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G.: A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates, Science, 278, 1257–1266, 1997.

Bown, P. R. and Young, J. R.: Techniques, in: Calcareous Nannofossil Biostratigraphy, edited by: Bown, P. R., Kluwer Academic Publishers, Dordrecht, Boston, London, 16–32, 1998.

Bradley, R. S.: Holocene perspectives on future climate change, in: Natural Climate Variability and Global Warming: A Holocene Perspective, edited by: Battarbee, R. W. and Binney, H. A., John Wiley & Sons, Ltd., Publication, 254–268, 2008.

Broerse, A. T. C., Ziveri, P., and Honjo, S.: Coccolithophore (-$CaCO_3$) flux in the Sea of Okhotsk: seasonality, settling and alteration processes, Mar. Chem., 39, 179–200, 2000.

Brunetti, M., Buffoni, L., Mangianti, F., Maugeri, M., and Nanni, T.: Temperature, precipitation and extreme events during the last century in Italy, Global Planet. Change, 40, 141–149, 2004.

Brunetti, M., Maugeri, M., Monti, F., and Nanni, T.: temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series, Int. J. Climatol., 26, 345–381, 2006.

Buccheri, G., Capretto, G., Di Donato, V., Esposito, P., Ferruzza, G., Pescatore, T., Russo Ermolli, E., Senatore, M. R., Sprovieri, M., Bertoldo, M., Carella, D., and Madonia, G.: A high resolution record of the last deglaciation in the southern Tyrrhenian sea: environmental and climatic evolution, Mar. Geol., 186, 447–470, 2002.

Colmenero-Hidalgo, E., Flores, J.-A., Sierro, F. J., Bárcena, M. A., Löwemark, L., Schönfeld, J., and Grimalt, J. O.: Ocean surface water response to short-term climate changes revealed by coccolithophores from the Gulf of Cadiz (NE Atlantic) and Alboran Sea (W Mediterranean), Palaeogeogr. Palaeocl., 205, 317–336, 2004.

Crispi, G., Crise, A., and Mauri, E.: A seasonal three-dimensional study of the nitrogen cycle in the Mediterranean Sea: Part II. Verification of the energy constrained trophic model, J. Mar. Syst., 20, 357–380, 1999.

De Bernardi, B., Ziveri, P., Erba, E., Thunell, R.C., 2005. Coccolithophore export production during the 1997-1998 El Niño event in Santa Barbara Basin (California). Mar. Micropaleontol. 55, 107-125.

Di Leonardo, R., Tranchida, G., Bellanca, A., Neri, R., Angelone, M., and Mazzola, S.: Mercury levels in sediments of central Mediterranean Sea: A 150-year record from box-cores recovered in the Strait of Sicily, Chemosphere, 65, 2366–2376, 2006.

Di Stefano, E. and Incarbona, A.: High resolution paleoenvironmental reconstruction of the ODP-963D Hole (Sicily Channel) during the last deglaciation, based on calcareous nannofossils, Mar. Micropaleontol., 52, 241–254, 2004.

Fabry, V. J.: Marine calcifiers in a High-CO_2 Ocean, Science, 320, 1020–1022, 2008.

Ferraro, S. and Mazzarella, A.: Solar Activity and Algal-bloom Occurrences in the Northern Adriatic Sea: Geomagnetic Connection, Theor. Appl. Climatol., 59, 129–134, 1998.

Flores, J.-A., Bárcena, M. A., and Sierro, F. J.: Ocean-surface and wind dynamics in the Atlantic Ocean off Northwest Africa during the last 140,000 years, Palaeogeogr. Palaeocl., 161, 459–478, 2000.

Flores, J.-A., Sierro, F. J., Francés, G., and Vázquez, A.: The last 100,000 years in the western Mediterranean: sea surface water and frontal dynamics as revealed by coccolithophores, Mar. Micropaleontol., 29, 351–366, 1997.

Frignani, M., Sorgente, D., Langone, L., Albertazzi, S., and Ravaglioli, M.: Behaviour of Chernobyl radiocesium in sediments of the Adriatic Sea offshore the Po River delata and the Emilia-Romagna coast, J. Environ. Radioactiv., 71, 299–312, 2004.

Frigola, J., Moreno, A., Cacho, I., Canals, M., Sierro, F.J., Flores, J.-A., Grimalt, J. O., Hodell, D. A., and Curtis, J. H.: Holocene climate variability in the western Mediterranean region from a deepwater sediment record, Paleoceanography, 22, PA2209, doi:10.1029/2006PA001307, 2007.

Gasparini, G. P., Ortona, A., Budillon, G., Astraldi, M., and Sansone, E.: The effect of the Eastern Mediterranean Transient on the hydrographic characteristics in the Strait of Sicily and in the Tyrrhenian Sea, Deep-Sea Res. Pt. I, 52, 915–935, 2005.

Goosse, H., Mann, M. E., and Renssen, H.: Climate of the past millennium: combining proxy data and model simulations, in: Natural Climate Variability and Global Warming: A Holocene Perspective, edited by: Battarbee, R. W. and Binney, H. A., John Wiley & Sons, Ltd., Publication, 163–188, 2008.

Grove, J. M.: Little Ice Ages: Ancient and Modern, Routledge, New York, 2004.

Holzhauser, H., Magny, M., and Zumbuhl, H. J.: Glacier and lake-level variations in west-central Europe over the last 3500 years, The Holocene, 15, 789–801, 2005.

Iglesias-Rodriguez, M. D., Halloran, P. R., Rickaby, R. E. M., Hall, I. R., Colmenero-Hidalgo, E., Gittins, J. R., Green, D. R. H., Tyrrell, T., Gibbs, S. J., von Dassow, P., Rehm, E., Armbrust, E. V., and Boessenkool, K. P.: Phytoplankton Calcification in a High-CO_2 World, Science, 320, 336–340, 2008.

Incarbona, A., Bonomo, S., Di Stefano, E., Zgozi, S., Essarbout, N., Talha, M., Tranchida, G., Bonanno, A., Patti, B., Placenti, F., Buscaino, G., Cuttitta, A., Basilone, G., Bahri, T., Massa, F., Censi, P., and Mazzola, S.: Calcareous nannofossil surface sediment assemblages from the Sicily Channel (central Mediterranean Sea): palaeoceanographic implications, Mar. Micropaleontol., 67, 297–309, 2008b.

Incarbona, A., Di Stefano, E., and Bonomo, S.: Calcareous nannofossil biostratigraphy of the central Mediterranean Basin during the last 430,000 years, Stratigraphy, 6, 33–44, 2009.

Incarbona, A., Di Stefano, E., Patti, B., Pelosi, N., Bonomo, S., Mazzola, S., Sprovieri, R., Tranchida, G., Zgozi, S., and Bonanno, A.: Holocene millennial-scale productivity variations in the Sicily Channel (Mediterranean Sea), Paleoceanography 23, PA3204, doi:10.1029/2007PA001581, 2008a.

Intergovernmental Oceanographic Commission, EU/IOC MEDAR/MEDATLAS II final workshop, Workshop Report IOC 155, 1–98, Paris, 1999.

Klein, P., and Coste, P.: Effects of wind stress variability on nutrient transport into the mixed layer, Deep-Sea Res., 31, 21–37, 1984.

Knappertsbusch, M.: Geographic distribution of living and Holocene coccolithophores in the Mediterranean Sea, Mar. Micropaleontol., 21, 219–247, 1993.

Krom, M. D., Brenner, N. K., Neori, A., and Gordon, L. I.: Nutrient dynamics and new production in a warm-core eddy from the Eastern Mediterranean Sea, Deep-Sea Res., 39, 467–480, 1992.

Langer, G., Nehrke, G., Probert, I., Ly, J., and Ziveri, P.: Strain-specific responses of *Emiliania huxleyi* to changing seawater carbonate chemistry, Biogeosciences, 6, 2637–2646, doi:10.5194/bg-6-2637-2009, 2009.

Lean, J.: Evolution of the Sun's Spectral Irradiance Since the Maunder Minimum, Geophys. Res. Lett., 27, 2425–2428, 2000.

Lermusiaux, P. F. J. and Robinson, A. R.: Features of dominant mesoscale variability, circulation patterns and dynamics in the Strait of Sicily, Deep-Sea Res. Pt. I 48, 1953–1997, 2001.

López Otálvaro, G.-E., Flores, J.-A., Sierro, F. J., and Cacho, I.: Variation in coccolithophorid productionin the Eastern Equatorial Pacific at ODP Site 1240 over the last seven glacial-interglacial cycles, Mar. Micropaleontol., 69, 52–69, 2008.

Lototskaya, A., Ziveri, P., Ganssen, G. M., and van Hinte, J. E.: Calcareous nannoflora response to Termination II at 45° N, 25° W (northeast Atlantic), Mar. Micropaleontol., 32, 47–70, 1998.

Malanotte-Rizzoli P. and Hecht, A.: Large-scale properties of the Eastern Mediterranean: A review., Oceanol. Acta, 11, 323–335, 1988.

Malinverno, E., Ziveri, P., and Corselli, C.: Coccolithophorid distribution in the Ionian Sea and its relationship to eastern Mediterranean circulation during late fall to early winter 1997, J. Geophys. Res., 108, doi:10.1029/2002JC001346, 2003.

Mann, M. E., Zhang, Z., Hughes, M. K., Bradley, R. S., Miller, S. K., and Rutherford, S.: proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia, P. Natl. A. Sci. India A., 105, 13252–13257, 2008.

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F.: Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly, Science, 326, 1256–1260, 2009.

Matthews, J. A. and Briffa, K. R.: The "Little Ice Age": re-evaluation of an evolving concept, Geografiska Annaler, 87 A, 17–36, 2005.

Mayewski, P. A., Meeker, L. D., Twickler, M. S., Whitlow, S., Yang, Q., Lyons, W. B., and Prentice, M.: Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year long glaciochemical series, J. Geophys. Res., 102, 26345–26366, 1997.

Mayewski, P. A., Rohling, E. J., Stager, J. C., Karlén, W., Maasch, K. A., Meeker, L. D., Meyerson, E. A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Straubwasser, M., Schneider, R. R., and Steig, E. J.: Holocene climate variability, Quat. Res., 62, 243–255, 2004.

Millot, C.: Circulation in the Western Mediterranean Sea, Oceanol. Acta, 10, 143–149, 1987.

Molfino, B. and McIntyre, A.: Nutricline variations in the equatorial Atlantic coincident with the Younger Dryas, Paleoceanography, 5, 997–1008, 1990.

Okada, H. and McIntyre, A.: Seasonal distribution of modern coccolithophores in the western North Atlantic Ocean, Marine Biology, 54, 319–328, 1979.

Onken, R., Robinson, A. R., Lermusiaux, P. F. J., Haley Jr, P. J., and Anderson, L. A.: Data-driven simulations of synoptic circulation and transports in the Tunisia-Sardinia-Sicily region, J. Geophys. Res., 108, 8123–8136, 2003.

Ovchinnikov, I. M.: The formation of Intermediate Water in the Mediterranean, Oceanology, 24, 168–173, 1984.

Riebesell, U., Zondervan, I., Rost, B., Tortell, P. D., Zeebe, R. E., Morel, F. M. M.: Reduced calcification of marine plankton in response to increased atmospheric CO_2, Nature, 407, 364–366, 2000.

Robinson, A. R. and Golnaraghi, M.: The physical and dynamical oceanography of the Mediterranean, in: Ocean Processes in Climate Dynamics: Global and Mediterranean Examples, edited by: Malanotte-Rizzoli, P. and Robinson, A. R., Kluwer Academic Publishers, The Netherlands, 255–306, 1994.

Robinson, A. R., Sellschopp, J., Warn-Varnas, A., Leslie, W. G., Lozano, C. J., Haley Jr, P. J., Anderson, L. A., and Lermusiaux, P. F. J.: The Atlantic Ionian Stream, J. Mar. Syst., 20, 129–156, 1999.

Rohling, E. J., Sprovieri, M., Cane, T., Casford, J. S. L., Cooke, S., Bouloubassi, I., Emeis, K. C., Schiebel, R., Rogerson, M., Hayes, A., Jorissen, F. J., and Kroon, D.: Reconstructing past planktic foraminiferal habitats using stable isotope data: a case history for Mediterranean sapropel S5, Mar. Micropaleontol., 50, 89–123, 2004.

Roth, P. H. and Coulbourn, W. T.: Floral and solution patterns of coccoliths in surface sediments of the North Pacific, Mar. Micropaleontol., 7, 1–52, 1982.

Sarmiento, J., Herbert, T., and Toggweiler, J. R.: Mediterranean nutrient balance and episodes of anoxia, Global Biogeochem. Cy., 2, 427–444, 1988.

Silenzi, S., Antonioli, F., and Chemello, R.: A new marker for sea surface temperature trend during the last centuries in temperate areas: Vermetid Reef, Global Planet, Change, 40, 105–114, 2004.

Stoll, H. M., Shimizu, N., Archer, D., and Ziveri, P.: Coccolithophore Productivity Response to Greenhouse Event of the Paleocene-Eocene Thermal Maximum, Earth Planet. Sci. Lett., 258, 192–206, 2007.

Takahashi, K. and Okada, H.: Environmental control on the biogeography of modern coccolithophores in the southeastern Indian Ocean offshore of Western Australia, Mar. Micropaleontol., 39, 73–86, 2000.

Taricco, C., Ghil, M., Alessio, S., and Vivaldo, G.: Two millennia of climate variability in the Central Mediterranean, Climate of the Past, 5, 171–181, 2009.

Tranchida, G., Bellanca, A., Angelone, M., Bonanno, A., Langone, L., Mazzola, S., Neri, R., and Patti, B.: Chronological records of metal deposition in sediments from the Strait of Sicily, central Mediterranean: Assessing natural fluxes and anthropogenic alteration, J. Marine Syst., 79, 157–172, 2010.

Vallefuoco, M.: Planktonic foraminiferal events and climatic variability in sediment of Southern Tyrrhenian Sea during the last 80 kyr. PhD Thesis, Università degli Studi di Napoli "Federico II", Italy, 1–262, 2008.

Velasco, V. M. and Mendoza, B.: Assessing the relationship between solar activity and some large scale climatic phenomena, Adv. Space Res., 42, 866–878, 2008.

Verschuren, D. and Charman, D. J.: Latitudinal linkages in late Holocene moisture-balance variation, in: Natural Climate Variability and Global Warming: A Holocene Perspective, edited by: Battarbee, R. W. and Binney, H. A., John Wiley & Sons, Ltd., Publication, 189–231, 2008.

Versteegh, G. J. M., de Leeuw, J. M., Taricco, C., and Romero, A.: temperature and productivity influences on Uk37 and their possible relation to solar forcing of the Mediterranean winter, Geochem. Geophys. Geosyst., 8, Q09005, doi:10.1029/2006GC001543, 2007.

Wanner, H., Beer, J., Bütikofer, J., Crowley, T. J., Cubasch, U., Flückiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J. O., Küttel, M., Müller, S. A., Prentice, I. C., Solomina, O., Stocker, T. F., Tarasov, P., Wagner, M., and Widmann, M.: Mid- to Late Holocene climate change: an overview, Quat. Sci. Rev., 27, 1791–1828, 2008.

Westbroek, P., Brown, C. W., van Bleijswijk, J., Brownlee, C., Brummer, G. J., Conte, M., Egge, J., Fernandez, E., Jordan, R., Knappertsbusch, M., Stefels, J., Veldhuis, M., Wal, P., and van der Young, J.: A model system approach to biological climate forcing, The example of Emiliania huxleyi, Global Planet. Change, 8, 27–46, 1993.

Wright, H. E., Kutzbach, J. E., Webb III, T., Ruddiman, W. F., Street-Perrot, E. A., and Bartlein, P. J.: Global Climates Since the Last Glacial Maximum, University of Minnesota Press, Minneapolis, 1993.

Yoshimura, H.: The solar-cycle period-amplitude relation as evidence of hystheresis of the solar-cycle nonlinear magnetic oscillation and the long term 55 year cyclic modulation, Astrophys. J., 227, 1047–1058, 1979.

Young, J. R.: Functions of coccoliths, in: Coccolithophores, edited by: Winter, A. and Siesser, W. G., Cambridge University Press, Cambridge, 63–82, 1994.

Young, J. R., Geisen, M., Cros, L., Kleijne, A., Sprengel, C., Probert, I., and Østergaard, J. B.: A guide to extant coccolithophore taxonomy, Journal of Nannoplankton Research Special Issue, 1, 1–121, 2003.

Ziveri, P., Rutten, A., de Lange, G. J., Thomson, J., and Corselli, C.: Present-day coccolith fluxes recorded in central eastern Mediterranean sediment traps and surface sediments, Palaeogeogr. Palaeocl., 158, 175–195, 2000.