Subdecadal paleoceanographic and paleoclimatic reconstructions of Late Holocene oceanographic conditions of the Eastern Mediterranean based on organic walled dinoflagellate cysts

Dissertation zur Erlangung des Doktorgrades der Naturwissenschaften
(Dr. rer. Nat) am Fachbereich Geowissenschaften
der Universität Bremen

Vorgelegt von

Liang Chen

Bremen, November, 2011

Gutachter:

PD Dr. Karin Zonneveld

Prof. Dr. Gesine Mollenhauer

Chen, Liang 08.11.2011

Department of Geosciences, Universität Bremen, Klagenfurter Strasse, D-28359 Bremen, Germany

-Erklärung-

Hiermit versichere ich, daß ich

1. die Arbeit ohne unerlaubte fremde Hilfe angefertigt habe,
2. keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt habe und
3. die den benutzten Werken wörttlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

Bremen, den 08.11.2011
Liang Chen

Acknowledgements

I am glad to have this opportunity to thank many people that helped me along during past few years. First of all, I would like to sincerely thank my supervisor PD Dr. Karin Zonneveld for giving me the opportunity to work with my PhD project in the attractive dinoflagellate world. I am deeply indebted to all her help no matter with lab work, presentation or scientific writing. She is always there whenever I need help. The thesis cannot be accomplished without her generous support and guidance. I also would like to express my gratitude to Prof. Dr. Gesine Mollenhauer for being the second reviewer of the thesis.

This project was funded by DFG and ESF/EuroMarc MOCCHA project “Multidisciplinary study of continental/ocean climate dynamics using high-resolution records from the eastern Mediterranean”. I thank DFG/ESF for offering the funding for my participation in several international conferences. I also thank IMAGES for financing my attendance in ICP10.

I appreciate Dr. Gerard Versteegh for your constructive comments and helpful suggestions throughout my PhD period. I enjoyed the time we travel to the conferences and the field excursion in the fascinating Adriatic seaside, your broad knowledge and accurate scientific work are always my goals. Other MOCCHA members: Marie-Louise Goudeau, Brice Robert, Prof. Gert de Lange (Utrecht Univ.), Anna-Lena Grauel and Prof. Stefano Bernasconi (ETH-Z), Arne Leider (Marum) are greatly thanked for subsampling and sharing of samples, dating of the piston cores, organization of cruises and group discussions, sharing of helpful papers, encouragement to my PhD and critical comments to my manuscripts all the time during the past three years. I also would like to thank Daniela Pittaurova and Dr. Helmut Fischer (IUP-Bremen) for dating of the multicore by measuring ^{210}Pb and ^{137}Cs.

I would like to express my gratitude to all the members from the Division of Historical Geology and Paleontology for different kind of help and being supportive during my PhD time in Bremen. Prof. Dr. Helmut Willems and Maria Petrogiannis are thanked for the kind logistical and administrative help. I warmly thank my officemate Sonja and Katarzyna for a lot of help with German sundries and interesting talks in life and science, which made me feel easy when I started my life in Germany. Qinghai and Xiaoxia are thanked for all the support and help in both work and life, you know talking in Chinese in the office really helped me feel homelike and free. Katarzyna, Uli, Stefanie, Kara, Sonja, Rehab, Marion, Dorothee, Sally, Vanessa, Ilham, Stijn, Ines, Catalina, Monika are thanked for the encouragement, support and useful comments and tips to my PhD all the time. Uli is again thanked for the help with German translating of the summary part of the thesis. I appreciate Kara for the help with correcting my English of parts of the thesis within limited time. Mirja is thanked for all the

support and encouragement to my PhD from the very beginning of my project and kind help with the German paperwork. Oliver is acknowledged for explaining with the transfer functions. Gabi, Monika, Anne, Sally and Christiane are thanked for laboratorial assistance. I also thank Petra for solving computer problems. Caroline Clotten, Malin Holler and Mirja Hoins are acknowledged for processing samples. Largely thanks go to Karin and Gerard for inviting me and my family members to your lovely house for several times.

I thank Inigo for many clever ideas, translating German and all the support to my PhD work. I thank Jan-Peter for your concern of my PhD throughout last three years and offering me job information. I appreciate my Chinese friends Ding Feng, Wang Li, Liwei, Xiaolei, Binghai and many many others from Bremen for all your care and friendship during past years, you let me feel not lonely. I have benefited a lot from the help and discussions with Dr. Xiang Rong, Dr. Li Gang and Dr. Luo Hui during the time when they visited Bremen. They shared me with scientific experience and knowledge that really inspired me, I appreciate that.

Most importantly, I am deeply grateful to my parents in China and my wife Jie for your endless love, patience, trust and understanding that always allows me to do whatever I want.

Table of contents

Summary

The recent abrupt rise in global temperature within the last century has resulted in major concerns about future climate change. Although it is obvious that natural processes influence climate, anthropogenic activities steer climate as well. This has resulted in intense discussions in the academic community and general society about what extent these natural processes might be responsible for the present change of climate. Unfortunately, the characteristics and influence of natural forcing mechanisms are far from clear.

One way to improve our understanding of climate mechanisms is to compare climatic and environmental change prior to human induced increases in greenhouse gasses with those of the last 150 years. For this, long, continuous, well dated, and high temporal resolution records have to be studied, which cover both pre-industrial and industrial climate change. To date, such records are extremely rare; however, unique sediment cores have recently been recovered from the Golfo di Taranto (Eastern Mediterranean) that fulfil these requirements. This thesis reports the results of marine palynological investigations on these sediments, notably of the dinoflagellate cyst content. Dinoflagellate cyst associations are very useful for reconstructing changes in marine environments, especially in coastal regions.

Since every region of the world has a unique dinoflagellate cyst association, detailed information about the relationship of modern day cyst associations and environment is a prerequisite for the establishment of adequate reconstructions. This thesis therefore first reports the outcome of a study on 48 surface samples from the middle and distal part of the Po river discharge plume area. The relationship between dinoflagellate species and environmental parameters, such as sea surface temperature and nutrient availability, were established. Based on multivariate analysis, four dinoflagellate associations can be distinguished that are characteristic for the major oceanographic settings in the region: (association 1) river discharge, (association 2) warm water, (association 3) oxygenated bottom water group and (association 4) Golfo di Taranto group. Establishing such relationships allow us to carry out high resolution climatic and oceanographic reconstructions in the study area.

In the following chapters, the strongly fluctuating environmental and climatic variations of the region are reconstructed for three selected time intervals using organic walled dinoflagellate cysts. In chapter 5, detailed information about the trophic history and climatic history of the region during the last 200 and 400 years, respectively, are reported. As some dinoflagellate cyst species react sensitively to anthropogenic eutrophication while other species react more strongly to naturally induced changes in the trophic state of the upper water column, we were able to document a clear separation between natural and anthropogenic effects. Anthropogenic eutrophication is reported as early as 1880 AD. Rapid fluctuations of sea surface temperatures and precipitation are reconstructed through the use of dinoflagellate associations and freshwater algal species. The cyclical nature of these variations are suggested to be influenced by natural climate forcing mechanisms, such as the North Atlantic Oscillation (NAO) and solar activity. Chapter 6 documents changes in the climatic history of the region between 990 and 1200 AD (Medieval Climate Anomaly). The reconstructed sea surface temperatures (SST) are suggested to be lower in the Medieval Period compared to that of today. Low river discharge/precipitation is shown for the Adriatic area during this period, and is synchronous to widespread drought events in other subtropical regions. It is also suggested that the climate is influenced by NAO and ENSO related large-scale ocean-atmosphere circulation shifts during the Medieval Period. Furthermore, we document that volcanic eruptions might have influenced the local climate and upper water nutrient conditions during the studied period. In chapter 7, the short-term climatic and oceanographic variability in the southern Italian region during the “Roman Classical Period” (60 BC - AD 200) were investigated based on dinoflagellate cyst records. Results indicate that the trophic state of the upper water column is closely linked to the variations of river discharge, which, in turn, is strongly related to precipitation in Italy. Predominant cycles of around 7-8 and 11 years are possibly related to variations in the NAO climate mode and solar activity. Apart from the cyclic climate variability, a good correlation between non-cyclic temperature decreases and global volcanic activity are observed, which indicates that the latter forms an additional major forcing factor for the southern Italian climate.

The thesis presents detailed high temporal resolution information about the climate and oceanographic history of three different time intervals over the last 2000 years. It provides a basis for solving the question as to what extent natural versus anthropogenic factors influence the environmental and climate change in the study region. The good match between dinoflagellate cyst based reconstructions and those from other proxy records, as well as environmental and climate information derived from historical sources, demonstrates that dinoflagellate cysts can be very useful and reliable indicators for past environmental and climate change on high temporal resolution that forms a prerequisite to obtain insight into the forcing mechanisms of the present day global temperature rise.

Zusammenfassung

Der abrupte Anstieg der globalen Temperatur innerhalb des letzten Jahrzehnts hat zu großer Besorgnis in Bezug auf zukünftigen Klimawandel geführt. Obwohl es offensichtlich ist, dass anthropogene Aktivitäten diesen Wandel beeinflussen, steuern auch natürliche Prozesse das Klima. Dies hat zu intensiven Diskussionen sowohl in der akademischen Gemeinschaft als auch in der Gesellschaft geführt, in denen es darum geht, zu welchem Anteil die natürlichen Prozesse zum derzeitigen Klimawandel beitragen. Leider sind bis heute Charakter und Tragweite der natürlichen Einflussmechanismen alles andere als geklärt.

Eine Möglichkeit, unser Verständnis der Klima-Mechanismen zu verbessern, ist die Veränderungen von Klima und Umwelt vor dem menschlich verursachten Anstieg von Treibhausgasen mit denen der letzten 150 Jahre zu vergleichen. Hierfür müssen lange, kontinuierliche, gut datierte Datensätze in hoher zeitlicher Auflösung untersucht werden, die sowohl den vorindustriellen als auch den industriellen Klimawandel abdecken. Solche Quellen sind sehr selten, jedoch wurden kürzlich einzigartige Sedimentkerne aus dem Golf von Taranto (östliches Mittelmeer) gewonnen.

Diese Doktorarbeit präsentiert die Ergebnisse von marinen palynologischen Untersuchungen an diesen Sedimenten vor allem auf den Gehalt an Dinoflagellatenzysten. Dinoflagellatenzysten-Gemeinschaften sind sehr hilfreich um die Veränderungen in der Vergangenheit im marinen Bereich zu rekonstruieren, vor allem in Küstenregionen. Da jedoch jede Region auf der Welt ihre einzigartige Artengemeinschaft aufweist, sind detaillierte Informationen über die Beziehung der heutigen Zysten-Gemeinschaft zu den Umweltbedingungen eine Grundvoraussetzung für entsprechende Rekonstruktionen.

Diese Dissertation zeigt daher die Ergebnisse vom mittleren und äußeren Teil der Flussablauffahne der Po-Mündung. Die Beziehungen zwischen den Dinoflagellaten-Arten und den Umweltparametern wie Oberflächen-Temperatur oder Nährstoffgehalt wurden charakterisiert. Basierend auf Multivariater Analyse wurden vier verschiedene Dinoflagellaten-Gemeinschaften identifiziert, die charakteristisch für die wichtigsten ozeanographischen Gegebenheiten in der Region sind: (Assoziation 1) Flusseintrag, (Assoziation 2) Warmwasser, (Assoziation 3) sauerstoffreiches Bodenwasser und (Assoziation 4) Golf von Taranto. Die Identifizierung dieser Beziehungen ermöglicht es uns, hochauflösende paläoklimatische und paleozeanographische Rekonstruktionen durchzuführen.

In den folgenden Kapiteln wurden mit Hilfe organisch-wandiger Dinoflagellatenzysten die Schwankungen der Umweltbedingungen und klimatischen Bedingungen während dreier ausgewählter Zeitintervalle rekonstruiert. In Kapitel 5 werden detaillierte Informationen über

den vergangenen Nährstoffeintrag und die klimatische Geschichte der Region innerhalb der letzten 200 bzw. 400 Jahren vermittelt. Da einige Dinoflagellatenzysten-Arten sehr empfindlich auf anthropogen induzierte Eutrophierung und andere Arten auf natürliche Schwankungen des Nährstoffgehalts in der oberen Wassersäule reagieren, sind wir in der Lage, eine klare Trennung zwischen natürlichen und anthropogenen Effekten zu vollziehen.

Anthropogen verursachte Eutrophierung wird bereits im Jahr 1880 dokumentiert. Schnelle Fluktuationen von Oberflächenwassertemperatur und Niederschlägen wurden mit Hilfe von Dinoflagellatengemeinschaften und Süßwasser-Arten rekonstruiert. Der zyklische Charakter dieser Schwankungen lässt vermuten, dass sie durch natürliche das Klima beeinflussende Mechanismen wie beispielsweise Nordatlantischer Oszillation (NAO) und Sonnenaktivität hervorgerufen wurden. Kapitel 6 dokumentiert die Klimageschichte in der Region zwischen 990 und 1200 n. Chr. (Mittelalterliche Klimaanomalie). Die rekonstruierte Meeresoberflächentemperatur für das Mittelalter scheint im Vergleich zu heute niedriger zu sein. Während dieser Zeit wurden in der Adriatischen Region geringerer Fluss-Ablauf sowie geringere Niederschläger festgestellt, was synchron zu verbreiteten Trockenereignissen in anderen subtropischen Regionen ist. Es wird vermutet, dass das Klima durch großskalige Verschiebungen in der Ozean-Atmosphären-Zirkulation im Zusammenhang mit NAO und ENSO beeinflusst wurde. Außerdem haben im untersuchten Zeitintervall möglicherweise auch Vulkanausbrüche sowohl lokal das Klima als auch den Nährstoffgehalt in der oberen Wassersäule beeinflusst. In Kapitel 7 wurde die kurzskalige klimatische und ozeanographische Variabilität in Süditalien während der Klassischen Römischen Zeit (60 v. Chr. - 200 n. Chr.) basierend auf Dinoflagellatendaten untersucht. Die Ergebnisse weisen darauf hin dass die Nährstoffbedingungen in der oberen Wassersäule eng mit den Schwankungen des Fluß-Ablaufs verbunden ist, der seinerseits stark mit den Niederschlägen in Italien zusammenhängt. Die vorherrschenden Zyklen von etwa 7-8 und 11 Jahren hängen vermutlich mit Variationen von NAO und Sonnenaktivität zusammen. Abgesehen von der zyklischen Klimavariabilität kann eine gute Korrelation zwischen nicht-zyklischen Temperaturminima und globaler vulkanischer Aktivität beobachtet werden. Dies weist darauf hin, dass letztere einen zusätzlichen wichtigen Faktor darstellt, der das süditalienische Klima beeinflusst.

Die Dissertation präsentiert ein detailliertes und hochauflösendes Abbild dreier verschiedener Zeitintervalle während der vergangenen 2000 Jahre. Dies stellt eine Möglichkeit dar, zu testen wie natürliche Faktoren im Verhältnis zu anthropogenen Faktoren zu Umweltveränderungen in einem bestimmten Gebiet beitragen. Die gute Entsprechung zwischen den auf Dinozysten basierten Rekonstruktionen und anderen Proxydaten bestätigt dass Dinozysten als zuverlässige Indikatoren verwendet werden können um Umweltveränderungen im östlichen Mittelmeer zu rekonstruieren.

1. Introduction

1. 1 Motivation and Objectives

The climate system is composed of complex interactions between atmosphere, hydrosphere and lithosphere. The global climate has been changing all the time throughout the earth history which has had significant influences to our daily life (Budyko, 1974). Interestingly, the occurrent global warming that was suggested to be caused by enhanced anthropogenic greenhouse gases has been increasingly accepted by scientists and public media (IPCC, 2007) (Fig 1). As a consequence, extensive discussions on how global warming can influence the individual components of our earth system have been carried out (e.g. Held and Soden, 2006; Kushner et al., 2001; Schiermeier, 2011). A new geological name "Anthropocene" was hence raised due to human's tremendous contribution on changing of earth environment since latter part of the 18th century (Crutzen and Stoermer, 2000). Although plentiful achievements have already been made with respect to climate changes and their potential influences, there are two crucial questions however need to be addressed explicitly. First, what roles have natural forcings for instance solar activities played during the 20th century global warming? Second, whether the current temperature increasing is unprecedented in the context of long term climate variability?

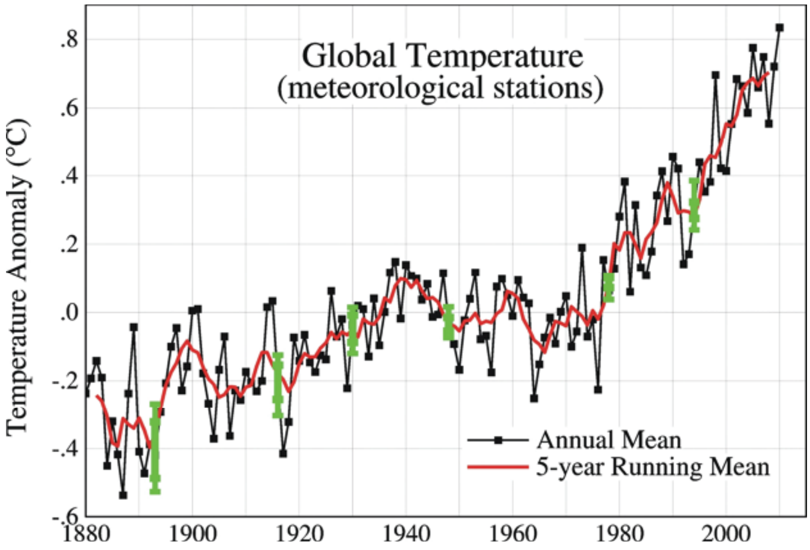


Fig 1. Global annual mean surface air temperature change. (From http://data.giss.nasa.gov)

The difficulties to answer these two questions are due to our poor understanding of the exact magnitude and effects of natural climate forcing mechanisms. Therefore there is an urgent need to collect more information on past climatic changes which can lead to more insight into the mechanisms that might cause these changes. One way to obtain this information is to study the high resolution environment change prior to the human induced increase in greenhouse gasses within those of the last 200 years, there are several special time periods during which climatic conditions were suggested to be as warm as or even warmer than the amplitude that recent global warming reached, for example Medieval Warm Period (800-1200 AD), Roman Warm Period (100 BC-200 AD) and Mid-Holocene Warm Period (6 ka BP). Studies on these time periods could provide us with straightforwardly opportunities to pinpoint how warm the recent global warming was in the Holocene history, and how local climate could be influenced by natural/anthropogenic activities.

1. 2 Research context and outline

For reconstructing the high fidelity of past climatic and environmental change in the Gulf of Taranto area by organic walled dinoflagellate cysts, we firstly need to investigate how different dinoflagellate species are distributed with the different environmental settings, for instance sea surface temperature, salinity and so on. In the **Manuscript 1** (Chapter 4), the relationship between region specific dinoflagellate cyst distribution in the Po river discharge area and oceanic environmental conditions have been studied based on surface sediments from 48 sites in the middle and distal part of the discharge plume area. Establishing such a relationship allows the reconstructions of the eutrophication history as well as the climatic and oceanographic variability in the study area. Therefore, in **Manuscript 2** (Chapter 5), human induced eutrophication has been reconstructed in the Southern Adriatic area during the last 200 years that based on the accumulation rates of the autotrophic dinoflagellate species *L. machaerophorum*, besides the high resolution of past temperature and precipitation changes are reconstructed during the last 400 years by dinoflagellate and algae species, the climate forcing mechanisms are discussed to separate the natural versus anthropogenic influences on recent climate change. Furthermore, for determining how warm the recent climate warming was in the preindustrial period or if there were time intervals during which climate conditions might have been similar with that of today, two representative candidates of the warm periods have been studied with respect to their temperature, marine nutrient availability and local river discharge and precipitation change, they are in **Manuscript 3** (Chapter 6) the Medieval Classical Period which was happened in around 1000 AD, and in **Manuscript 4** (Chapter 7) the Roman Classical Period that can be dated back to approximately 2000 years ago, the potential natural forcing factors which might cause the climatic and oceanographic changes during these times for instance the solar activity, volcanism are also discussed.

1. 3 Climate variability in Eastern Mediterranean during the past two millennia

The Mediterranean is an ideal location for paleoclimate study since it is located between low and mid-latitudes and shows highly sensitivity to both monsoonal and North Atlantic climate systems. Considerable studies have been carried out in Mediterranean regions with the purpose of reconstructing past climatic and oceanographic changes cover last 2000 years that were based on instrumental, documentary and natural proxy records during last decades. Instrumental records provide high quality and relatively long and continuous information on meteorological parameters such as temperatures, pressures and humidity in Italian and Spanish Mediterranean regions during the last 500 years (e.g. Camuffo, 1984; Camuffo, 2002; Maugeri et al., 1998; Maugeri et al., 2004); documentary evidence registers irregular information on historical disasters like flood and drought that can be dated back as early as 5th century BC, although these records usually are not consecutive, they form another useful tool to learn past climate conditions when instrumental records were not available (Camuffo, 1987; Camuffo and Enzi, 1995; Dominguez-Castro et al., 2010; Llasat et al., 2005; Pfister et al., 1999 and references therein). In eastern Mediterranean area, paleoclimate and paleoceanography data were largely increased based on natural proxy methods during the last decades, such as tree rings (Galli et al., 1994; Touchan et al., 2005), speleothems (BarMatthews et al., 1997; Frisia et al., 2005; Orland et al., 2008), corals (Felis et al., 2004; Rimbu et al., 2006) and marine sediments (e.g. Sangiorgi et al., 2003; Taricco et al., 2009). However, the resolutions of most of these studies are not sufficient to inspect the highly fluctuated climate variability within the time interval of the last 2000 years.

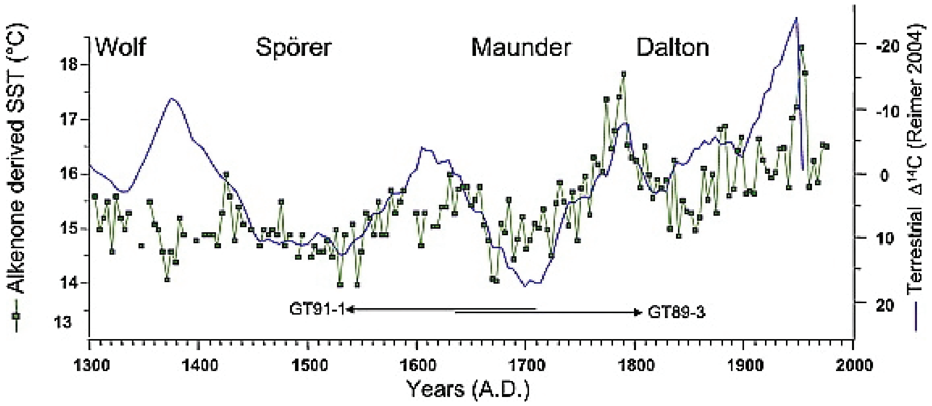


Figure 2. Alkenone derived SST and comparison with atmospheric $\Delta^{14}C$ since 1300 AD. From Versteegh et al. (2007).

One of the noticeable and intriguing issues is that there is an increasing number of studies that are devoted to improve our understanding on how natural forcings for examples solar activities can be associated with the climate changes in Mediterranean area on centennial-millennial scales. For example, based on the information of carbonate content (Castagnoli et al., 1992a; Castagnoli et al., 1992b) and stable isotopes of planktic foraminifera from marine sediments (e.g. Castagnoli et al., 1999; Taricco et al., 2009), the Torino cosmogeophysics group have built clear connections between solar activities and climate in Gulf of Taranto area for more than 20 years. Versteegh et al (2007) has also shown that sea surface temperatures (SST) in the same study area are driven by solar forcing on centennial scale before grand anthropogenic interference (Fig 2). Besides, in the Po basin (Northern Italy), the relationship between North Atlantic Oscillation (NAO) and Po river discharge is suggested to be related to the solar activities (Landscheidt, 2000; Zanchettin et al., 2008).

1. 4 Dinoflagellates

1. 4. 1 Dinoflagellates and their life cycle

Dinoflagellates are primarily unicellular eukaryotic organisms with two distinctive flagella and a characteristic nucleus (Fensome et al., 1993). There are approximately 2000 known dinoflagellate species (~90%) living in various aquatic environment, from lakes to oceans and from equator to polar regions. Together with diatoms and coccolithophorids, dinoflagellates constitute the majority of the marine eukaryotic phytoplankton (e.g. Parsons et al., 1984). They have different feeding strategies, for example autotrophic, heterotrophic, mixotrophic, symbiotic and parasitic among which about half are autotrophic (Schnepf and Elbrachter, 1992). About 10-20 % of the species produce cyst that are highly resistant to dissolution and thus can be well preserved in the sediments (Dale, 1976). The size of organic walled dinoflagellate cysts also called dinocysts usually range from 15 µm to 150 µm. Although dinoflagellates dwell in wide range of environment conditions, fossil dinoflagellate cysts show particularly high abundance in continental margins (Stover et al., 1996).

Dinoflagellates have a complex life cycle that involves many different stages including sexual and asexual, motile and non-motile period (Fig 3). It is suggested that the majority of dinocysts are produced during the sexual stage (Taylor, 1987). During the sexual life cycle, dinoflagellates produce gametes which fuse to produce zygotic resting cysts called hypnozygotes. They form the resting cyst during which the normal life is greatly reduced, the hypnozygotes can be protected by a thick wall which is composed of highly resistant organic materials called dinosporin, and the material is very resistant to adverse conditions and thus can be well preserved in the sediments (Kokinos et al., 1998; Wall and Dale, 1967). The obligate dormancy period is highly variable that could vary from 12 hours to several months (Pfiester and Anderson, 1987). After this dormancy period, the protoplast emerges through an aperture called archeopyle. There are many environmental factors for example light, temperature, nutrient and endogenous rhythms which can trigger the excystment (Dale, 1983).

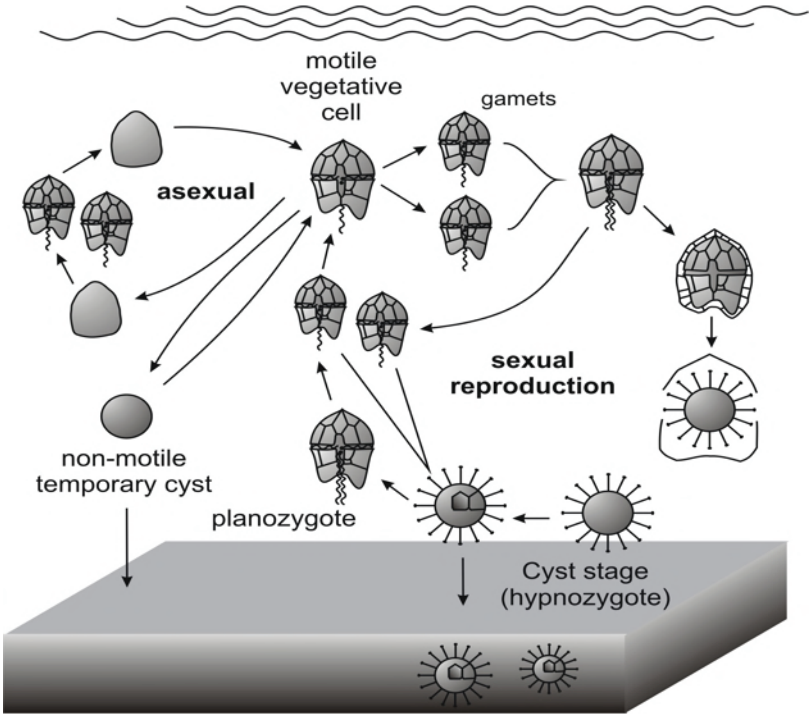


Fig 3. Life cycle of the cyst producing dinoflagellates. After Dale, (1986).

1. 4. 2 Applications and limitations

Since the early studies on paleoenvironment reconstructions by Wall and Dale (1967) and Wall et al. (1977), increasing number of investigations have been carried out in different areas by organic walled dinoflagellate cysts (dinocysts) records (e.g. Bouimetarhan et al., 2009; Dale et al., 2002; de Vernal et al., 2005; Esper and Zonneveld, 2007; Harland et al., 1999; Harris and Tocher, 2003; Holzwarth et al., 2010; Sangiorgi et al., 2002; Zonneveld, 1997). Dinocysts have been shown to be a suitable proxy for establishing environmental and climatic reconstructions as the cyst associations reflect even small changes in upper water conditions such as sea surface temperature (SST), salinity (SSS) and nutrient availability (e.g. Dale et al., 2002; De Vernal et al., 1997; Marret et al., 2001; Pospelova et al., 2006; Sangiorgi et al., 2002). Additionally, dinoflagellate species and associations have also been used to gain the information on human induced waste discharge and industrial pollution (Dale et al., 1999; Harland et al., 2006; Pospelova et al., 2002; Pospelova and Kim, 2010; Radi et al., 2007; Zonneveld et al., 2011).

However, there are some cautions which need to be noticed when using dinocyst in the paleoenvironment reconstructions. First, in some areas, the environmental parameters reconstructed by dinocyst records such as SST and SSS can show covaried characters, and it is not easy to determine which one is best reconstructed with the specific dinoflagellate signal (de Vernal and Marret, 2007). Second, the dinocyst recovered from marine sediments represent many years average ecological signals therefore inhibit the acquisition of information on actual environmental conditions and seasonal dinoflagellate production (Zonneveld et al., 1997). Third, it was traditionally assumed that dinoflagellates might be transported away long distances before they sink to the sea bottom (Dale, 1992), this can alter the fossil dinoflagellate cyst associations. Finally, it has recently became clear that post-depositional aerobic organic matter (OM) degradation can severely alter dinoflagellate cyst signal (Kodrans-Nsiah et al., 2008; Versteegh and Zonneveld, 2002; Zonneveld et al., 2007), therefore the species which are sensitive to degradation for instance *Brigantidinium spp.* have to be used with caution.

References

BarMatthews, M., Ayalon, A., and Kaufman, A. (1997). Late quaternary paleoclimate in the eastern Mediterranean region from stable isotope analysis of speleothems at Soreq Cave, Israel. *Quaternary Research* **47,** 155-168.

Bouimetarhan, I., Dupont, L., Schefuß, E., Mollenhauer, G., Mulitza, S., and Zonneveld, K. (2009). Palynological evidence for climatic and oceanic variability off NW Africa during the late Holocene. *Quaternary Research* **72,** 188-197.

Budyko, M. I. (1974). Climate and Life. *Academic Press* **p508**.

Camuffo, D. (1984). Analysis of the Series of Precipitation at Padova, Italy. *Climatic Change* **6,** 57-77.

Camuffo, D. (1987). Freezing of the Venetian Lagoon since the 9th-Century Ad in Comparison to the Climate of Western-Europe and England. *Climatic Change* **10,** 43-66.

Camuffo, D. (2002). History of the long series of daily air temperature in Padova (1725-1998). *Climatic Change* **53,** 7-75.

Camuffo, D., and Enzi, S. (1995). The analysis of two bi-millenary series: Tiber and Po River floods. *In: P. D. Jones, R. S. Bradley, and J. Jouzel (Eds) Climatic Variations and Forcing Mechanisms of the Last 2000 Years.* **Springer Verlag, Stuttgart, Vol. 41,** p433-450.

Castagnoli, G. C., Bernasconi, S. M., Bonino, G., Della Monico, P., and Taricco, C. (1999). 700 year record of the 11 year solar cycle by planktonic foraminifera of a shallow water Mediterranean core. *In* "Helioseismology and Solar Variability." (C. Frohlich, and B. H. Foing, Eds.), pp. 233-236. Advances in Space Research.

Castagnoli, G. C., Bonino, G., Provenzale, A., Serio, M., and Callegari, E. (1992a). The Caco3 Profiles of Deep and Shallow Mediterranean-Sea Cores as Indicators of Past Solar-Terrestrial Relationships. *Nuovo Cimento Della Societa Italiana Di Fisica C-Geophysics and Space Physics* **15,** 547-563.

Castagnoli, G. C., Bonino, G., Serio, M., and Sonett, C. P. (1992b). Common Spectral Features in the 5500-Year Record of Total Carbonate in Sea Sediments and Radiocarbon in Tree Rings. *Radiocarbon* **34,** 798-805.

Crutzen, P. J., and Stoermer, E. F. (2000). The "Anthropocene". *Global Change Newsletter* **41,** 12-13.

Dale, B. (1976). Cyst Formation, Sedimentation, and Preservation - Factors Affecting Dinoflagellate Assemblages in Recent Sediments from Trondheims Fjord, Norway. *Review of Palaeobotany and Palynology* **22,** 39-60.

Dale, B. (1983). Dinoflagellate resting cysts: “benthic plankton”. In: Fryxell, G.A. Editor, Survival strategies of the algae, Cambridge University Press, pp 69-136.

Dale, B. (1986). Life cycle strategies of oceanic dinoflagellates. *UNESCO Technical Papers in Marine Science* **49,** 65-72.

Dale, B. (1992). Dinoflagellate contribution to the open ocean sediment flux. In: Honjo, S., Ed., Dinoflagellate Contributions to the Deep Sea, Ocean Biocoenosis Series, 5. *Woods Hole: Woods Hole Oceanographic Institution***,** 1-32.

Dale, B., Dale, A. L., and Jansen, J. H. F. (2002). Dinoflagellate cysts as environmental indicators in surface sediments from the Congo deep-sea fan and adjacent regions. *Palaeogeography Palaeoclimatology Palaeoecology* **185,** 309-338.

Dale, B., Thorsen, T. A., and Fjellsa, A. (1999). Dinoflagellate cysts as indicators of cultural eutrophication in the Oslofjord, Norway. *Estuarine Coastal and Shelf Science* **48,** 371-382.

de Vernal, A., Eynaud, F., Henry, M., Hillaire-Marcel, C., Londeix, L., Mangin, S., Matthiessen, J., Marret, F., Radi, T., Rochon, A., Solignac, S., and Turon, J. L. (2005). Reconstruction of sea-surface conditions at middle to high latitudes of the Northern Hemisphere during the Last Glacial Maximum (LGM) based on dinoflagellate cyst assemblages. *Quaternary Science Reviews* **24,** 897-924.

de Vernal, A., and Marret, F. (2007). Organic-Walled Dinoflagellate Cysts : Tracers of Sea-Surface Conditions. *In Developments in Marine Geology (2007) Volume: 1, Issue: 07, Pages: 371-408.*

De Vernal, A., Rochon, A., Turon, J. L., and Matthiessen, J. (1997). Organic-walled dinoflagellate cysts: Palynological tracers of sea-surface conditions in middle to high latitude marine environments. *Geobios* **30,** 905-920.

Dominguez-Castro, F., Garcia-Herrera, R., Ribera, P., and Barriendos, M. (2010). A shift in the spatial pattern of Iberian droughts during the 17th century. *Climate of the Past* **6,** 553-563.

Esper, O., and Zonneveld, K. A. F. (2007). The potential of organic-walled dinoflagellate cysts for the reconstruction of past sea-surface conditions in the Southern Ocean. *Marine Micropaleontology* **65,** 185-212.

Felis, T., Lohmann, G., Kuhnert, H., Lorenz, S. J., Scholz, D., Patzold, J., Al-Rousan, S. A., and Al-Moghrabi, S. M. (2004). Increased seasonality in Middle East temperatures during the last interglacial period. *Nature* **429,** 164-168.

Fensome, R. A., Taylor, F. J. R., Norris, G., Sarjeant, W. A., Wharton, D. I., and Williams, G. L. (1993). Micropaleontology, Special Publication, 7: A Classification of Modern and Fossil Dinoflagellates. *Sheridan Press, Hanover, NH***,** 351pp.

Frisia, S., Borsato, A., Spotl, C., Villa, I. M., and Cucchi, F. (2005). Climate variability in the SE Alps of Italy over the past 17 000 years reconstructed from a stalagmite record. *Boreas* **34,** 445-455.

Galli, M., Guadalupi, M., Nanni, T., Ruggiero, L., and Salerno, A. (1994). Proxy winter temperatures from Ravenna Pinus pinea forest, 1653-1985: Climatic trends and anomalies in Europe 1675-1715, Ed. B. Frenzel, Gustav Fischer Verlag, Stuttgart, Jena, New York.

Harland, R., FitzPatrick, M. E. J., and Pudsey, C. J. (1999). Latest Quaternary dinoflagellate cyst climatostratigraphy for three cores from the Falkland Trough, Scotia and Weddell seas, Southern Ocean. *Review of Palaeobotany and Palynology* **107,** 265-281.

Harland, R., Nordberg, K., and Filipsson, H. L. (2006). Dinoflagellate cysts and hydrographical change in Gullmar Fjord, west coast of Sweden. *Science of the Total Environment* **355,** 204-231.

Harris, A. J., and Tocher, B. A. (2003). Palaeoenvironmental analysis of Late Cretaceous dinoflagellate cyst assemblages using high-resolution sample correlation from the Western Interior Basin, USA. *Marine Micropaleontology* **48,** 127-148.

Held, I. M., and Soden, B. J. (2006). Robust responses of the hydrological cycle to global warming. *Journal of Climate* **19,** 5686-5699.

Holzwarth, U., Meggers, H., Esper, O., Kuhlmann, H., Freudenthal, T., Hensen, C., and Zonneveld, K. A. F. (2010). NW African climate variations during the last 47,000 years: Evidence from organic-walled dinoflagellate cysts. *Palaeogeography Palaeoclimatology Palaeoecology* **291,** 443-455.

IPCC. (2007). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. *IPCC, Geneva, Switzerland***,** 104pp.

Kodrans-Nsiah, M., de Lange, G. J., and Zonneveld, K. A. F. (2008). A natural exposure experiment on short-term species-selective aerobic degradation of dinoflagellate cysts. *Review of Palaeobotany and Palynology* **152,** 32-39.

Kokinos, J. P., Eglinton, T. I., Goni, M. A., Boon, J. J., Martoglio, P. A., and Anderson, D. M. (1998). Characterization of a highly resistant biomacromolecular material in the cell wall of a marine dinoflagellate resting cyst. *Organic Geochemistry* **28,** 265-288.

Kushner, P. J., Held, I. M., and Delworth, T. L. (2001). Southern Hemisphere atmospheric circulation response to global warming. *Journal of Climate* **14,** 2238-2249.

Landscheidt, T. (2000). River Po discharges and cycles of solar activity - Discussion. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* **45,** 491-493.

Llasat, M. C., Barriendos, M., Barrera, A., and Rigo, T. (2005). Floods in Catalonia (NE Spain) since the 14th century. Climatological and meteorological aspects from historical documentary sources and old instrumental records. *Journal of Hydrology* **313,** 32-47.

Marret, F., De Vernal, A., Benderra, F., and Harland, R. (2001). Late Quaternary sea-surface conditions at DSDP Hole 594 in the southwest Pacific Ocean based on dinoflagellate cyst assemblages. *Journal of Quaternary Science* **16,** 739-751.

Maugeri, M., Bellume, M., Buffoni, L., and Chlistovsky, F. (1998). Reconstruction of daily pressure maps over Italy during some extreme events of the 19th century. *Nuovo Cimento Della Societa Italiana Di Fisica*

C-Geophysics and Space Physics **21,** 135-147.

Maugeri, M., Brunetti, M., Monti, F., and Nanni, T. (2004). Sea-level pressure variability in the PO plain (1765-2000) from homogenized daily secular records. *International Journal of Climatology* **24,** 437-455.

Orland, I. J., Bar-Matthews, M., Kita, N. T., Ayalon, A., Matthews, A., and Valley, J. W. (2008). Seasonal climate change as revealed by ion microprobe analysis of delta(18)O in Soreq Cave (Israel) speleothems. *Geochimica Et Cosmochimica Acta* **72,** A709-A709.

Parsons, T. R., Takahashi, M., and Hargrave, B. (1984). Biological oceanographic processes. *Pergamon Press, Oxford, p 330.*

Pfiester, L. A., and Anderson, D. M. (1987). Dinoflagellate reproduction. in F. J. R. Taylor, ed. The biology of dinoflagellates. Botanical Monographs 21:611-648.

Pfister, C., Brazdil, R., Glaser, R., Barriendos, M., Camuffo, D., Deutsch, M., Dobrovolny, P., Enzi, S., Guidoboni, E., Kotyza, O., Militzer, S., Racz, L., and Rodrigo, F. S. (1999). Documentary evidence on climate in sixteenth-century Europe. *Climatic Change* **43,** 55-110.

Pospelova, V., Chmura, G. L., Boothman, W. S., and Latimer, J. S. (2002). Dinoflagellate cyst records and human disturbance in two neighboring estuaries, New Bedford Harbor and Apponagansett Bay, Massachusetts (USA). *Science of the Total Environment* **298,** 81-102.

Pospelova, V., and Kim, S. (2010). Dinoflagellate cysts in recent estuarine sediments from aquaculture sites of southern South Korea. *Marine Micropaleontology* **76,** 37-51.

Pospelova, V., Pedersen, T. F., and de Vernal, A. (2006). Dinoflagellate cysts as indicators of climatic and oceanographic changes during the past 40 kyr in the Santa Barbara Basin, southern California. *Paleoceanography* **21**.

Radi, T., Pospelova, V., de Vernal, A., and Barrie, J. V. (2007). Dinoflagellate cysts as indicators of water quality and productivity in British Columbia estuarine environments. *Marine Micropaleontology* **62,** 269-297.

Rimbu, N., Felis, T., Lohmann, G., and Patzold, J. (2006). Winter and summer climate patterns in the European-Middle East during recent centuries as documented in a northern Red Sea coral record. *Holocene* **16,** 321-330.

Sangiorgi, F., Capotondi, L., and Brinkhuis, H. (2002). A centennial scale organic-walled dinoflagellate cyst record of the last deglaciation in the South Adriatic Sea (Central Mediterranean). *Palaeogeography Palaeoclimatology Palaeoecology* **186,** 199-216.

Sangiorgi, F., Capotondi, L., Nebout, N. C., Vigliotti, L., Brinkhaus, H., Giunta, S., Lotter, A. F., Morigi, C., Negri, A., and Reichart, G. J. (2003). Holocene seasonal sea-surface temperature variations in the southern Adriatic Sea inferred from a multiproxy approach. *Journal of Quaternary Science* **18,** 723-732.

Schiermeier, Q. (2011). Increased flood risk linked to global warming. *Nature* **470,** 316.

Schnepf, E., and Elbrachter, M. (1992). Nutritional Strategies in Dinoflagellates - a Review with Emphasis on Cell Biological Aspects. *European Journal of Protistology* **28,** 3-24.

Stover, L. E., Brinkhuis, H., Damassa, S. P., Verteuil, L., Helby, R. J., Monteil, E., Partridge, A., Powell, A. J., Riding, J. B., Smelror, M., and Williams, G. L. (1996). Mesozoic-Tertiary dinoflagellates, acritarchs and prasinophytes. In: Jansonius, J. and McGregor, D.C. (Eds.), Palynology: principles and applications. American Association of Stratigraphic Palynologists Foundation, Dallas. pp. 641-750.

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

Taylor, F. J. R. (1987). General group characteristics, special features, short history of dinoflagellate study. Taylor F.J.R. (Ed.) The biology of Dinoflagellates. Botanical Monographs, Vol. 21, Blackwell Scientific Publications, Oxford**.,** pp1-23.

Touchan, R., Xoplaki, E., Funkhouser, G., Luterbacher, J., Hughes, M. K., Erkan, N., Akkemik, U., and Stephan, J. (2005). Reconstructions of spring/summer precipitation for the Eastern Mediterranean from tree-ring widths and its connection to large-scale atmospheric circulation. *Climate Dynamics* **25,** 75-98.

Versteegh, G. J. M., de Leeuw, J. W., Taricco, C., and Romero, A. (2007). Temperature and productivity influences on U-37(K') and their possible relation to solar forcing of the Mediterranean winter. *Geochemistry Geophysics Geosystems* **8**.

Versteegh, G. J. M., and Zonneveld, K. A. F. (2002). Use of selective degradation to separate preservation from productivity. *Geology* **30,** 615-618.

Wall, D., and Dale, B. (1967). The resting cysts of modern marine dinoflagellates and their palaeontological significance. *Review of Palaeobotany and Palynology* **2,** 349-354.

Wall, D., Dale, B., Lohmann, G. P., and Smith, W. K. (1977). Environmental and Climatic Distribution of Dinoflagellate Cysts in Modern Marine-Sediments from Regions in North and South-Atlantic Oceans and Adjacent Seas. *Marine Micropaleontology* **2,** 121-200.

Zanchettin, D., Rubino, A., Traverso, P., and Tomasino, M. (2008). Impact of variations in solar activity on hydrological decadal patterns in northern Italy. *Journal of Geophysical Research-Atmospheres* **113**.

Zonneveld, K. A. F. (1997). Dinoflagellate cyst distribution in surface sediments from the Arabian Sea (northwestern Indian Ocean) in relation to temperature and salinity gradients in the upper water column. *Deep-Sea Research Part Ii-Topical Studies in Oceanography* **44,** 1411-1443.

Zonneveld, K. A. F., Bockelmann, F., and Holzwarth, U. (2007). Selective preservation of organic-walled dinoflagellate cysts as a tool to quantify past net primary production and bottom water oxygen concentrations. *Marine Geology* **237,** 109-126.

Zonneveld, K. A. F., Chen, L., Elshanawany, R., Fischer, H. W., Hoins, M., Ibrahim, M. I., Pittaurova, D., and Versteegh, G. J. M. (2011). The use of dinoflagellate cysts to separate human induced and natural variability in the trophic state of the Po-river discharge plume during the last two centuries. *Marine Pollution Bulletin, in press*.

Zonneveld, K. A. F., Versteegh, G. J. M., and deLange, G. J. (1997). Preservation of organic-walled dinoflagellate cysts in different oxygen regimes: A 10,000 year natural experiment. *Marine Micropaleontology* **29,** 393-405.

2. Study area

2. 1 Climate conditions

The Mediterranean Sea is almost enclosed by land that covers an area of approximately 3.5 million km^2 (Fig 1). Its climate is characterized by hot and dry summers and cool and relatively wet winters (Saliot, 2005). Mediterranean is located between low and mid-latitudes and its climate is therefore highly sensitivity to upper air circulation variations (e.g. Cassou et al., 2004; Hurrell and VanLoon, 1997).

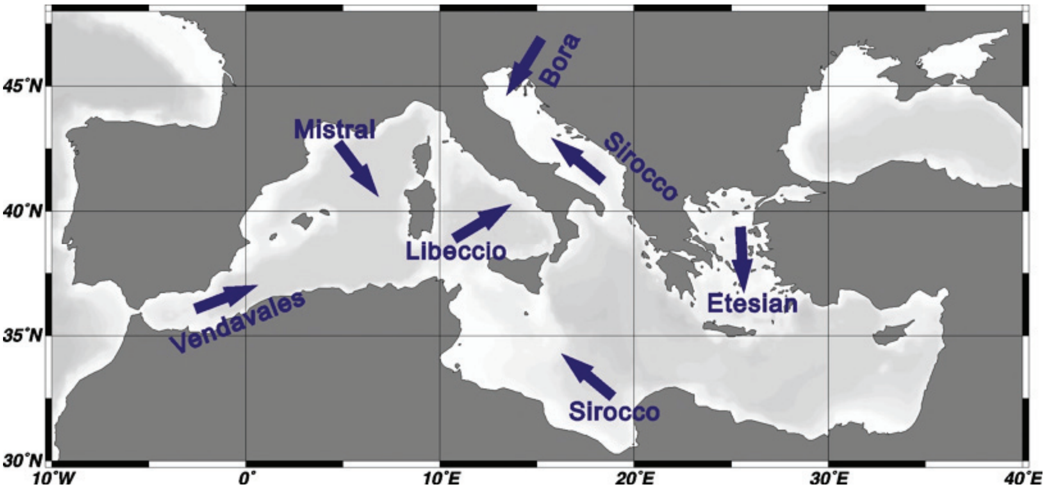


Fig 1. Mediterranean Sea and main winds. Modified after Lionello and Sanna (2005).

One of the most prominent climate modes influencing the Mediterranean climate is the so-called North Atlantic Oscillation (NAO) which represents the dipole-like pressure gradient between the Azores (high) and Iceland (low) (Hurrell, 1995). When the NAO index is in positive phase, northern Europe experiences excess precipitation. In turn, its negative phase brings excess precipitation and high temperatures in southern Europe and Mediterranean area (Lionello and Sanna, 2005). Consequently, variations of NAO have strong effects on the Italian precipitation, with enhanced precipitation resulting in excess discharge of the Po and Apennine rivers into the Adriatic Sea. In turn this results in an extension of the ASW “plume” and enhanced inflow of ASW into the Gulf of Taranto. During winter time, cold and dry Bora winds blow from the northeastern in strong pulses over the study region (Fig 1). This results in sea level fluctuates in downwind and upwind regions as result of the wind-curl effects on the ocean current system (Orlic et al., 1994). These sea level fluctuations vary in intensity as a result of maxima and minima in Bora strength. Apart from this the ocean current system and the oceanographic environmental conditions can be strongly influenced by northward blowing Sirocco winds that origin in the Sahara and that bring warm and humid air into the region

(Cavaleri et al., 1997; Pasaric et al., 2007). It is suggested that strong Sirocco wind may reverse the currents that are observed along the Adriatic coast (Orlic et al., 1994). Therefore both Bora and Sirocco can play an important role on regulating the oceanographic system in the research area despite the fact that they only last several days during the year.

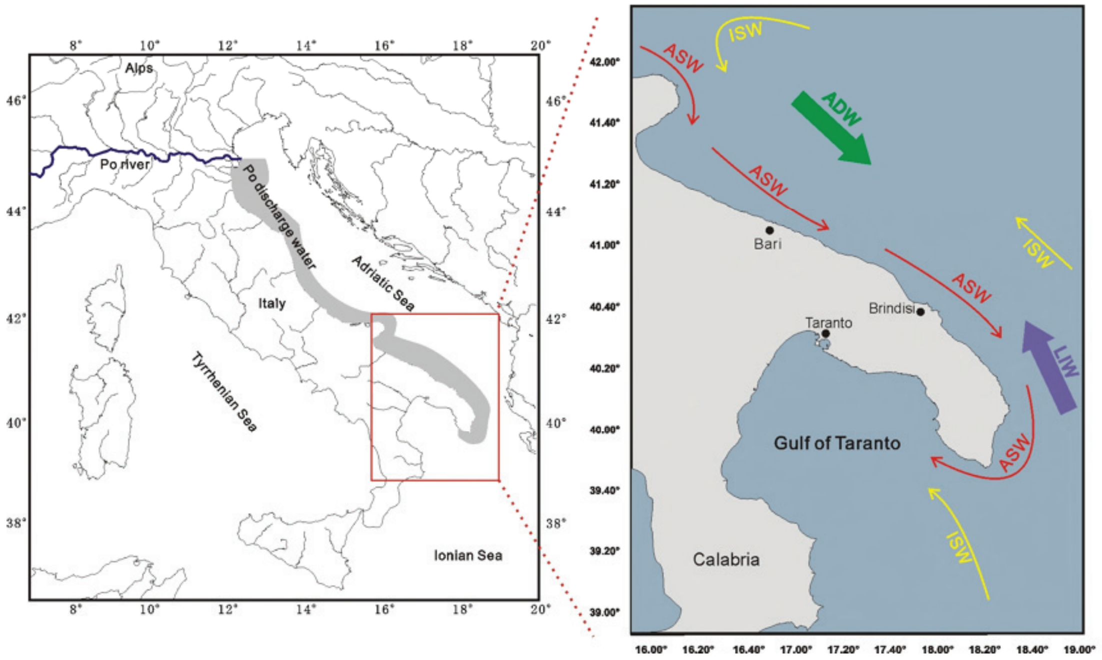


Fig 2. Study area and ocean circulation. ASW - Adriatic Surface Water, ISW - Ionian Sea Water, LIW - Levantine Intermediate Water, ADW - Adriatic Deep Water.

2. 2 Ocean Circulations

The ocean circulation of Gulf of Taranto area is strongly related to that of the Adriatic Sea. Surface waters in the southeastern part form the distal part “river-discharge” waters that can be traced along the whole eastern Italian coast. The main source of these waters is from the Po river (Fig 2). The Po river is the largest Italian river with a length of about 673 km that drains the southern part of the Alps and northern part of Italy. It supplies high amounts of fresh water, nutrients and suspended matter into the northwestern Adriatic basin (Boldrin et al., 2005; Degobbis et al., 1986). These waters which are traditionally classified as the Adriatic Surface Waters (ASW) are characterized by high chlorophyll-a concentrations. The cyclonic surface currents of the Adriatic Sea induced by Coriolis forcing press these southeastward flowing waters against the western coastal margin of the Adriatic Sea (Lee et al., 2007). Local eastern Italian rivers additionally spice the plume-waters on their way southwestward. However, the amounts of suspended matter and nutrients these local rivers discharge into the system are considerably less than the Po river discharge (Degobbis et al., 1986; Milligan and Cattaneo, 2007). Within the Gulf of Taranto, the circulation is generally cyclonic with ASW entering along the eastern part the basin. Additionally, Ionian Sea Waters (ISW) enters the Gulf of Taranto at the eastern side where these waters gradually mix with ASW (Fig 2). The ISW is characterized by relatively high temperature, high salinity, a low suspended matter load and low nutrients concentrations (Boldrin et al., 2005; Caroppo et al., 2006; Socal et al., 1999). Within the Gulf, intermediate water is formed by Levantine Intermediate Water (LIW) which originates from the Levantine basin (Greece), and can be observed between 150 and 600 m water depth. Below 600m depth a shift towards much cooler waters of the dense Adriatic Deep Water (ADW) can be observed (e.g. Hainbucher et al., 2006; Sellschopp and Alvarez, 2003).

References

Boldrin, A., Langone, L., Miserocchi, S., Turchetto, M., and Acri, F. (2005). Po River plume on the Adriatic continental shelf: Dispersion and sedimentation of dissolved and suspended matter during different river discharge rates. *Marine Geology* **222,** 135-158.

Caroppo, C., Turicchia, S., and Margheri, M. C. (2006). Phytoplankton assemblages in coastal waters of the northern Ionian Sea (eastern Mediterranean), with special reference to cyanobacteria. *Journal of the Marine Biological Association of the United Kingdom* **86,** 927-937.

Cassou, C., Terray, L., Hurrell, J. W., and Deser, C. (2004). North Atlantic winter climate regimes: Spatial asymmetry, stationarity with time, and oceanic forcing. *Journal of Climate* **17,** 1055-1068.

Cavaleri, L., Bertotti, L., and Tescaro, N. (1997). The modelled wind climatology of the Adriatic Sea. *Theoretical and Applied Climatology* **56,** 231-254.

Degobbis, D., Gilmartin, M., and Revelante, N. (1986). An annotated nitrogen budget calculation for the Northern Adriatic Sea. *Marine Chemistry* **20,** 159-177.

Hainbucher, D., Rubino, A., and Klein, B. (2006). Water mass characteristics in the deep layers of the western Ionian Basin observed during May 2003. *Geophysical Research Letters* **33**.

Hurrell, J. W. (1995). Decadal trends in the North-Atlantic Oscillation - Regional temperatures and precipitation. *Science* **269,** 676-679.

Hurrell, J. W., and VanLoon, H. (1997). Decadal variations in climate associated with the north Atlantic oscillation. *Climatic Change* **36,** 301-326.

Lee, C. M., Orlic, M., Poulain, P. M., and Cushman-Roisin, B. (2007). Introduction to special section: Recent advances in oceanography and marine meteorology of the Adriatic Sea. *Journal of Geophysical Research-Oceans* **112,** 3.

Lionello, P., and Sanna, A. (2005). Mediterranean wave climate variability and its links with NAO and Indian Monsoon. *Climate Dynamics* **25,** 611-623.

Milligan, T. G., and Cattaneo, A. (2007). Sediment dynamics in the western Adriatic Sea: From transport to stratigraphy. *Continental Shelf Research* **27,** 287-295.

Orlic, M., Kuzmic, M., and Pasaric, Z. (1994). Response of the Adriatic Sea to the Bora and Sirocco Forcing. *Continental Shelf Research* **14,** 91-116.

Pasaric, Z., Belusic, D., and Klaic, Z. B. (2007). Orographic influences on the Adriatic sirocco wind. *Annales Geophysicae* **25,** 1263-1267.

Saliot, A. (2005). The Mediterranean Sea. *Springer Verlag***,** p428.

Sellschopp, J., and Alvarez, A. (2003). Dense low-salinity outflow from the Adriatic Sea under mild (2001) and strong (1999) winter conditions. *Journal of Geophysical Research-Oceans* **108**.

Socal, G., Boldrin, A., Bianchi, F., Civitarese, G., De Lazzari, A., Rabitti, S., Totti, C., and Turchetto, M. M. (1999). Nutrient, particulate matter and phytoplankton variability in the photic layer of the Otranto strait. *Journal of Marine Systems* **20,** 381-398.

3. Materials and methods

3. 1 Materials

The samples used in the Chapter 4 (Manuscript 1) are collected by multicores along the western Adriatic coast from Po delta area to the Gulf of Taranto region during the R.V. Poseidon cruise P339 “Cappuccino” in June 2006 (Zonneveld, 2008).

Materials (Multicore GeoB 10709-5) used in Chapter 5 (Manuscript 2) was collected also during the R.V. Poseidon cruise P339 “Cappuccino” in June 2006 at 39°45.39'N and 17°53.57'E from a water depth of 172.3m (Fig1) (Zonneveld, 2008).

Chapter 6 and 7 (Manuscript 3 and 4) are based on samples from the section 8 of the piston core DP30PC which was retrieved during the R.V. Pelagia, DOPPIO cruise, 2008 (39° 50.07' N, 17°48.05' E, water depth 270 m).

3. 2 Sample preparation

The sediments have been frozen and stored at -20°C immediately after the recovery. Previous to sampling the still frozen cores were stored at -4°C for one day enabling high precision cutting of the core in slices of 2.5 mm. The cutting was carried out in a cold storage room at 4°C. Care was taken that the core temperature remained under -2°C to avoid damaging the core structure. After subsampling the material at every 2.5 mm, 1 ml of each sample was dried overnight at 60 ^{o}C and weighted to determine the dry bulk density. Successively the material was brought into suspension in tap water and sieved over a 100 μm sieve. The material of size > 100 μm was dried and stored for future study. The remnant material <100 μm was treated using standard palynological preparation techniques according to the aliquot method as described by Zonneveld et al. (2009). Dry materials were firstly reacted with HCL (10%), after neutralized by KOH (10%), HF (40%) was added into the samples for 2 hours agitation and additional 2 days without agitation in order to remove the siliceous fraction, finally samples were processed ultrasonically and sieved over a 20 μm stainless steel sieve (Stork Veco, mesh; 570), the residue was centrifuged (6 min, 3200 rpm) and transfered to 1.5 ml eppendorf tube. The fraction smaller than 20um were decanted through the 5um sieve and stored for later pollen research. After centrifuging again, the samples were concentrated to 0.5 ml eventually. 50-100 μl of homogenized material was placed on a slide by the pipette with 1 μl scale interval. The material was embedded in glycerine jelly and insulated from air by paraffin wax. Palynomorphs were counted under a light microscope at 400 or 1000 × magnification, when a slide contained less than 150 diniflagellate cysts, another slide was counted. Taxonomy of dinoflagellate species is according to that cited in Marret and Zonneveld (2003) and Radi and de Vernal (2008). Round, brown cyst with a smooth cell wall without ornamentation were grouped as

Brigantedinium spp.. The classification of the species *Polykrikos kofoidii* and *P. schwarzii* is according to Matsuoka et al. (2009).

3. 3 Statistical methods

3. 3. 1 Multivariate analysis

To compare the environmental variables such as sea surface temperature, sea surface salinity and chlorophyll-a concentration with the relative and absolute abundance of dinoflagellate species, multivariate ordination methods Redundancy Analysis (RDA) from the CANOCO for Windows software package is used (Jongman et al., 1987; ter Braak and Smilauer, 1998). The preformed analyses are based on the assumption of a linear response of the species in relation to environmental variables which has been confirmed by a Detrended Correspondence Analysis (DCA) carried out prior to the analysis. DCA analysis is used to test the unimodal or linear characters of the data. The variations shown by DCA axis is interpreted by one or more environmental parameters. If the length of the first axis is smaller than 2 SD, the linear relationship is presented between species concentrations and the environmental parameters.

3. 3. 2 Time series analysis

It is of great interest to inspect the cyclic characteristics from the complex and disorderly dataset. In this study, frequency analysis of the reconstructed SST, nutrient availability and precipitation series have been performed using the red-noise spectrum analysis of the program REDFIT which is based on Lomb periodogram and particularly suitable for unevenly spaced time series, the significance levels are presented to test reliability of periodicities as shown by spectral peaks (Schulz and Mudelsee, 2002). To validate if there is any spurious signal from REDFIT, we additionally performed an analysis using the multiTaper Method (MTM) of SSA-MTM Toolkit. This method can reduce the spectral leakage by using small tapers (Ghil et al., 2002).

Wavelet analysis can examine the temporal distribution of frequency throughout the entire series that forms a supplement to the common Fourier transform. It can be calculated based on a certain window size and computer the transform in the individual time period. The Continuous Wavelet Transform (CWT) is a usual tool to analyze the localized intermittent oscillations within the time series, it is especially helpful when examining two time series together to check if they show similar cyclic characters (Grinsted et al., 2004). The matlab package of CWT which based on Morlet wavelet is used in this study to investigate the cyclic characters of the individual indicator properties throughout the sequence.

References

Ghil, M., Allen, M. R., Dettinger, M. D., Ide, K., Kondrashov, D., Mann, M. E., Robertson, A. W., Saunders, A., Tian, Y., Varadi, F., and Yiou, P. (2002). Advanced spectral methods for climatic time series. *Reviews of Geophysics* **40**.

Grinsted, A., Moore, J. C., and Jevrejeva, S. (2004). Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics* **11,** 561-566.

Jongman, R. H. G., ter Braak, C. J. F., and Van Tongeren, O. F. R. (1987). Data Analysis in Community and Landscape Ecology. Cent. Agric. Publ. Doc. (Pudoc), Wageningen.

Marret, F., and Zonneveld, K. A. F. (2003). Atlas of modern organic-walled dinoflagellate cyst distribution. *Review of Palaeobotany and Palynology* **125,** 1-200.

Matsuoka, K., Kawami, H., Nagai, S., Iwataki, M., and Takayama, H. (2009). Re-examination of cyst-motile relationships of Polykrikos kofoidii Chatton and Polykrikos schwartzii Butschli (Gymnodiniales, Dinophyceae). *Review of Palaeobotany and Palynology* **154,** 79-90.

Radi, T., and de Vernal, A. (2008). Dinocysts as proxy of primary productivity in mid-high latitudes of the Northern Hemisphere. *Marine Micropaleontology* **68,** 84-114.

Schulz, M., and Mudelsee, M. (2002). REDFIT: estimating red-noise spectra directly from unevenly spaced paleoclimatic time series. *Computers & Geosciences* **28,** 421-426.

ter Braak, C. J. F., and Smilauer, P. (1998). Canoco 4. Centre for Biometry, Wageningen.

Zonneveld, K. A. F. (2008). Report and preliminary results of R/V POSEIDON Cruise P339, Piräus - Messina, 16 June - 2 July 2006. CAPPUCCINO - Calabrian and Adriatic palaeoproductivity and climatic variability in the last two millenia. *Berichte, Fachbereich Geowissenschaften, Universität Bremen* **No. 268,** 61.

4. Environmental significance of dinoflagellate cysts from the proximal part of the Po-river discharge plume (off southern Italy, Eastern Mediterranean)

Karin A.F. Zonneveld[1, *], Liang Chen[1], Jürgen Möbius[2] and Magdy S. Mahmoud[3]

1. Fachbereich 5-Geowissenschaften, Postfach 330440, D-28334 Bremen, Germany.
2. Institut für Biogeochemie und Meereschemie, Bundesstraße 55, 20146 Hamburg, Germany.
3. Geology Department, Faculty of Science, Assiut University, Assiut 71516, Egypt.

* Corresponding author.

***Journal of Sea Research*, 2009, 62(4): 189-213**

Abstract

To determine the relationship between region specific dinoflagellate cyst distribution in the Po-river discharge area and oceanic environmental conditions, surface sediments of 48 sites in the middle and distal part of the discharge plume area have been studied. Establishing such a relationship is a prerequisite to create reconstructions of the eutrophication history as well as the palaeoclimatic and palaeoceanography history of the area.

Literature based information about the sedimentation rates based on ^{210}Pb dating methods are available for 18 sites. This enables the calculation of cyst accumulation rates of individual cyst species which reflect their cyst production. Correlation of the accumulation rates of individual species with environmental parameters of the upper waters allows us to adapt and refine the ecological characteristics of a selection of cyst species. This latter is trivial since the current concepts on the ecological significance of dinoflagellate cyst have to be revised as a result of the current developments in the dinoflagellate research field. These developments have elucidated that a considerable part of the relative abundance datasets that form the basis for the present day ecological concepts of dinoflagellate cysts might have suffered from so called “closed sum effects” and have been overprinted by early diagenetic processes.

The dinoflagellate cyst association reflects both upper and bottom water circulation. Based on the relative abundance data four associations can be distinguished that are characteristic for the major oceanographic settings in the region. (1) River discharge association. This association consists of *Echinidinium* spp., *Lejeunecysta sabrina, Lingulodinium machaerophorum, Polykrikos kofoidii, Polykrikos schwarzii,* cysts of

Protoperidinium stellatum, Selenopemphix quanta and reworked cysts. These species have high relative abundances in sites where bottom waters are low in oxygen and upper waters are influenced by river discharge waters that are characterized by high productivity and relative low salinity. (2) Warm water association. This association consists of *Spiniferites mirabilis, Spiniferites pachydermus, Spiniferites ramosus* and *Spiniferites* spp. which have their highest relative abundances in the sites at the plume margin that are characterized by relative warm upper waters and intermediate chlorophyll-a concentrations. (3) Oxygenated bottom water group. Species of this group; *Impagidinium aculeatum, Impagidinium patulum, Impagidinium sphaericum, Operculodinium centrocarpum* and *Operculodinium israelianum* have their highest relative abundances at sites where bottom waters are formed by well ventilated Adriatic Deep Water or Eastern Mediterranean Deep Water. (4) Golfo di Taranto group consisting of round brown cysts produced by *Protoperidinium* species (grouped as *Brigantedinium spp.*).

The variation in accumulation rates can be related to gradiental changes in the trophic state of the surface waters linked to river outflow. Most species show a positive relationship between cyst production and nutrient/trace element availability in upper waters. No negative correlation between cyst production and nutrient/trace element availability could be documented. Production of *Briganitidinium* spp., *Echinidinium* spp., *Lejeunecysta Sabrina, Lingulodinium machaerophorum, Polykrikos kofoidii/schwarzii, Spiniferites* spp., *Spiniferites mirabilis* and *Selenopemphix quanta* shows the most pronounced increase with increasing nutrient/trace element availability. These species can be considered as valuable indicators for reconstructing changes in the trophic state of the upper waters within the Po-river area in palaeo-environmental studies.

1. Introduction

River plume waters can contain an excessive concentration of organic and inorganic components which enhance bioproductivity in upper waters. Globally, the amplified human activity within the vicinity of rivers of the last hundred years has resulted into increased eutrofication of the marine ecosystems in the vicinity of river outlets. In many cases this has a negative effect by e.g. increasing the occurrence of massive benthos and fish mortality, anoxic events, loss of diversity, toxic algal blooms and mucilage production that in turn, results in major economic and human-health effects (e.g. Spatharis et al., 2007 and references therein). As result of the often high sediment load of the plume waters, river plume areas can contain depositional sites that are characterized by high sedimentation rates. Here natural archives can be found that have the potential to enable the study of anthropogenic effects on the marine ecosystem on a high temporal resolution. Furthermore, these archives provide a valuable source for the establishment of the high resolution climatic reconstructions that are urgently needed within the scope of the current concern about global climate change (Jansen et al. 2007).

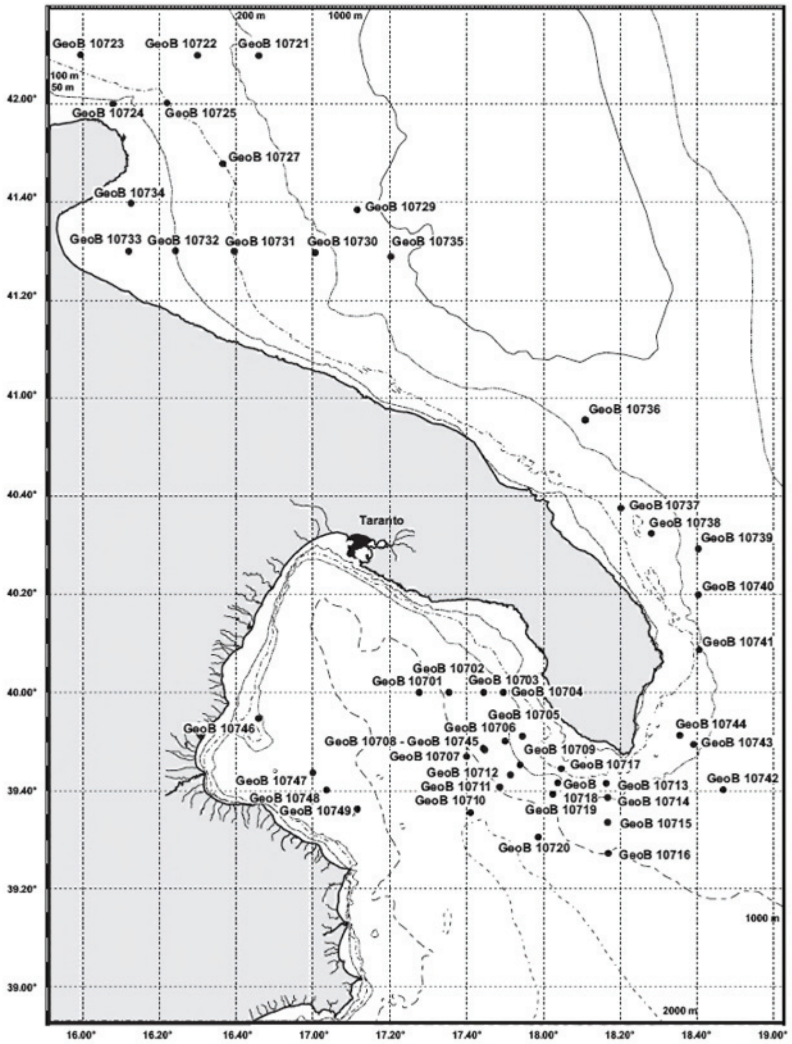


Fig. 1. Map of the South Adriatic Sea, Strait of Otranto and the Golfo di Taranto depicting the sample positions.

One of the major European river systems in which plume area such archives can be found is the Po-river (e.g. Cini Castagnoli et al., 1997; Nittrouer et al., 2004). This river drains the southern part of the Alps and the northern part of Italy into the North Adriatic Sea, the northernmost part of the Mediterranean Sea. With a length of 673 km and drainage basin of 71,000 km^2 it flows through one of the most productive agricultural and industrial regions of Italy (Boldrin et al., 2005). The river forms the primary source of nutrients to the Adriatic Sea and massive dinoflagellate and diatom blooms, sometimes associated with red tides and toxicity, are well known from the discharge area (Boni et al., 1992; Boni et al., 2000; Boldrin et al., 2002, 2005). Logically, changes in amount and quality of the Po-river discharge have large effects on the marine environment (Penna et al., 2004).

Pilot studies have documented the high potential of the natural archives in the region for palaeo-environmental and palaeo-climatic studies (Cini Castagnoli et al., 1999; Sangiorgi and Donders, 2004). However, this information is extremely sparse and an extensive detailed high temporal resolution reconstruction of past environmental and climate variability or anthropogenic influence on the marine ecosystem covering a time span that extents the last few hundred years, is not available yet. A useful proxy for establishing such records is the organic-walled dinoflagellate cyst record. Dinoflagellate cyst associations in marine sediments reflect the environmental conditions of upper waters in detail (e.g. Rochon et al., 1999; de Vernal et al., 2001, 2005; Marret and Zonneveld, 2003; Pospelova et al., 2006; Esper and Zonneveld, 2007; Radi et al., 2007; Pospelova et al., 2008). In time series analysis this aspect can be used to determine past variations in upper water environmental conditions such as human induced eutrophication, changes in sea surface salinity, sea surface temperature, turbulence and nutrient content (e.g. Filipsson et al., 2004; Harland et al., 2006; Marret et al., 2008; Dale, 2008). Studies on fossil dinoflagellate cyst associations can also provide valuable information about the history and possible causes of dinoflagellate induced harmful algal blooms (e.g. Siringan et al., 2008). However, within the last few years it has become clear that, although there are some generalities, every river plume or estuarine system has an unique cyst associations when studied in detail (e.g. Blanco, 1995; Grill and Guerstein, 1995; Matsuoka et al., 1999; Marret et al., 2001; Sangiorgi et al., 2002; Azanza et al., 2004; Orlova et al., 2004; Giannakourou et al., 2005; Pospelova et al., 2005; Borel et al., 2006; Holzwarth et al., 2007; Novichkova and Polyakova, 2007; Radi et al., 2007). Furthermore, strong environmental gradients in the upper waters result in an abrupt change of cyst associations within small geographic areas. Consequently for an adequate use of the sedimentary dinoflagellate cyst association for palaeoenvironmental and oceanographic reconstructions in river system areas a detailed survey with a high geographic resolution is required.

To obtain such a basis for future studies in the Po-river discharge plume area we have studied the dinoflagellate cyst content of 48 surface sediment samples that are located in a dense network along the middle and distal end of the river plume, the western part of the South Adriatic Sea, the Strait of Ontranto and the Golfo di Taranto (Fig. 1). To date some sparse information on the cyst association in sediments in the vicinity of the river mouth in the northern Adriatic Sea is present on a low spatial resolution (Rubino et al., 1997; Rubino et al., 2000; Sangiorgi et al., 2005). For the distal part of the plume area information is restricted to a few data points only (Belmonte et al., 1995; Rubino et al., 1997; Rubino et al., 2002). In this paper we obtain information about the relationship between the modern day cyst distribution and environmental conditions in surface waters by comparing the geographic distribution of individual cyst species with seasonal information of the total amount of primary production in surface water in terms of the chlorophyll-*a* concentration, local sea surface temperatures and sea surface salinities. Furthermore we compare the cyst distribution with additional sedimentary parameters such as the Nitrate and organic Carbon concentrations as well as the oxygen penetration depth. The study of relative abundance data allows us to determine dinoflagellate cyst associations that are characteristic for several oceanographic regimes. Detailed information about the sedimentation rates of 18 sites based on ^{210}Pb analyses enables the calculation of accumulation rates of individual cyst species reflecting the cyst production.

By combining both methods, we show that the dinoflagellate cyst association and production clearly mirrors the position of river influenced surface waters. Comparison of the cyst accumulation rates with upper water environmental characteristics leads to an adaptation and refinement of the ecological characterization of several modern dinoflagellate cyst species such as *Brigantidinium* spp., *Echinidinium* spp., *Impagidinium aculeatum, Impagidinium patulum, Lingulodinium machaerophorum, Polykrikos kofoidii/schwarzii, Spiniferites mirabilis* and *Selenopemphix quanta*. As several of these species are common components in estuary and river systems that are sometimes strongly polluted, this information will lead to advanced reconstructions of past changes in eutrophication and river outflow in estuarine and river influenced regions well beyond the Po-river discharge plume area.

2. Oceanographic setting

The Po-river is the largest Italian river draining the southern part of the Alps and northern part of Italy. It enters the north-western North Adriatic Sea through a deltaic system (Fig. 2). The discharge waters that have entered the marine realm have a clear physical and biological character that can be traced along the eastern Italian margin southward as the so called Po-discharge plume. Along the way, the plume waters are additionally spiced by sediment loaded, fresh, nutrient and element rich waters from local eastern Italian rivers. However, the loads of nutrients and sediments of these local rivers are considerably lower with respect to the Po-river discharge (e.g. Penna et al., 2004; Milligan and Cattaneo, 2007 and references therein).

As a result of an anti-clockwise surface water circulation induced by Coriolis forcing, the fresh, nutrient rich Po-river discharge water is pressed against the western coastal margin of the Adriatic Sea (e.g. Lee et al., 2007). As a consequence, a band of enhanced productivity reflected by high chlorophyll-*a* concentration in surface waters, can be observed along the whole western margin of the Adriatic Sea, the Strait of Otranto, around the Calabrian Peninsula into the Golfo di Taranto (Fig. 3). Classically these relative cool, nutrient and suspended matter rich, low salinity waters are classified as Adriatic Surface Water (ASW). Along the eastern side of the south Adriatic Sea and the Strait of Otranto high temperature, high salinity and low suspended matter and nutrient concentration Ionian Surface Water (ISW) coming from the Eastern Mediterranean enters the basin. Within the Golfo di Taranto, the circulation is generally cyclonic with ASW entering along the eastern part the basin. Within the Golfo di Taranto a mixing between ASW and ISW occurs (e.g. Socal et al., 1999; Boldrin et al., 2005; Caroppo et al., 2006; Lee et al., 2007 and references in the Journal of geophysical research, vol. 112, 2007).

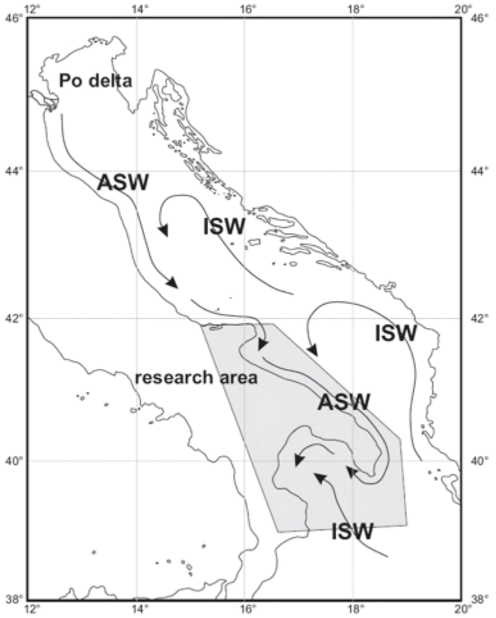


Fig. 2. Map of the upper ocean current system in the research area. ASW=Adriatic Sea surface Water, ISW=Ionian Sea surface Water.

Intermediate waters in the research area are formed by the relatively nutrient rich, high salinity waters of the Levantine Intermediate Water (LIW). This water that is characterized by a mean annual salinity concentration higher than 38.70 and has a core at about 200m depth. In the Adriatic Sea a shift towards more cooler waters of the dense Adriatic Deep Water (ADW) can be observed below about 600m depth. Along the Italian coast fresher but colder North Adriatic Dense Water (NADW) forms a southward flowing bottom water current. Both ADW and NADW are recognized as contributors to the eastern Mediterranean Deep Waters, although recently having competition by deep water that is produced in the Aegean Sea (e.g. Sellschopp and Álvarez, 2003; Hainbucher et al., 2006; Grbec et al., 2007).

The ocean circulation and related to that, primary production within the research area shows large interannual variation (Fig. 3). Typically the Po-river discharge demonstrates two discharge peeks during spring (May-June) with the highest snow melt in the Alps and in autumn (October – November) related to enhanced precipitation. In the Adriatic Sea, the Po-discharge plume occupies a wider area during these periods. Within the Golfo di Taranto enhanced ASW inflow can be observed in winter. In the southern Adriatic and Golfo di Taranto, vertical mixing convection occurs in winter or early spring as result of the cooling of the surface waters (Boldrin et al., 2002; Casotti et al., 2003; D'Ortenzio et al., 2003; Caroppo et al., 2006). This process strongly affects primary production processes, rising the deep nutrients to the upper photic layers. Based on satellite image studies it has been revealed that the increase in biomass is related to strong events of heat loss with the magnitude of biomass enhancement to be directly related to the intensity of the atmospheric events (e.g. Casotti et al., 2003; D'Ortenzio et al., 2003; Santoleri et al., 2003). Several studies give evidence that this extensive late-winter, early spring bloom in the Golfo di Taranto is a relatively recent feature that can be related to a change in the Eastern Mediterranean circulation around the early 1990's characterized as the Eastern Mediterranean Transient (EMT). Prior to the EMT, thermohaline circulation involved only one deep water formation zone in the Adriatic Sea (Roether and Putzka, 1996). The new observations indicate that the Cretan/Aegean Sea has become an additional driving engine of the intermediate and deep circulation displacing the older Eastern Mediterranean Deep Water, thus rising the isopycnal surfaces and nutricline by several hundred meters. It has been shown that although this rise in nutricline did not affect the surface biological dynamic in the majority of the Ionian Sea, the western part forms an exception.

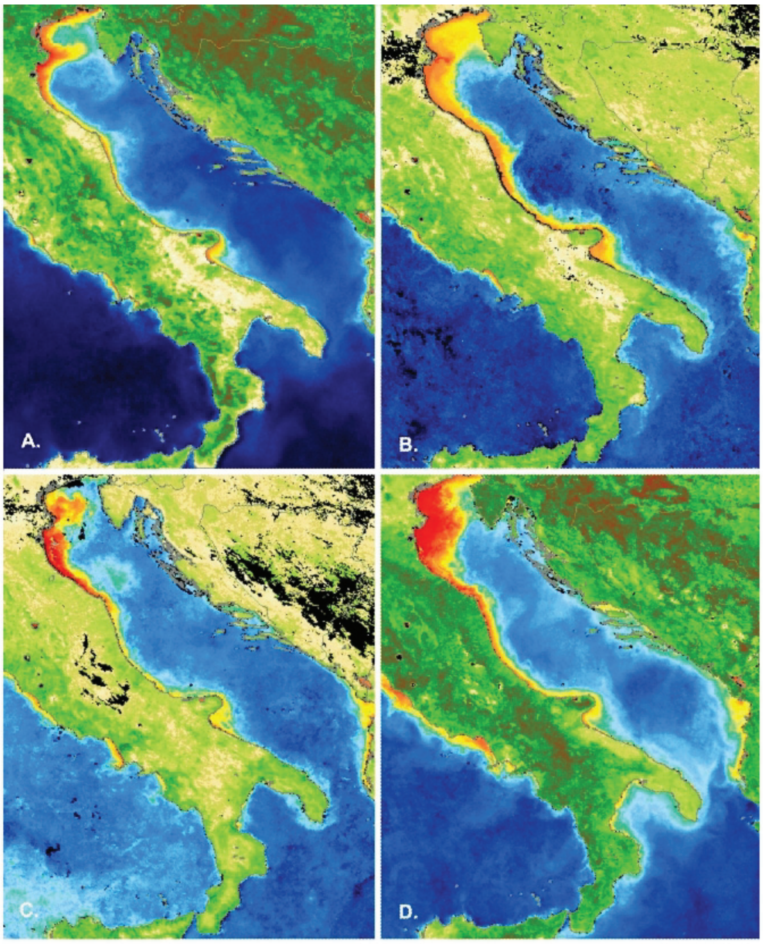


Fig. 3. Compiled satellite image of upper ocean chlorophyll-a concentrations in (a) summer, (b) autumn, (c) winter, (d) spring.

Satation	Lattitude	Longtude	O$_2$ Layer (cm)	N (%)	Corg (%)	Ch sp	Ch su	Ch au	Ch wi	T an °C	T au °C	T wi °C	T sp °C	T su °C	S an psu	S sp psu	S su psu	S au psu	S wi psu	WD (m)	Lithology	SR (cm/y)	Ref dating
GeoB 10701	40°00.00′	017°28.01′	11.0	0.11	0.793	0.30	0.15	0.22	0.26	18.64	21.50	14.49	17.40	25.57	38.21	38.58	38.43	38.47	37.96	1187	mud		
GeoB 10702	40°00.01′	017°35.15′	6.0	0.11	0.813	0.30	0.16	0.24	0.29	18.62	21.41	14.47	17.50	25.43	38.20	38.54	38.43	38.46	37.94	910	mud		
GeoB 10703	40°00.00′	017°44.49′	7.0	0.14	0.963	0.35	0.17	0.25	0.34	18.62	21.34	14.21	17.70	25.32	38.20	38.52	38.31	38.50	38.46	273	mud		
GeoB 10704	40°00.00′	017°50.00′	1.5	0.13	0.920	0.35	0.18	0.26	0.37	18.61	21.30	14.03	17.80	25.26	38.18	38.37	38.31	38.54	38.46	215	mud	0.07	Boudena 2004
GeoB 10705	39°51.20′	017°54.76′	3.0	0.12	0.939	0.32	0.18	0.27	0.32	18.67	21.14	14.19	17.90	25.16	38.18	38.36	38.31	38.52	38.35	124	mud	0.07	Boudena 2004
GeoB 10706	39°49.51′	017°50.01′	2.5	0.12	0.880	0.31	0.16	0.25	0.28	18.67	21.26	14.31	17.80	25.25	38.18	38.42	38.31	38.54	38.35	214	mud	0.07	Boudena 2004
GeoB 10707	39°47.00′	017°35.00′	6.0	0.08	0.587	0.29	0.13	0.21	0.24	18.70	21.46	14.75	17.50	25.50	38.21	38.64	38.36	38.41	38.24	1599	mud		
GeoB 10708	39°48.50′	017°43.99′	1.0	0.08	0.806	0.29	0.15	0.23	0.27	18.70	21.33	14.47	17.70	25.32	38.21	38.61	38.46	38.55	38.35	682	mud		
GeoB 10709	39°45.40′	017°53.58′	4.0			0.28	0.15	0.22	0.25	18.81	21.30	14.59	17.80	25.22	38.23	38.33	38.31	38.51	38.35	168	mud	0.07	Boudena 2004
GeoB 10710	39°35.50′	017°41.00′	4.0	0.05	0.367	0.26	0.12	0.19	0.22	18.81	21.44	14.82	17.60	25.41	38.23	38.61	38.61	38.59	38.24	2036	mud		
GeoB 10711	39°41.00′	017°47.99′	13.0	0.06	0.382	0.26	0.13	0.20	0.23	18.81	21.38	14.82	17.80	25.31	38.23	38.55	38.60	38.55	38.37	1045	mud		
GeoB 10712	39°43.59′	017°51.69′	4.0	0.09	0.714	0.28	0.15	0.22	0.25	18.81	21.30	14.59	17.80	25.22	38.23	38.55	38.60	38.55	38.37	614	mud		
GeoB 10713	39°41.51′	018°17.02′	4.0	0.06	0.457	0.28	0.16	0.24	0.31	18.83	21.18	14.39	16.26	25.34	38.24	38.18	37.98	38.31	37.73	123	sandy mud		
GeoB 10714	39°38.41′	018°17.00′	3.0	0.04	0.332	0.28	0.16	0.24	0.31	18.83	21.18	14.39	16.26	25.34	38.24	38.18	37.98	38.31	37.73	202	sandy mud		
GeoB 10715	39°33.51′	018°16.98′	20.0	0.06	0.398	0.24	0.14	0.18	0.23	18.98	21.41	14.92	18.20	25.39	38.27	38.30	38.28	38.53	38.12	693	sandy mud		
GeoB 10716	39°20.70′	018°17.01′	14.0	0.04	0.327	0.23	0.11	0.15	0.21	18.98	21.83	15.11	18.20	25.36	38.27	38.38	38.28	38.51	38.34	1325	sandy mud		
GeoB 10717	39°44.51′	018°04.80′	4.0	0.05	0.448	0.33	0.18	0.30	0.39	18.78	21.02	13.88	18.00	25.14	38.23	38.19	38.31	38.50	38.46	92	sabdy mud	0.07	Boudena 2004
GeoB 10718	39°41.57′	018°03.48′	7.0	0.08	0.624	0.28	0.15	0.24	0.30	18.78	21.24	14.62	18.00	25.25	38.23	38.20	38.60	38.52	38.46	214	sandy mud		
GeoB 10719	39°39.20′	018°02.50′	3.0	0.08	0.527	0.28	0.15	0.24	0.30	18.78	21.24	14.62	18.00	25.25	38.23	38.27	38.88	38.48	38.72	612	mud		
GeoB 10720	39°30.41′	017°58.73′	17.0	0.05	0.285	0.26	0.12	0.18	0.23	18.93	21.18	14.52	18.20	25.34	38.25	38.37	38.88	38.45	38.55	1384	mud		
GeoB 10721	42°10.00′	016°46.00′	7.0	0.05	0.356	0.23	0.14	0.20	0.24	18.16	21.48	14.99	17.90	25.34	38.19	38.36	38.06	38.44	38.44	200	sandy mud	0.06	Frignani et al, 2005
GeoB 10722	42°09.99′	016°30.00′	6.0	0.08	0.453	0.25	0.17	0.25	0.28	18.09	20.05	14.60	16.70	24.76	38.18	38.25	38.11	38.22	38.40	138	sandy mud	0.19	Palinkas and Nittrouer 2006
GeoB 10723	42°10.00′	015°59.99′	3.0	0.11	0.674	0.32	0.23	0.40	0.44	18.06	19.90	14.37	16.50	24.73	38.10	37.65	37.85	37.88	38.25	110	mud	0.91	Palinkas and Nittrouer 2006
GeoB 10724	42°00.03′	016°12.99′	4.0	0.03	0.209	0.40	0.28	0.48	0.70	18.02	20.10	13.73	15.10	24.89	38.17	37.04	37.86	37.42	37.90	45	sandy mud	0.46	Frignani et al, 2005
GeoB 10725	42°00.03′	016°12.99′	4.0	0.10	0.702	0.34	0.24	0.41	0.43	18.02	20.06	13.97	16.30	24.79	38.17	38.28	37.92	38.15	38.36	94	mud	0.19	Palinkas and Nittrouer 2006
GeoB 10727	41°48.03′	016°37.00′	4.0	0.09	0.590	0.30	0.21	0.32	0.36	18.03	19.96	14.16	16.60	24.82	38.26	38.02	37.72	38.21	38.47	97	sandy mud	0.19	Palinkas and Nittrouer 2006
GeoB 10729	41°38.79′	017°11.47′	15.0	0.05	0.323	0.27	0.13	0.18	0.21	18.05	20.00	14.39	17.10	24.77	38.27	38.31	38.23	38.48	38.53	708	sandy mud	0.08	Turchetto et al 2007
GeoB 10730	41°29.99′	017°03.00′	7.0	0.03	0.210	0.26	0.13	0.19	0.22	17.93	19.96	14.47	17.00	24.66	38.28	38.32	38.10	38.37	38.36	179	sandy mud	0.19	Palinkas and Nittrouer 2006
GeoB 10731	41°29.98′	016°39.49′	4.0	0.10	0.649	0.33	0.26	0.39	0.45	17.87	20.19	14.10	16.60	25.00	38.27	37.92	37.63	38.07	37.08	93	mud	0.32	Palinkas and Nittrouer 2006
GeoB 10732	41°30.00′	016°24.45′	5.0	0.12	0.787	0.59	0.39	0.58	0.91	17.83	20.44	13.14	16.40	25.13	38.25	37.60	37.42	38.03	37.08	46.5	mud	0.78	Palinkas and Nittrouer 2006
GeoB 10733	41°30.01′	016°13.46′	2.0	0.11	0.728	0.79	0.47	0.83	1.43	17.83	20.56	12.76	16.20	25.23	38.29	37.25	37.31	38.29	37.08	18.3	mud	0.49	Frignani et al, 2005
GeoB 10734	41°40.00′	016°14.49′	4.0	0.06	0.483	1.15	0.67	1.00	1.89	17.89	20.54	13.07	16.20	25.44	38.29	33.93	37.24	37.59	37.97	13.8	mud	0.57	Frignani et al, 2005
GeoB 10735	41°30.01′	017°18.50′	27.0	0.11	0.742	0.29	0.12	0.18	0.21	18.01	20.08	14.25	17.30	24.81	38.28	38.58	38.24	38.49	38.59	730	mud		
GeoB 10736	40°45.50′	018°11.51′	3.0	0.11	0.763	0.36	0.22	0.37	0.54	18.57	20.54	13.59	18.10	24.82	38.21	38.10	38.00	37.86	37.40	119	mud	0.08	Turchetto et al 2007
GeoB 10737	40°37.50′	018°19.73′	3.0	0.10	0.759	0.32	0.20	0.30	0.47	18.64	20.56	13.73	18.30	24.88	38.18	38.12	37.94	37.93	37.45	109	mud		
GeoB 10738	40°32.75′	018°27.99′	4.0	0.11	0.801	0.32	0.20	0.31	0.46	18.64	20.56	13.84	18.40	24.87	38.18	38.28	37.86	37.88	37.45	108	mud		
GeoB 10739	40°30.00′	018°38.50′	4.0	0.09	0.661	0.26	0.16	0.24	0.30	18.64	20.42	14.33	18.60	24.82	38.17	38.24	38.09	37.96	37.67	561	mud		
GeoB 10740	40°23.51′	018°35.00′	5.0	0.03	0.261	0.32	0.19	0.32	0.47	18.66	20.60	13.76	18.50	24.88	38.16	38.19	38.06	37.79	37.56	124	sandy mud		
GeoB 10741	40°14.01′	018°39.99′	2.0	0.09	0.670	0.29	0.18	0.29	0.40	18.66	20.61	14.00	18.60	24.84	37.99	38.18	38.07	37.85	37.64	286	sandy mud		
GeoB 10742	39°42.90′	018°46.59′	18.0	0.07	0.427	0.24	0.14	0.18	0.23	18.91	21.30	15.14	18.70	24.87	38.26	38.25	37.95	38.37	38.08	595	mud		
GeoB 10743	39°49.50′	018°38.54′	12.0	0.11	0.747	0.26	0.16	0.21	0.30	18.76	21.00	14.55	18.60	24.86	38.22	38.10	38.03	38.27	37.66	120	sandy mud		
GeoB 10744	39°51.00′	018°35.99′	3.0	0.10	0.718	0.26	0.16	0.21	0.30	18.76	21.00	14.55	18.60	24.86	38.22	38.08	38.02	38.20	37.72	113	mud		
GeoB 10746	39°54.50′	016°45.50′	2.0	0.10	0.631	0.45	0.21	0.27	0.33	18.90	21.73	14.54	16.70	25.58	38.26	38.26	38.66	38.38	28.39	153	mud		
GeoB 10747	39°43.49′	016°58.49′	5.0	0.10	0.645	0.39	0.18	0.24	0.27	19.08	21.72	14.54	16.90	25.65	38.29	38.27	38.66	38.32	28.39	242	mud		
GeoB 10748	39°39.99′	017°03.00′	3.0	0.10	0.630	0.33	0.16	0.23	0.27	19.08	21.64	14.56	17.00	25.61	38.29	38.27	38.59	38.29	38.20	284	mud		
GeoB 10749	39°36.01′	017°10.99′	4.0	0.09	0.535	0.32	0.16	0.22	0.26	18.87	21.62	14.53	17.10	25.59	38.26	38.26	38.66	38.37	38.16	275	mud		

Table 1. Sample position, environmental variables, sedimentation rates and literature source for the dating. O2layer = depth of oxygen penetration in cm, N = N concentration in surface sediment, Corg = total organic carbon in surface sediment, Ch sp, Ch su, Ch au, Ch wi = sea surface chlorophyll-a concentration in spring, summer, autumn and winter respectively, T an = mean annual sea surface temperature, T au, T wi, Tsp, T su = sea surface temperature in autumn, winter, spring and summer respectively, S an = mean annual sea surface salinity, S sp, S su, S au, S wi = sea surface salinity in spring, summer, autumn and winter respectively. WD = water depth, SR = sedimenta tion rate, Ref. = reference of dating.

3. Material/methods

Surface sediments derived from 48 sample sites from the southern Adriatic Sea, the Stait of Ontranto and the Golfi di Taranto have been collected by multicores during the POSEIDON cruise "CAPPUCCINO" in June 2006 (Fig. 1, Table 2; Zonneveld et al. 2008a). The multicore provided sediments with an undisturbed sediment-water interface. Samples containing the upper half centimeter of sediment have been processed using standard palynological techniques according to the Lycopodium method described by Marret and Zonneveld (2003). No oxidative agents or heavy liquid separation has been preformed to avoid selective cyst degradation during sample preparation. Taxonomy is according to Marret and Zonneveld (2003). *Brigantidinium* spp. Includes all round brown dinoflagellate cysts, *Spiniferites* spp. Includes al *Spiniferites* cysts that can not be determined on species level.

Another sample set has been taken to determine organic carbon and total nitrogen contents. Samples were stored cool until being freeze dried and subsequently grounded for analysis with a Carlo Erba 1500 Element Analyzer in the home lab. Organic carbon has been analyzed after threefold removal of $CaCO_3$ with 1N HCl. Another sample set has been taken to determine organic carbon and total nitrogen contents. Samples were stored cool until being freeze dried and subsequently grounded for analysis with a Carlo Erba 1500 Element Analyzer in the home lab. Organic carbon has been analyzed after threefold removal of $CaCO_3$ with 1N HCl.

Relative abundance data have been calculated by dividing the amount of cysts of a particulate species with the total sum of observed cyst specimens.

Detailed information about the sedimentation rates of 18 sites based on ^{210}Pb analyses enables the calculation of accumulation rates of individual cyst species reflecting the cyst production. Detection of the ^{137}Cs in the sediments that result of the Bombing experiments during the last century made exact dating possible (see references given in Table 2). Cyst accumulation rates have been calculated as follows:

$$AR\ (c/cm^2/y) = cyst/g\ (c/g) \times DBD\ (g/cm^2) \times SR\ (cm/y)$$

AR = accumulation rates, cystg = amount of cysts per gram dry sediment, DBD = dry bulk density, SR = sedimentation rate.

Relative and absolute abundances have been compared with seasonal values of upper water chlorophyll-*a* concentratons, seasonal and mean annual SST and SSS values using the mutlivariate ordination methods Redundancy Analysis (RDA) from the CANOCO for Windows software package (Jongman et al., 1987; ter Braak and Smilauer, 1998). The preformed analyses are based on the assumption of a linear response of the species in relation to environmental variables which has been confirmed by a Detrended Correspondance Analys (DCA) carried out prior to the analysis. Seasonal chlorophyll-a and sea surface temperatures data have been derived from compiled SeaWifs satellite data (from 1997 to present) of the years 2002 – 2006. Satellite data from “Coastal Zone Color Scanner (CZCS, from 1979 – 1985) have not been taken into account since these data are generated before the EMT. Sedimentation rates in the region are generally extremely high. We collected the upper surface of the sediments which we assume to be deposited after the EMT. Data are retrieved from the OBPG MODIS-Aqua Monthly Global 9-km database (http://reason.gsfc.nasa.gov /OPS/Giovanni/ocean.aqua.shtml) on a 0.1° resolution. Seasonal sea surface salinity data are retrieved from the MEDATLAS bottle database samples (http://odv.awi.de/data/ocean/medatlasii.html). Data from the last 20 years on a 0.2° grid resolution have been compiled. Exceptions are formed by samples GeoB 10714 and GeoB 10715 which summer SSS data are retrieved from the NOAA World Ocean Data Atlas 2005 on a 0.25° resolution. This hold as well for autumn-SSS data from samples GeoB 10731, 10732 and 10733 winter-SSS data from samples GeoB 10748 and 10749 as well as the annual mean annual temperature and salinity data. Seasons are defined as such: Winter: December – February, Spring: March – May, Summer: June – August, Autumn: September – November.

Sedimentation rates of individual samples are based on literature derived ^{210}Pb datings. For reference of these data see Table 1.

4. Results

Surface sediment samples of the southwestern Adriatic Sea and Golfo di Taranto contain a diverse dinoflagellate cyst association. The redundancy analysis (RDA) clearly illustrates that high chlorophyll-*a* concentrations in the upper 1 m of the water column correspond to relatively low salinity and temperature values in spring as well as to low oxygen penetration depths in the sediments (Fig. 5). Increased N and Corg concentrations can be observed at sites where high Chlorophyll-a concentrations in the surface water layer exist.

4.1 Relative abundance data

The environmental variables “autumn SST”, “winter SST”, “autumn Chlorophyll-*a”*, “summer Chlorophyll-*a”*, “spring Chlorophyll-*a”, “*winter SSS”, “summer SSS” and “oxygen penetration depth” vary significantly in relationship to the relative cyst distribution (95% confidence interval). All other environmental parameters strongly co-vary with these environmental variables or do not significantly vary in relationship to the spatial distribution of the individual cysts species (Fig. 5, Table 3). Summer SST strongly co-varies with autumn SST and can therefore statistically be considered as one gradient. The same holds for the upper water Chlorophyll-*a* concentration in winter and summer that strongly co-varies with “autumn Chlorophyll-*a*” and “spring Chlorophyll-*a*”. [N] and [C_{org}] positively co-vary with chlorophyll-*a* concentrations in upper waters during autumn and spring. The oxygen penetration depth co-varies negatively with these parameters.

The majority of the variation in cyst distribution correlates to temperature variance in autumn (14%). Gradients in the upper water chlorophyll-*a* concentrations in autumn and spring correlated to 9% and 7% respectively of the variation in cyst distribution.

Based on both the visual examination of the distribution patterns of individual cyst species as well as on the results of the RDA several groups of species with related distribution patterns can be distinguished.

Group 1: Po-river discharge plume group: *Echinidinium* spp., *Lejeunecysta sabrina, Lingulodinium machaerophorum, Polykrikos kofoidii/schwarzii,* cysts of *Protoperidinium stellatum, Selenopemphix quanta* and reworked cysts. These species have their highest relative abundance in the most coastal sites of the southwestern Adriatic Sea, the Strait of Ontranto and around the Calabrian Peninsula where a mix of local eastern Italian rivers and Po-discharge waters can be observed in the upper water layers in spring and autumn (Figs 5,7). Relative abundances of these species gradually decrease when the river plume is followed into direction of its distal proximity in the Golfo di Taranto where the plume waters lose their characteristic features when mixed with other Eastern Mediterranean surface waters. Lowest relative abundances of these species are found in sites where surface waters are formed by ASW, ISW and bottom waters that consist of ADW and EMDW. Increasing relative abundances of these species can be related to increasing chlorophyll-*a* concentrations in spring and autumn.

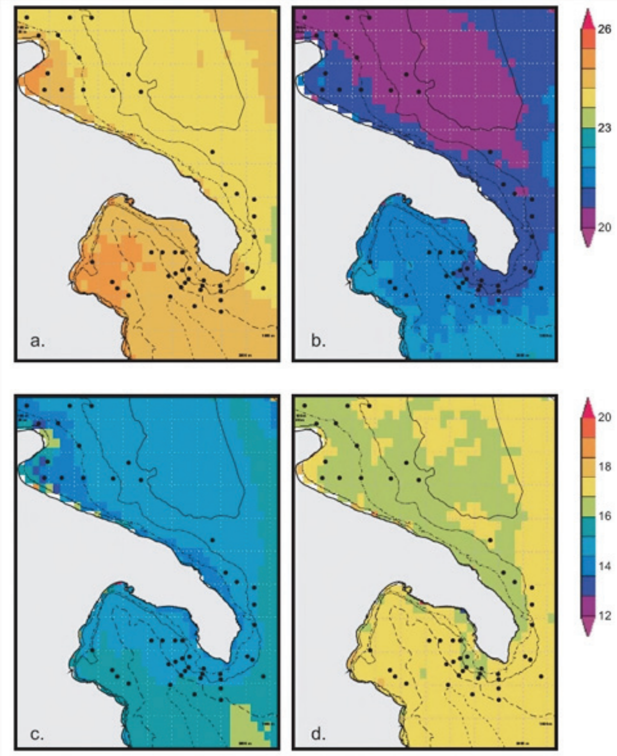


Fig. 4. Compiled satellite image of upper ocean temperatures in (a) summer, (b) autumn, (c) winter, (d) spring.

Group 2. Warm water group: *Spiniferites mirabilis, Spiniferites pachydermus, Spiniferites ramosus* and *Spiniferites* spp. The relative abundance of these species increases in relationship with increasing autumn surface water temperatures at sites with intermediate chlorophyll-*a* concentrations (Fig. 8). No significant relationship with other environmental parameters or ocean circulation patterns can be observed.

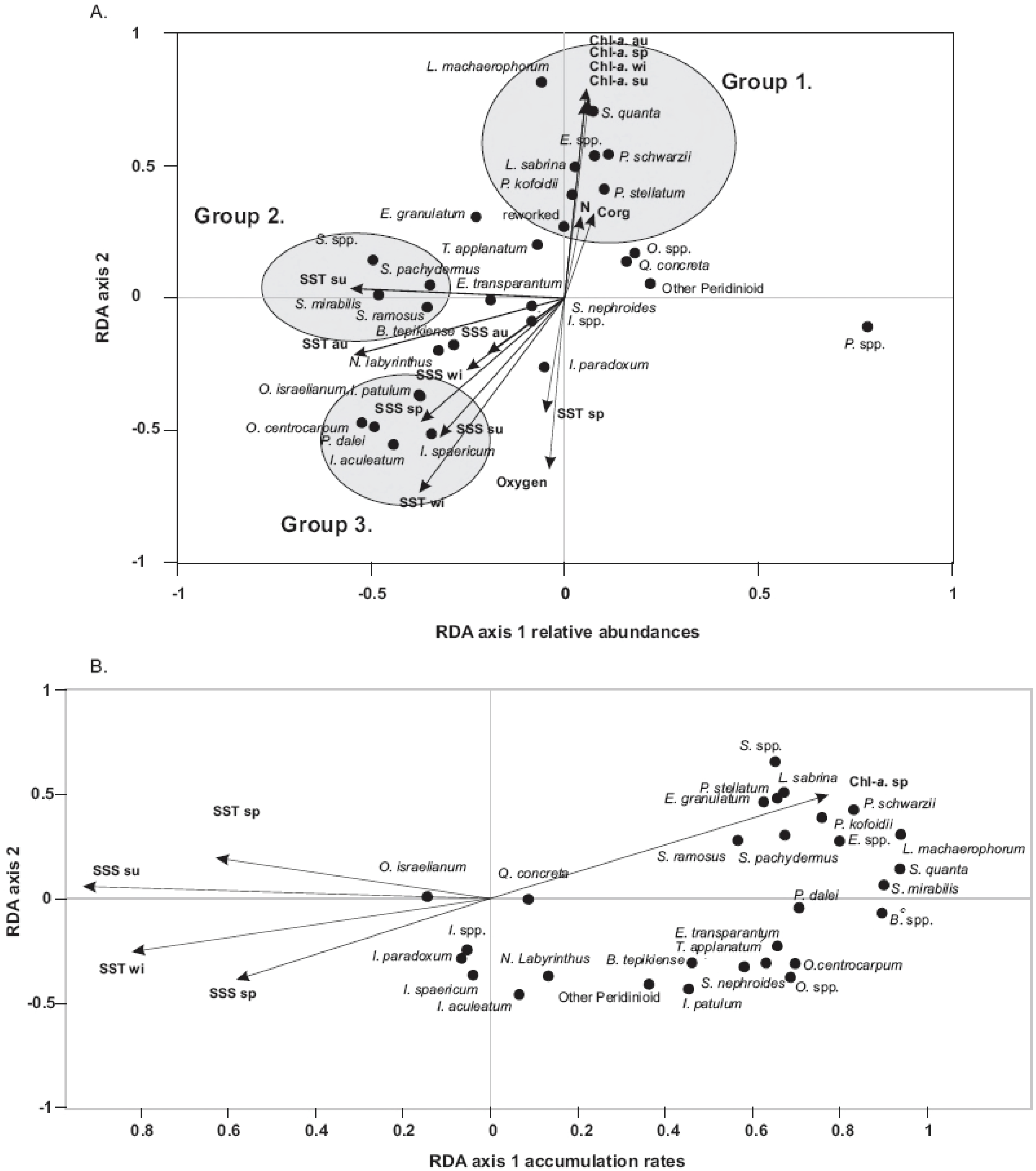


Fig. 5. Results of the RDA analyses on (a) relative abundance data, (b) accumulation rate data. Chl-a.=chlorophyll-a, SST=sea surface temperature, SSS=sea surface salinity, oxygen=oxygen penetration depth, wi=winter, sp=spring, su=summer, au=autumn.

Group 3. Oxygenated bottom water group: *Impagidinium aculeatum, Impagidinium patulum, Impagidinium sphaericum, Operculodinium centrocarpum* and *Operculodinium israelianum.* High relative abundances of these species are found in sites where bottom waters are formed by ADW or EMDW (Figs. 9, 9a). They show increasing relative abundances with increasing autumn surface water temperatures and decreasing Chlorophyll-*a* concentrations.

Group 4. Golfo di Taranto group. Round brown cysts produced by *Protoperidinium* species (grouped as *Brigantedinium* spp.) form a major part of the cyst association in all samples (Fig. 10b). Highest relative abundances of these species are found in the inner part of the Golfo di Taranto where mixing of the plume waters and ISW occurs and along the offshore edge of the river-plume in the South Adriatic Sea. Their relative abundances increase in the surface sediments in relationship with decreasing autumn and winter temperatures.

The distribution of all other species shows no clear relationship with the investigated environmental variables or ocean circulation patterns.

4.2 Accumulation rates

The variables “spring chlorophyll-a, spring SST, spring SSS, summer SSS and winter SST relate significantly to the variance in accumulation rates (Fig. 5, Table 3). Generally all species show increased accumulation rates in relationship to increased chlorophyll-*a* concentrations and decreasing salinity and temperature gradients (Fig. 11, 15). The accumulation rates of *Brigantidinium* spp., *Echinidinium* spp., *Lejeunecysta Sabrina, Lingulodinium machaerophorum, Polykrikos kofoidii/schwarzii, Spiniferites* spp., *Spiniferites mirabilis* and *Selenopemphix quanta* most strongly increase with increasing chlorophyll-a concentrations and decreasing temperature and salinity gradients (Figs 5, 11, 15). The species *Impagidinium aculeatum, Impagidinium paradoxum, Impagidinium sphaericum, Impagidinium* spp., *Operculodinium israelianum* and *Quinquecuspis concreta* plot in the middle of the analyzed gradients (Figs. 5, 11).

	Accumulation rates			Relative abundances		
Environmental variable	% var.	P	F	% var	P	F
SST summer	5	0.94	0.04	14	0.41	0.91
SST autumn	8	0.77	0.17	***14***	***0.05***	***7.02***
SST winter	***55***	***0.085***	***2.71***	***13***	***0.15***	***5.42***
SST spring	***33***	***0.325***	***1.03***	3	0.715	0.46
SSS summer	***69***	***0.005***	***36.39***	***9***	***0.4***	***3.78***
SSS autumn	20	0.635	0.31	8	0.425	0.8
SSS winter	45	0.885	0.07	**3**	**0.1**	**2.33**
SSS spring	***29***	***0.09***	***2.26***	5	0.785	0.3
Chlorophyll-a summer	58	0.55	0.51	***8***	***0.075***	***5.28***
Chlorophyll-a autumn	61	0.61	0.42	***9***	***0.15***	***2.31***
Chlorophyll-a winter	55	0.68	0.23	8	0.59	0.56
Chlorophyll-a spring	***48***	***0.205***	***1.72***	***7***	***0.1***	***4.67***
oxygen panetration	6	0.875	0.08	***2***	***0.075***	***2.79***
[N]				1	0.52	0.66
[Corg]				6	0.49	0.73

Table 2. Table summarizing the statistical results of the RDA analyses on relative and absolute abundance data. % var= amount of variance in the dataset explained without correcting for co-variance. Bold/italic Indicate relationships that are significant (F>1).

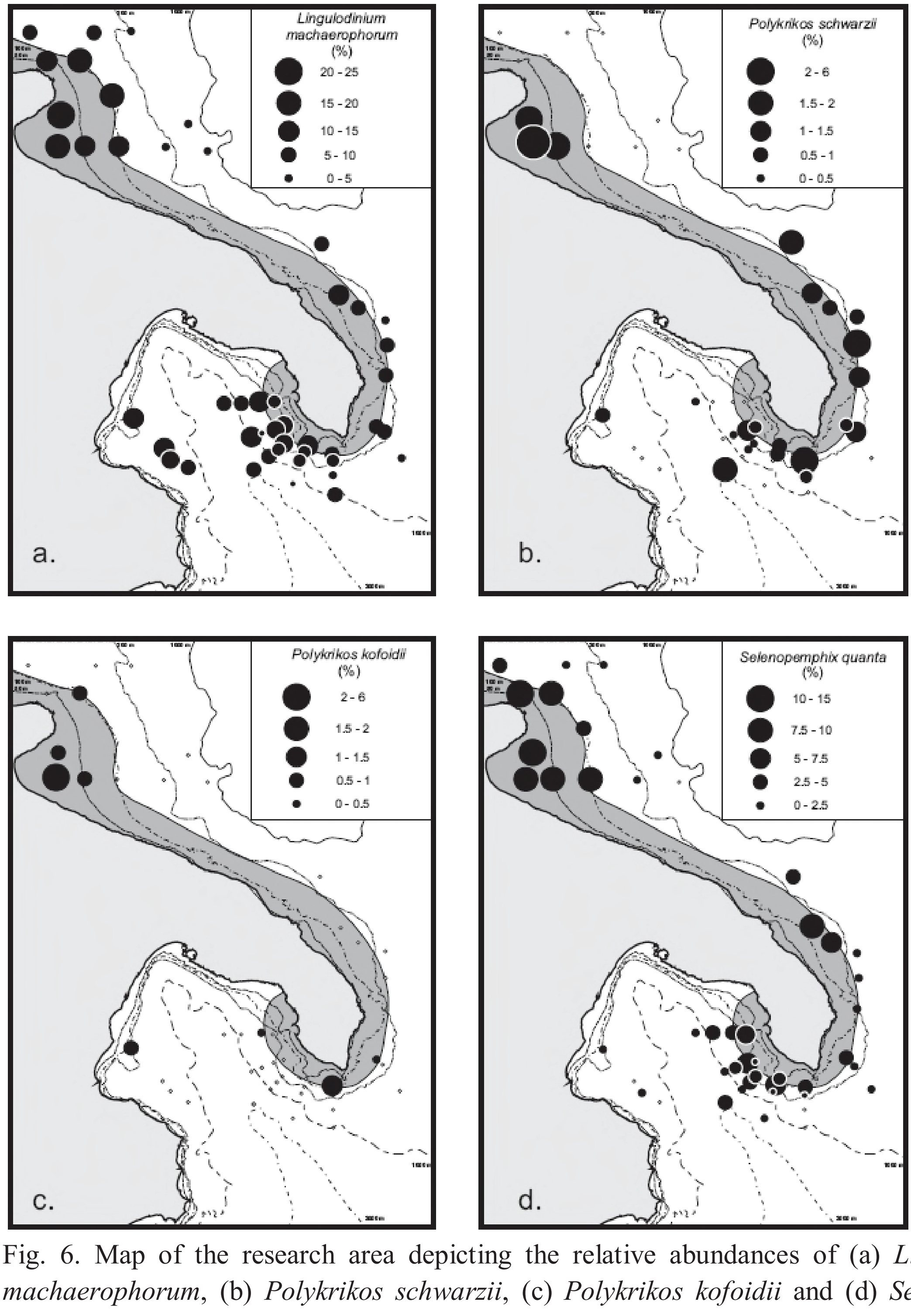


Fig. 6. Map of the research area depicting the relative abundances of (a) *Lingulodinium machaerophorum*, (b) *Polykrikos schwarzii*, (c) *Polykrikos kofoidii* and (d) *Selenopemphix quanta* in upper sediments. Grey area represents the maximal extension of the river plume in spring.

5. Discussion

The present results show that the dinoflagellate cyst association in surface sediments in the research area reflects both the upper and bottom water ocean circulation and characteristics. The most prominent feature that is reflected in the association is the position of Po-river discharge plume. The Po-river plume that can be traced along the eastern Italian margin is spiced by sediment loaded, fresh, nutrient and element rich waters from the Po-river as well as from local eastern Italian rivers. High nutrient and trace element concentrations can be found in the vicinity of the river mouth and a gradient to lower concentrations towards the distal part (Fig. 3). The opposite is the case for the salinity gradients in the plume. This is well reflected by the statistical analysis where we find an opposite direction of the chlorophyll-*a* and salinity gradients (Fig. 5). We observe a positive relationship between chlorophyll-a, [N] and [C_{org}] in surface sediments. To date, satellite measurements routinely provide global chlorophyll-*a* biomass. Since the remote sensing determination of phytoplankton carbon has been proven to be elusive, net primary production estimates use chlorophyll-*a* as an index of phytoplankton biomass (e.g. Campbell et al., 2002). Although the above mentioned method has constrains and it is assumed that about 30% of daily water-column photosynthesis is missed by satellite based estimates (e.g. Behrenfeld et al., 2005; Mouw and Yoder, 2005), we can safely assume that chlorophyll-*a* is a qualitative reflection of net primary production. Within our research area net primary production is enhanced within the plume discharge area in spring and autumn when peaks in river discharge enhance nutrient and trace elements in surface waters. In the Golfo di Taranto, primary production is high in winter when mixing of the upper water masses reduces the upper water temperature and enhances nutrient concentration in the upper water. In our study area, the sedimentary parameters [Corg] and [N] therefore reflect the upper water primary production which is strongly related to the trophic state of the upper waters. As such we can consider the chlorophyll-a and salinity gradients to co-vary with nutrient and trace-element concentration gradients in the upper waters.

The Po and local rivers in the region transport large amounts of sediments that are deposited in several depo-centers within our research area (Rossi et al. 1983; Nittrouer et al., 2004; Palinkas and Nittrouer, 2006; Milligan and Cattaneo, 2007). Since dinoflagellate cysts belong to the silt sediment fraction it has often been suggested that cysts might easily be transported by ocean currents during their sinking process and after deposition (e.g. Dale, 1992). However, indisputable evidence for large scale dislocation of cysts due to natural or anthropogenic induced processes is rare (e.g. Reid et al., 1981; Zonneveld and Brummer, 2000; Sprangers et al., 2003; Giannakourou et al., 2005). If lateral transport would have strongly influenced the cyst distribution pattern in our research area, we would expect to find the highest cyst accumulation rates in the depo-centers, assuming that cysts behave like the silt fraction of the sediment load. Furthermore, we would expect to find a gradual change in association and concentration from the shelf to the deeper sites and from the depo-centers towards the plume proximity. However, we find a random relationship between sediment accumulation rates and cyst accumulation rates or association. Furthermore, we find a clear reflection of the ocean current systems in our association and not a gradual change towards the deeper sites and plume proximity. We therefore assume that dislocation of cysts did not severely affect the cyst distribution in the studied sites.

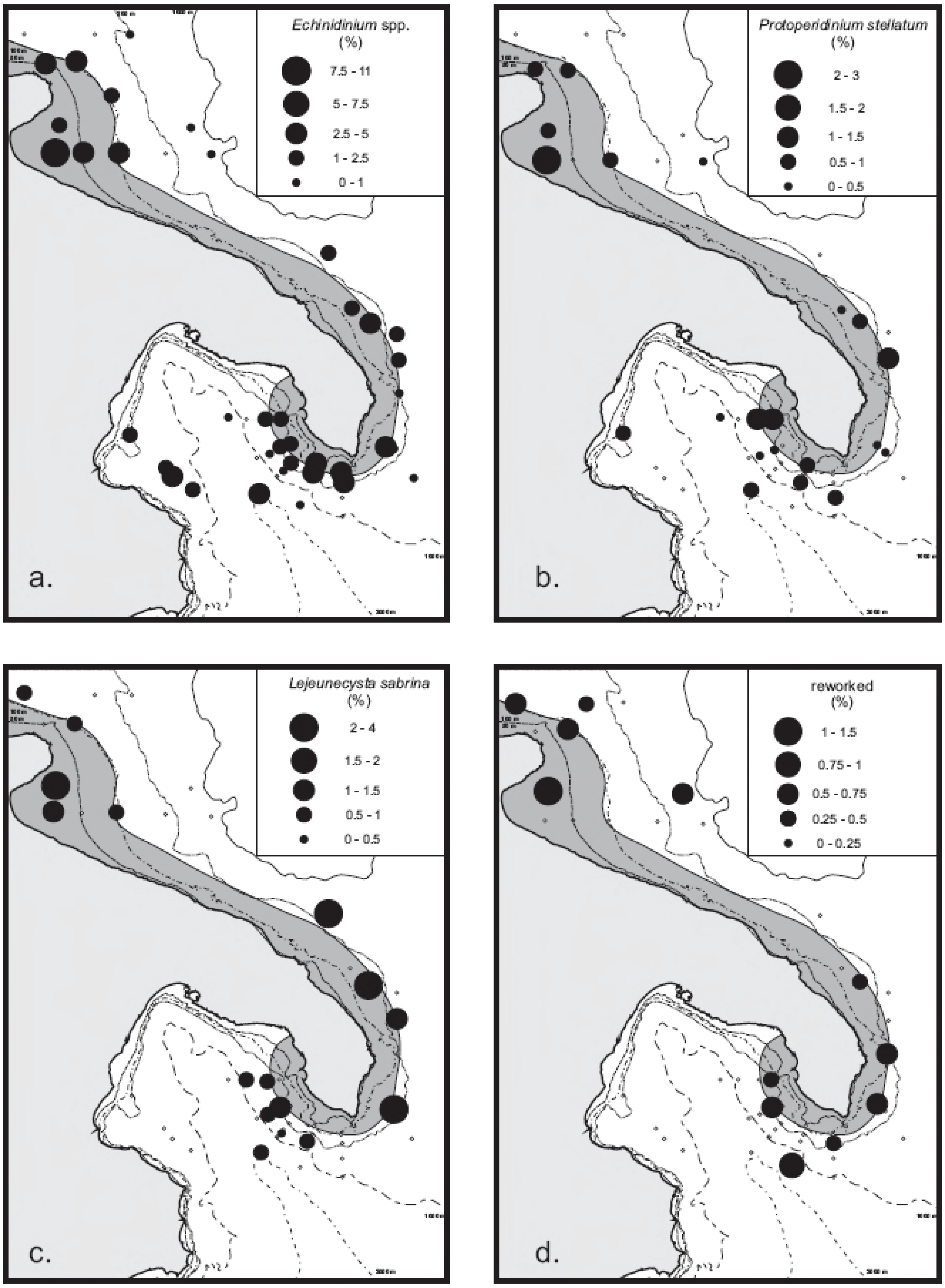


Fig. 7. Map of the research area depicting the relative abundances of (a) *Echinidinium spp.*, (b) *Protoperidinium stellatum*, (c) *Lejeunecysta sabrina* and (d) reworked cysts in upper sediments. Grey area represents the maximal extension of the river plume in spring.

5.1 Preservation

Within the last decades it became clear that aerobic early diagenetic processes and predation can affect the dinoflagellate cyst fraction in the sediments on a species specific level in natural environments in a very short time interval (Zonneveld et al., 1997; Zonneveld et al., 2001; Persson and Rosenberg, 2003; Kodrans-Nsiah et al., 2008). To date there is a strong indication that apart from factors that are known to influence the exposure time of organic particles to oxygen such as sedimentation rates, one of the main factors influencing the cyst degradation rate, is the bottom water oxygen concentration (Zonneveld et al., 2007; Zonneveld et al., 2008b). Within our study we have no information about the bottom water oxygen concentrations at the individual sites. It is, therefore, not possible to establish a detailed relationship between changes in cyst association and bottom water oxygen concentration. We do have, however, information about the oxygen penetration depth. This factor, in combination with the sedimentation rates gives a rough estimate about the time organic particles in the sediments have been exposed to oxygen. Although detailed information about the sedimentation rates at the individual sites is present for a part of the stations only, we can assume that the deeper the oxygen penetration in the sediment at the sample site, the larger the risk that organic components in the sediments have been prone to aerobic degradation. We observe a strong negative correlation between the chlorophyll-*a* concentration in the upper waters and the oxygen penetration depth (Fig. 5). Furthermore, we observe that when the oxygen penetrates deeper in the sediments, the studied surface sediments contain less total organic matter. This is an indication that aerobic degradation might have affected the organic matter content of the sediments and we can not exclude early diagenesis as a process that has changed the composition of our cyst association post-depositionally. However, this does not form a restriction to determine region characteristic dinoflagellate cyst associations that can be used for palaeoceanographic studies in this region when oxygen is considered as one of the environmental parameters that affects the cyst distribution. The different oceanic settings in the study area are well defined with Po-river discharge plume waters characterized by a relatively low salinity, high nutrient and element concentrations but low oxygen concentrations whereas ASW, ISW, ADW and EMDW are characterized by high salinity, low nutrient and relatively high oxygen concentrations. A change in precipitation on the Italian peninsula and/or on the southern part of the Alps, will result in a change in river outflow. This will alter both upper and bottom water characteristics at several sites in the research area which, based on the results presented in this paper, can be expected to be reflected in the dinoflagellate cyst association as a result of a change in the combination of environmental parameters that characterize the different ocean currents and affect the dinoflagellate cyst assemblage.

5.2 Characterisation of oceanographic regimes for palaeoceanographic use

Based on the relative abundance distribution patterns we can recognize four cyst associations that can be addressed to different oceanographic regimes; (1) River plume association, (2) warm water association (3) oxygenated bottom water association (4) Golfo di Taranto association.

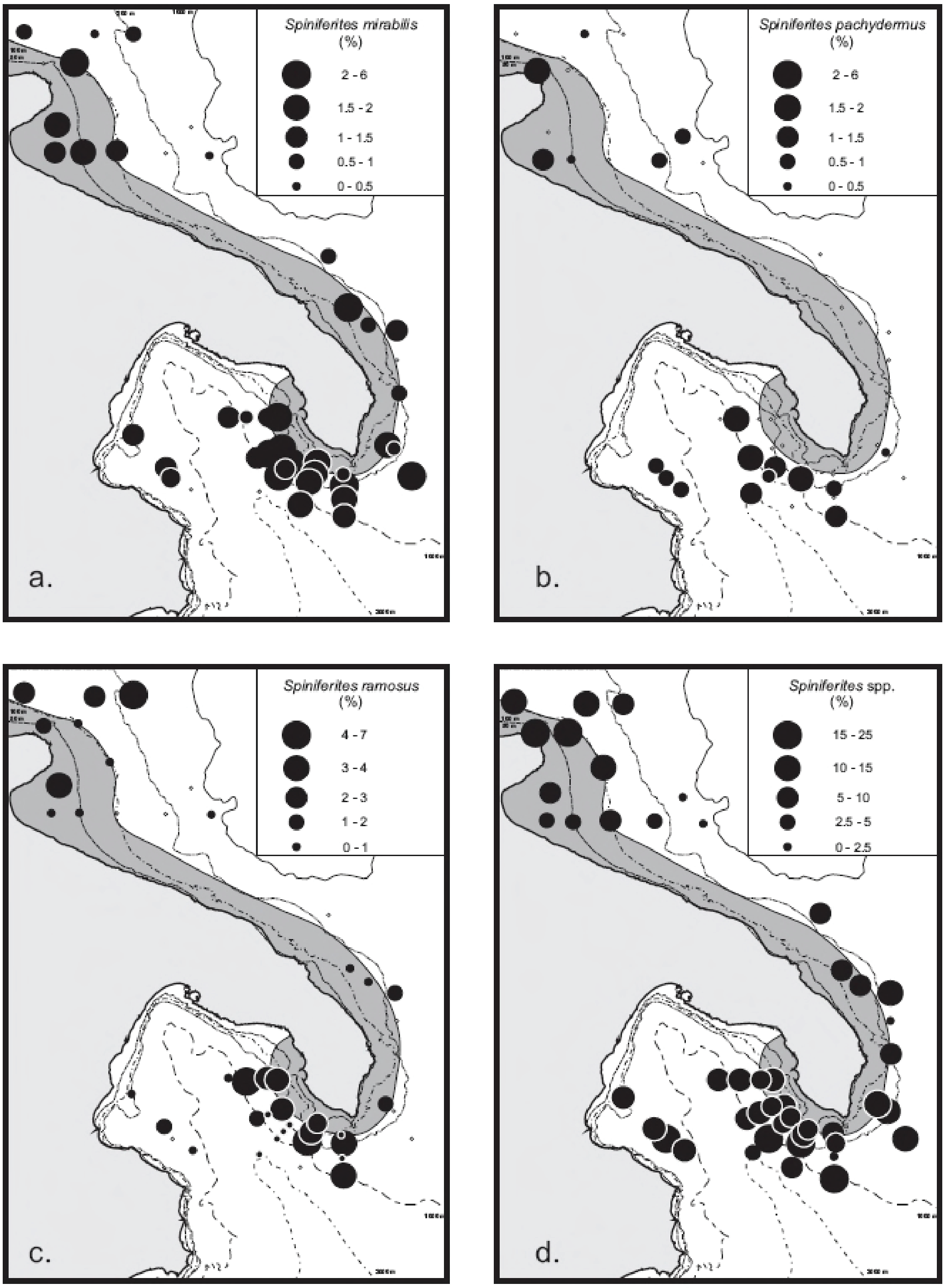


Fig. 8. Map of the research area depicting the relative abundances of (a) *Spiniferites mirabilis*, (b) *Spiniferites pachydermus*, (c) *Spiniferites ramosus* and (d) *Spiniferites spp.* in upper sediments. Grey area represents the maximal extension of the river plume in spring.

Group 1, river plume association.

Echinidinium spp., *Lejeunecysta sabrina, Lingulodinium machaerophorum, Polykrikos* cysts, cysts of *Protoperidinium stellatum, Selenopemphix quanta* and reworked cysts have their highest relative cyst abundances in, or are restricted to, sediments of sites located close to the coast in regions that are influenced by Po-river discharge water (Figs 5,7). Their relative abundances change positively with changing chlorophyll-*a* concentrations in upper waters during spring and autumn (Fig. 5). Within the research area, maximal outflow of the Po and local eastern Italian rivers occurs during spring and autumn as a result of the melting of the snow in the Alps and Appenines and enhanced precipitation in the region respectively (Boldrin et al., 2002; Casotti et al., 2003; D'Ortenzio et al., 2003; Caroppo et al., 2006). Bottom waters below the river plume are characterized by low oxygen concentrations and especially in the vicinity of the Po-river mouth, episodes of anoxia are common features in this region (e.g. Socal et al., 1999).

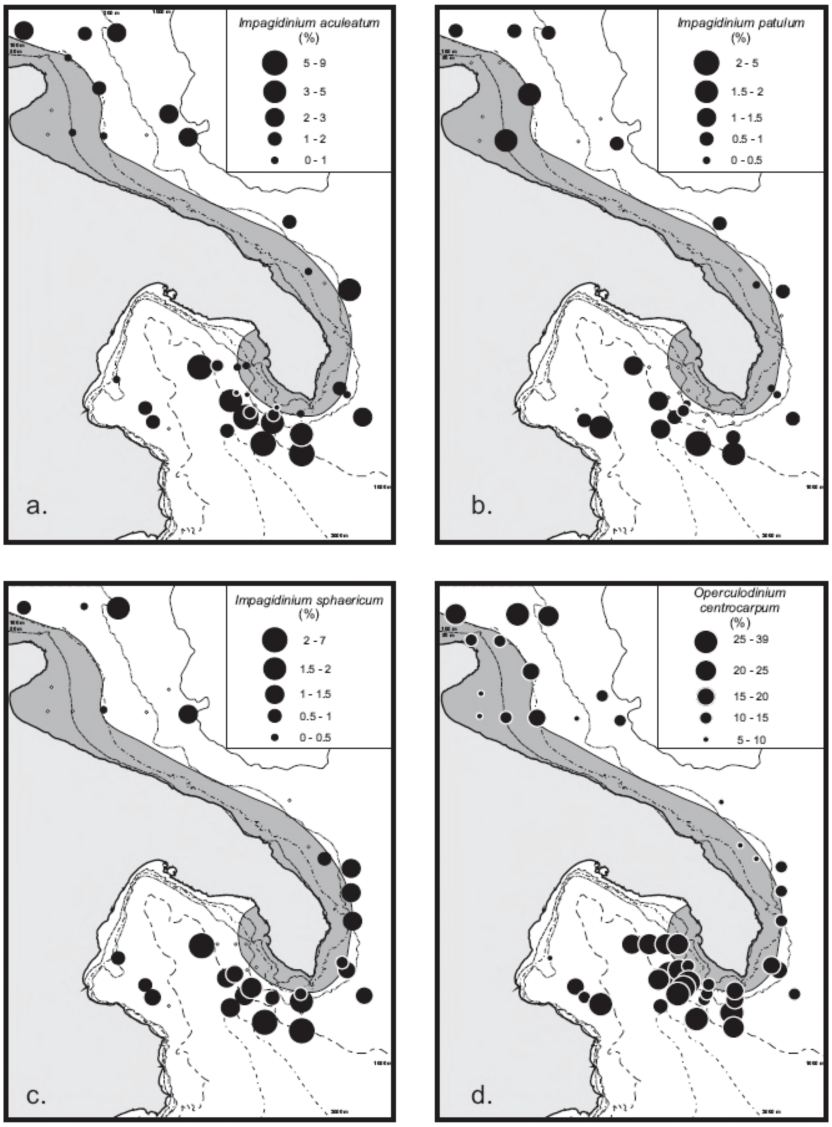


Fig. 9. Map of the research area depicting the relative abundances of (a) *Impagidinium aculeatum*, (b) *Impagidinium patulum*, (c) *Impagidinium sphaericum* and (d) *Operculodinium centrocarpum* in upper sediments. Grey area represents the maximal extension of the river plume in spring.

The occurrences of reworked cysts, can be explained by the erosion of older sediments at times of maximal outflow. One of the most prominent species within this group is *Lingulodinium machaerophorum.* Before discussing its ecology (see next chapter) we can make some remarks about its paleoceanographical significance. *L. machaerophorum* is often observed in high and sometimes overwhelming amounts present in sediments from river plumes (Fig. 6a, Lewis, 1988; Dale and Fjellså, 1994; Lewis and Hallett, 1997; Dale et al., 1999; de Vernal et al., 2001; Dale et al., 2002; Pospelova et al., 2004; Wang et al., 2004; Giannakourou et al., 2005; Pospelova et al., 2005). In the northern Adriatic Sea, red tides caused by this species are frequent occurrences (e.g. Boni et al., 1986). In that region, high concentrations of this species are observed in surface sediments in the close vicinity of the Po-river delta with concentrations decreasing with increasing distance from the delta (Rubino et al., 2000; Sangiorgi et al., 2005). Also in the vicinity of river mounds of nearby Greek rivers that drain in the Aegean Sea, cyst concentrations of *L. machaerophorum* are highest in close vicinity of the river mouths (Giannakourou et al., 2005). We therefore conclude that for palaeoceanographic studies in the research area, *L. machaerophorum* forms a useful key species to reconstruct past variations in river outflow. The more since *L. machaerophorum* is observed to be moderately resistant against aerobic degradation minimizing the risk that diagenetic overprint destroys the initial signal post-depositional (Zonneveld et al., 2008b and references therein).

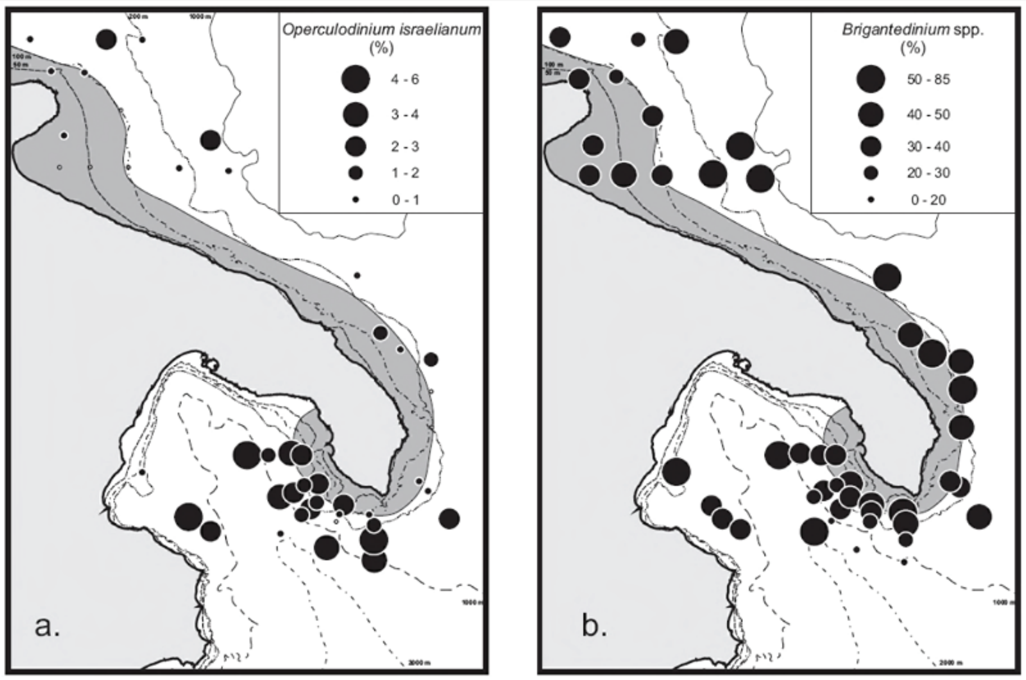


Fig. 10. Map of the research area depicting the relative abundances of (a) *Operculodinium israelianum* and (b) *Brigantedinium spp.* in upper sediments. Grey area represents the maximal extension of the river plume in spring.

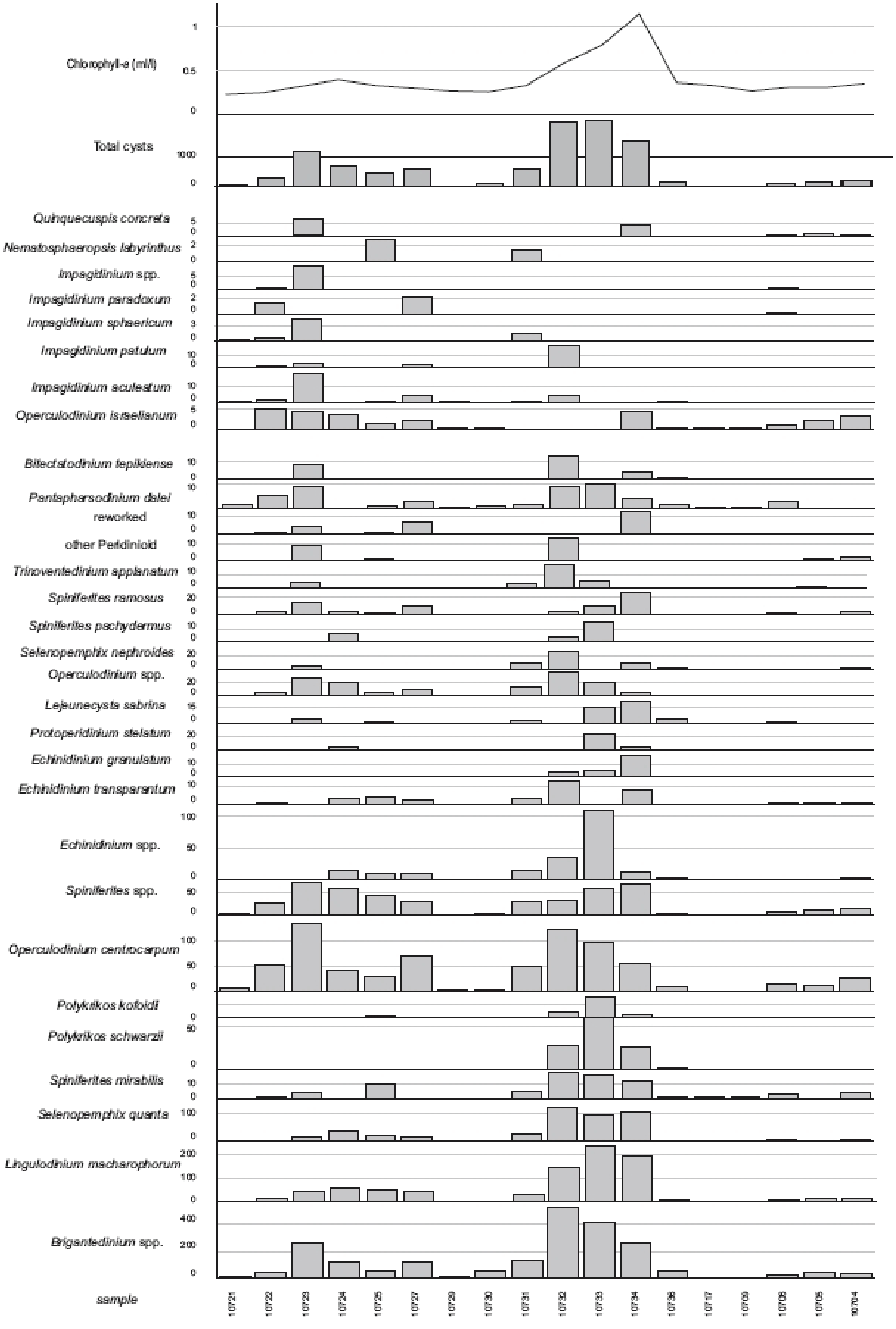


Fig. 11. Accumulation rates of the individual cyst species in relationship to chlorophyll-a concentrations in spring.

When associations of river systems or estuaries in the world are compared, it can be observed that next to *L. machaerophorum,* cysts of *Polykrikos kofoidii* and/or *Polykrikos schwarzii* contribute characteristically to the cyst association sediments deposited in the vicinity of river mouths in temperate to subtropical regions (e.g. Figs. 6b, 5c, Kobayashi et al., 1986; Matsuoka, 1987; Larrazabal et al., 1990; Matsuoka and Lee, 1994; Grill and Guerstein, 1995; Matthiessen and Brenner, 1995, 1996; Rochon et al., 1999; Cho and Matsuoka, 2000; de Vernal et al., 2001; Cho et al., 2003; Orlova et al., 2004; Pospelova et al., 2004, 2005; Radi and de Vernal, 2004; Wang et al., 2004; Matthiessen et al., 2005; Borel et al., 2006; Cremer et al., 2007; Holzwarth et al., 2007; Novichkova and Polyakova, 2007; Radi et al., 2007; Pospelova et al., 2008; Siringan et al., 2008). Our results are in good agreement with these observations.

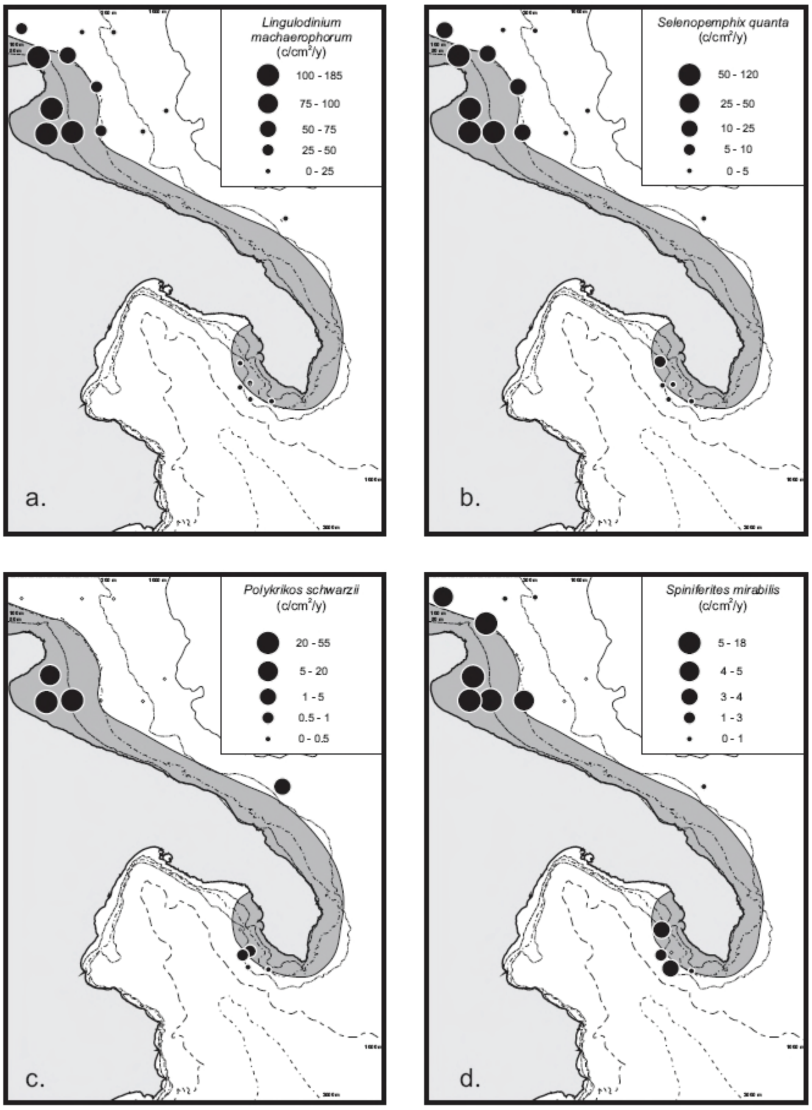


Fig. 12. Map of the research area depicting the accumulation rates of (a) *Lingulodinium machaerophorum*, (b) *Selenopemphix quanta*, (c) *Polykrikos schwarzii* and (d) *Spiniferites mirabilis* in upper sediments. Grey area represents the maximal extension of the river plume in spring.

Apart from *Lingulodinium machaerophorum, Polykrikos kofoidii* and *Polykrikos schwarzii* we observe that distribution of *Echinidinium* spp., *Lejeunecysta sabrina,* cysts of *Protoperidinium stellatum* and, *Selenopemphix quanta* is restricted to the discharge plume (Figs 5, 7). The world-wide distribution of the species we observe in the Po-river plume are not restricted to estuarine environments. Nevertheless, the combination of species in group 1 is unique for the Po-river and clearly reflects river influence in our research area. It can therefore be used to trace past variations in river discharge in the research area. This is in accordance to previous investigations in the vicinity of the Po-river mouth in the North Adriatic Sea area where increased relative abundances of species of this group are regarded to be the result of the combined effect of increased preservation and enhanced nutrient availability of the surface waters caused by eutrophication events (Rubino et al., 2000; Sangiorgi and Donders, 2004; Sangiorgi et al., 2005, Note: *Echinidinium* spp. is documented as dinocyst type 3 and dinocyst type 4 in Rubino et al. (2000). Furthermore Rubino et al. did not make a separation between *Polykrikos kofoidii* and *Polykrikos schwarzii* and *Selenopemphix quanta* is documented under its motile name).

In the latter area,

Group 2. Warm water association. In the research area, high relative abundances of *Spiniferites mirabilis, Spiniferites pachydermus, Spiniferites ramosus* and *Spiniferites* spp. are found in sites where upper water temperatures are relatively warm (Fig. 8). This is in agreement with the global distribution of these species that shows that they are more common in subtropical to tropical regions (Marret and Zonneveld, 2003). In temperate regions their relative abundances are often higher in the warmest water sites of the study regions (e.g. Rochon et al., 1999; Esper and Zonneveld, 2007; Radi et al., 2007; Pospelova et al., 2008). Within the Adriatic Sea increase in relative abundances of these species reflects increases in temperature related to termination 1b of the last deglaciation (e.g. Zonneveld, 1996; Combourieu-Nebout et al., 1998). However, although sea surface temperature might be a factor that influences the cyst distribution of these species relative to the other dinoflagellate cyst species, our study setup does not provide evidence for causality but only shows a significant relationship. Furthermore, we observe a negative relationship between the cyst production of these species and temperature (Fig. 5, see next chapter). Consequently, care has to be taken by interpreting past changes in this association in terms of temperature changes.

Group 3. Oxygenated bottom water group. Our survey documents that *Impagidinium aculeatum, Impagidinium patulum, Impagidinium sphaericum, Operculodinium centrocarpum* and *Operculodinium israelianum* have their highest relative abundance data in sites that where bottom waters consist of Adriatic Deep Water or Eastern Mediterranean Deep water that are characterized by high oxygen concentrations. Apart from this observation, the results of the RDA analysis document a clear negative relationship of the cyst distribution with upper water chlorophyll-*a* concentrations. In our research area, the gradual change in water depth, bottom water oxygen concentration and upper ocean chlorophyll-*a* concentration strongly co-varies. It is therefore not clear at first sight in how far these individual environmental parameters have influenced the cyst distribution in our research area. In the pioneering phase of dinoflagellate cyst ecology studies, water depth was considered to be a major important factor determining the cyst distribution in sediments (e.g. Wall and Dale, 1968; Dale, 1976; Harland, 1983). Later, more detailed studies on the modern cyst distribution and sediment traps gave evidence that the trophic state of the surface waters, which often co-varies with water depth, is a much more important steering factor (e.g. de Vernal et al., 2001; Marret and zonneveld, 2003. ; Radi and de Vernal, 2004; Rochon and Marret, 2004). Accordingly, water depth has been considered to be an important steering factor for a few lagoonal species only. The species we observed in this study are all known to occur in a wide variety of water depths (Marret and Zonneveld, 2003). Furthermore most species show a clear increased cyst production on the shelf (see next chapter). Consequently we assume that water depth is not an important steering factor.

From the species classified in group 3, only the species *Impagidinium patulum* is characteristically found in high relative abundances in low productivity regions (e.g. Dale, 1986; Zonneveld, 1997; Dale, 1996; de Vernal et al., 1998; Devillers and de Vernal, 2000; Dale et al., 2002; Marret and zonneveld, 2003. ; Marret et al., 2004; Matthiessen et al., 2005; Bockelmann et al., 2007; Esper and Zonneveld, 2007; Holzwarth et al., 2007; Radi et al., 2007; Pospelova et al., 2008). The others; *Impagidinium aculeatum, Impagidinium sphaericum, Operculodinium centrocarpum,* and *Operculodinium israelianum* can frequently found in high relative abundances in eutrophic areas as well (see world wide distribution charts in Marret and Zonneveld (2003). All species of group 3 are known, however, to be resistant against aerobic degradation (Zonneveld et al., 1997; Zonneveld et al., 2001; Bockelmann et al., 2007; Kodrans-Nsiah et al., 2008; Zonneveld et al., 2008b). We therefore assume that, apart from the trophic state of the surface waters, early diagenetic processes have affected the cyst association in the deeper sites increasing the relative abundances of these species.

Group 4. Within this group, species that are classified within the genus *Protoperidinium* are categorized. Highest abundances of these species are found in the inner part of the Golfo di Taranto (Fig. 10b). Here the traces of the characteristic river plume waters are lost due to mixing of the plume waters with ISW. This region is the coldest of the research area, especially during the winter months. Within this area highest bioproduction in upper waters occurs in winter. Since dinoflagellate species that form *Protoperidinium* cysts are known to be heterotrophic it might be expected that maximal production of these species occurs when a maximum of food is available. Consequently, it is likely that a positive relationship with the chlorophyll-a concentration in the upper waters exists. However, although we observe a strong positive relationship between the accumulation rates of this species with chlorophyll-a concentrations in spring (see next chapter, Fig. 15), we do not observe a significant relationship of the relative abundance data to the chlorophyll-*a* concentration in surface waters in any season.

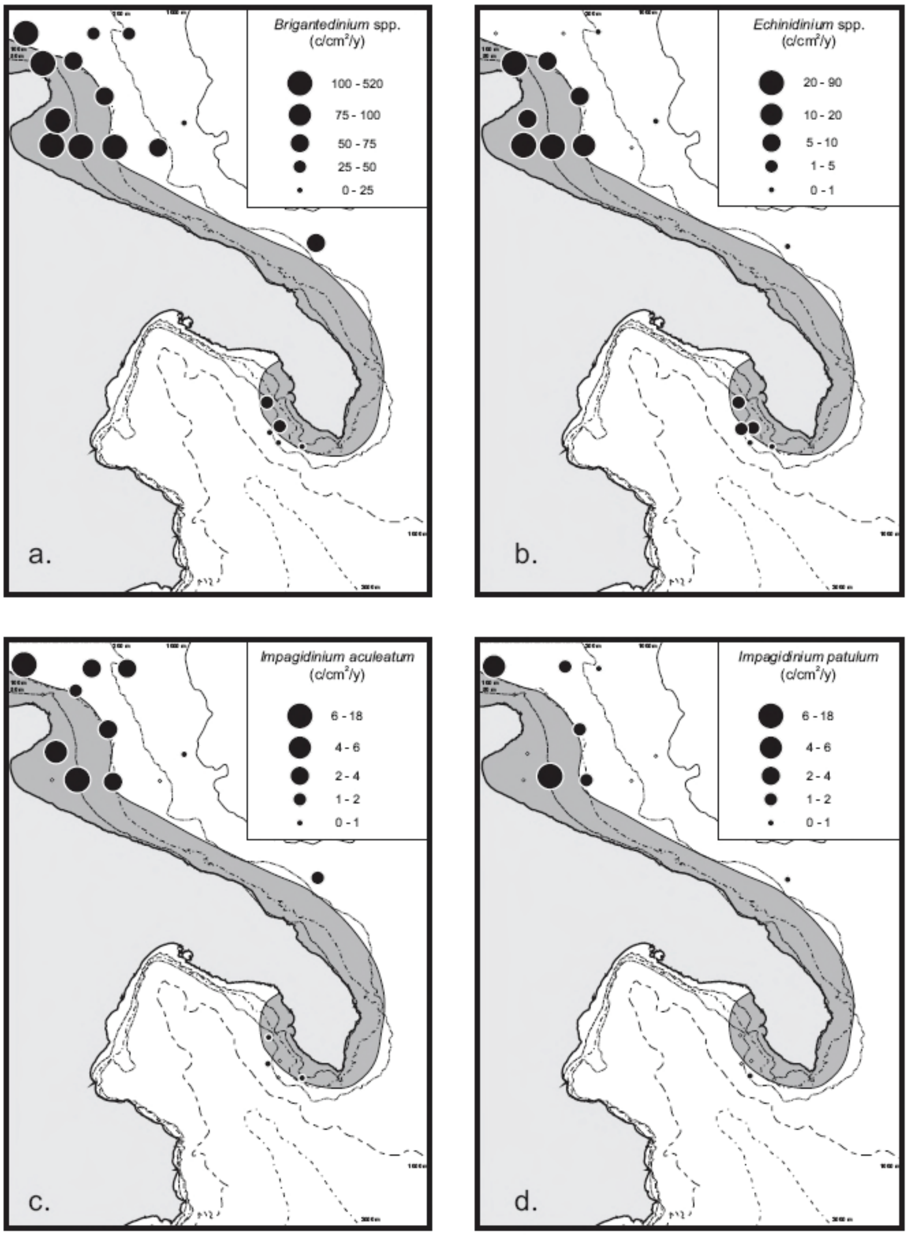


Fig. 13. Map of the research area depicting the accumulation rates of (a) *Brigantedinium spp.*, (b) *Echinidinium spp.*, (c) *Impagidinium aculeatum* and (d) *Impagidinium patulum* in upper sediments. Grey area represents the maximal extension of the river plume in spring.

5.3 Ecological remarks on selected cyst species based on accumulation rates

Current concepts on dinoflagellate cyst ecology are mainly based on the comparison of the relative cyst abundance in surface sediments with physical and chemical characteristics of the upper water column (e.g. Marret and zonneveld, 2003; Rochon and Marret , 2004; Radi et al. 2007; Pospelova et al. 2008). Changes in cyst proportion are often interpreted to reflect changes in cyst production. However, this can lead to wrong conclusions when the data suffer from alteration by early diagenetic processes (e.g. Zonneveld et al. 2008b, and references therein). Species-specific aerobic degradation is a logarithmic process. When sensitive species are deposited in oxic environment their accumulation rates might initially reflect upper ocean production but concentrations will decrease rapidly when the exposure time increases (see reaction times in Kodrans-Nsiah et al. (2008). Since the exposure time is generally not known and can vary remarkably between samples, e.g. as result of different sedimentation rates, it is difficult to estimate how much of the reactive species have been degraded. As result we decided for this study to stay "on the safe side" and base our ecological characterization of species on well dated shelf sites where bottom water oxygen concentrations are low. Our assumption that the dinoflagellate cyst accumulation rate signal is indeed not overprinted by degradation processes is subscribed by the fact that oxygen penetration depth is not significantly related to the cyst accumulation rate patterns as documented by the RDA analysis (Fig. 5).

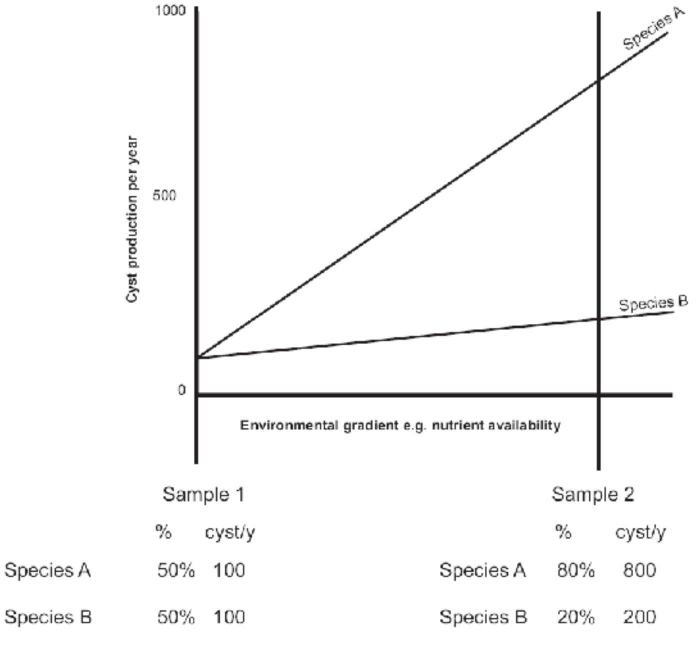


Fig.14. Schematic drawing elucidating the closed sum effect. The cyst production of two dinoflagellate species increase in relationship to increasing values of an environmental gradient, e.g. nutrient availability. Although both species increase their cyst production with increasing nutrient availability, relative abundance of species B decreases.

Apart from diagentic overprint, relative abundance data can suffer from the so called, "closed-sum effects" (Fig. 14). For example, when several species react on a change of an environmental parameter by increasing their cyst production, the accumulation rates of all species will increase. However, when the rate of this increase in cyst production is not equal for al species, the relative abundances of the species with the highest rates will increase whereas the relative abundances of species with lower rates will decrease (Fig. 14). As an example we consider or own dataset and have plotted the accumulation rates of several cyst species in non-oxidized sites against the chlorophyll-*a* concentrations in spring (Fig. 15). When we would calculate the relative abundances of species in this subset of samples, this would result in an increase in relative abundance of the strong increasing species *Brigantedinium* spp., *Lingulodinium machaerophorum* and *Selenopemphix quanta* but a decrease in relative abundance of the "slower" species such as *Impagidinium patulum, Trinovantedinium applanatum, Spiniferites pachydermus, Spiniferites ramosus* etc. (note: the discussion of chapter 5.2 is based on the complete dataset that includes aerobic sites as well, resulting in different relative abundance data-trends for the sensitive species *Brigantidinium* spp.). By restricting the study on relative abundances we could easily wrongly conclude that *Impagidinium patulum, Trinovantedinium applanatum, Spiniferites pachydermus, Spiniferites ramosus* are "oligotrophic" species. Consequently, we avoid bias as a result of the closed-sum effect by concentrating our ecological discussion on data of the accumulation rates of cysts rather than on relative abundance data.

Studies in natural environments show that maximal cyst production occurs during or just after dinoflagellate cyst blooms (Wall and dale, 1968; Ishikawa and Taniguchi, 1996; Montresor et al., 1998; Kremp and Heiskanen, 1999; Godhe et al., 2001). That this hold as well for our research area is suggested by two studies on two inner-bay sites in the "Mar Grande" and "Mar Piccolo" located near the city of Taranto at the proximity of the area where river plume waters can be traced (Belmonte et al., 1995; Rubino et al., 1998). Here maximal motile and cyst production is observed in spring and autumn at times of maximal plume extension (Fig. 3).

Within the upper waters of our accumulation rate sites, changes in salinity, temperature and chlorophyll-*a* gradients co-vary with the nutrient/trace element concentrations. Nutrient/trace elements form, next to light availability, the most important factor steering phytoplankton growth (Margalef, 1978; Smayda and Reynolds, 2003). Within the research area, we have no information in how far light limitation is influencing dinoflagellate and dinoflagellate cyst production. The surface waters in the region are well stratified such that turbulence is not a factor that induces light limitation here. Light limitation might occur though overshadowing by suspended material or other plankton. If this latter would be the case we could expect to find relatively low accumulation rates of cysts of photosynthetic dinoflagellates at places with high sediments load and/or high phytoplankton production which is in the north of the research area. For cysts of heterotrophic dinoflagellates we do not expect to find such a pattern as growth of these species is independent of light. However, we do not observe such a pattern. On the contrary, accumulation rates of all species are enhanced in the north of the research area. We therefore assume that light availability is not a factor that strongly influences cyst production in the research area.

Within the research area strong gradients in the upper water salinity concentrations can be observed. Although salinity is an important parameter influencing the geographic distribution of dinoflagellates, it is not known to trigger or influence their sexuality and cyst production.

Apart from the above mentioned factors, temperature, day length and an endogenic encystment rhythms are known to influence encystment of dinoflagellates; (e.g. Pfiester and Anderson, 1987; Taylor, 1987). It has been shown that although several dinoflagellates are able to produce cysts in a narrow temperature window, temperature itself, is not a triggering factor. Day length and endogenous rhythms are however likely to have influenced cyst production in our research area. Unfortunately our study setup does not allow us to estimate the rate in which these factors might have influenced our data.

We observe a strong positive correlation between cyst production and total phytoplankton production as well as a negative correlation between temperature in spring/winter and salinity in spring/summer. As mentioned before, in spring the maximal river outflow can be observed whereas in winter deep mixing of cold waters occurs in the Golfo di Taranto. Both processes enhance nutrient/trace element concentrations in upper waters which result in a gradual change of the upper water environmental paramenters as described above. We therefore assume that nutrient/trace element availability is the most important steering factor influencing the dinoflagellate cyst accumulation rate patterns.

The cyst production of the majority of species increases with increasing nutrient/trace element concentrations in the upper waters (Fig. 11). No species shows a negative relationship with increasing nutrient availability. The most pronounced positive relationship is documented for *Brigantidinium* spp., *Echinidinium* spp., *Lingulodinium machaerophorum, Polykrikos kofoidii/schwarzii, Spiniferites mirabilis* and *Selenopemphix quanta.* This suggests that these species are valuable indicators for changes in the trophic state of the upper waters within the Po-river area. To date there are not many studies present that investigate the relationship between cyst production and environmental conditions in the surface waters. The studies available support our observations for instance for *L. machaerophorum* which is one of the few cyst forming species from which a wealth of ecological information is available that is not based on its relative abundance data but on plankton surveys, sediment trap studies and culture experiments. Enhanced cyst production of this species is found in upwelling areas at times of upwelling relaxation and in the vicinity of river mouths where water masses are stratified but contain high amounts of nutrient concentrations (Lewis and Hallett, 1997; Smayda and Reynolds, 2003; Dale, 2008 and references therein). It is thought that the strong swimming ability of *L. machaerophorum* is advantageous in obtaining nutrients from deeper parts of the water column. Our results subscribe previous observations about the cyst production of *Lingulodinium machaerophorum* with enhancing cyst production related to increasing nutrient/trace element concentrations (Figs 11, 12a).

Information about the relationship between the cyst production of the other species and environmental conditions of the upper waters is rather sparse but supports our observations. Enhanced cyst production of *Selenopemphix quanta* has been observed in the Swedish Koljö Fjord in spring, the season with highest nutrient concentrations in surface waters in this region (Harland et al., 2004). Sediment trap records of the upwelling region off NW Africa document a relationship between enhanced production of *S. nephroides* related to enhanced amount of lithogen in the trap samples (Susek et al., 2005). Off NW Africa, lithogen components originate from the Saharan desert and are transported into the region in the form of dust. This dust contains important trace elements that enhance primary production in the region. In sediment trap studies other than the above mentioned studies, cyst concentrations of this species are, unfortunately, not high enough to distinguish a seasonal pattern or species specific information about the cyst production is lacking (Montresor et al., 1998; Morquecho and Lechuga-Devéze , 2004; Zonneveld and Brummer, 2000). *Polykrikos schwarzii* and *Polykrikos kofoidii* are often documented in river plume areas and increased cyst production has been related to eutrophication events in several studies (e.g. Matsuoka et al., 2003; Pospelova et al., 2005; Dale, 2008 and references therein). *Polykrikos kofoidii* is known as a predator of *Lingulodinium machaerophorum* (e.g. Jeong et al., 2001). The pattern observed here might therefore reflect this predator-prey relationship.

Within the Arabian Sea all *Echinidinium* species are typically produced within the upwelling season when nutrient concentrations are enhanced in surface waters and off NW Africa cyst production is enhanced when lithogen concentrations are high (Zonneveld and Brummer, 2000; Susek et al., 2005). In the Koljö Fjord and Bay of Napels enhanced production *Echinidinium* spp. and “round spiny reddish” cysts can be observed in spring when nutrient and trace element concentrations are enhanced (Montresor et al., 1998; Harland et al., 2004). However, Montresor et al. (1998) document high accumulation rates of “spiny reddish cysts” in autumn as well. In this embayment nutrient concentrations are much lower in autumn compared to spring. This suggests that an endogenic rhythm might steer cyst production as well.

The only information we could trace about the cyst production of *Spiniferites mirabilis* comes from the eastern Arabian Sea where enhanced production of these cysts can be found at the end of the upwelling season when nutrient concentrations are still high but turbulence has decreased (Zonneveld and Brummer, 2000). More studies on the cyst production of this species are urgently needed to test if the present observations of cyst production of *S. mirabilis* correspond to increased nutrient/trace element variability are valid for regions other than the Po-discharge area. Although the relative abundances of *S. mirabilis* are high in relatively warm waters, the cyst production in this study is negatively related to temperature gradients. Based on relative abundance data this species is often characterized as warm-water indicator (e.g. Marret and Zonneveld, 2003). However, our results suggest that temperature is not a causal factor steering the production of this species.

High concentrations of *Brigantedinium* spp. are traditionally related to eutrophic conditions and variations in its relative and absolute abundance are often used to reconstruct past primary productivity and changes and the trophic state of the upper waters (Marret and Zonneveld, 2003; Reichart and Brinkhuis, 2003; Radi et al., 2007; Dale, 2008 and references therein). Within this study we find a positive relationship between cyst production of these species and upper water nutrient availability (Figs. 5, 11, 15a). When we focus on ecological studies of this species that are based on data where aerobic degradation is unlikely to have overprinted the initial production signal, the results are not uniform. A clear increase in cyst production at times of increased nutrient/trace element availability reflected by increased lithogen input can be observed off NW Africa (Susek et al., 2005). Also in the Arabian Sea and Southern Ocean increased cyst production is observed in seasons and sites where nutrient/trace element concentrations in upper waters are enhanced (Harland and Pudsey, 1999; Zonneveld and Brummer, 2000). However, in the northern North Atlantic, most traps recording a seasonal signal with an optimum cyst production of *Brigantedinium* spp. in May/June and in the autumn season (Dale and Dale, 1992). In this region nutrient concentrations are maximal in late winter/early spring but depleted in autumn. Consequently, apart from the trophic level of the upper waters, cyst production is probably steered by a strong seasonal signal as well. This latter is also observed in the Bay of Napels, where the production of *Brigantedinium* is maximal in autumn when nutrients in surface waters are depleted (Montresor et al., 1998). In a survey about the seasonal occurrence of cysts in the flocculent layer in the Koljö Fjord, the cyst association is dominated throughout the year but highest cyst counts can be observed in June and September when phosphate concentrations in the Fjord are at a minimum. (Harland et al,. 2004). An extensive review about the relationship between eutrophication and cyst production of *Protoperidinium* is recently published by Dale (2008). He also notes that there is not always an uniform signal. He observed that cyst production of this group is sometimes increasing, sometimes decreasing in relationship to eutrophication events in different fjord systems. One explanation of these contrasting observations might be that in different regions of the world cysts of different dinoflagellates are grouped within this morphogenus. Furthermore, the results from Bay of Napels, northern North Atlantic and the Koljö Fjord suggest that cyst production might be steered by a strong endogenic rhythm which can be independent from the trophic state of the surface waters. Consequently, although our results suggest that within the research area *Brigantedinium* spp.

might be a good indicator for the trophic state of the upper waters, care that has to be taken when generalizing the ecologies of different species from a single genus. It shows that the (palaeo) ecology of dinoflagellates has to be considered on species level.

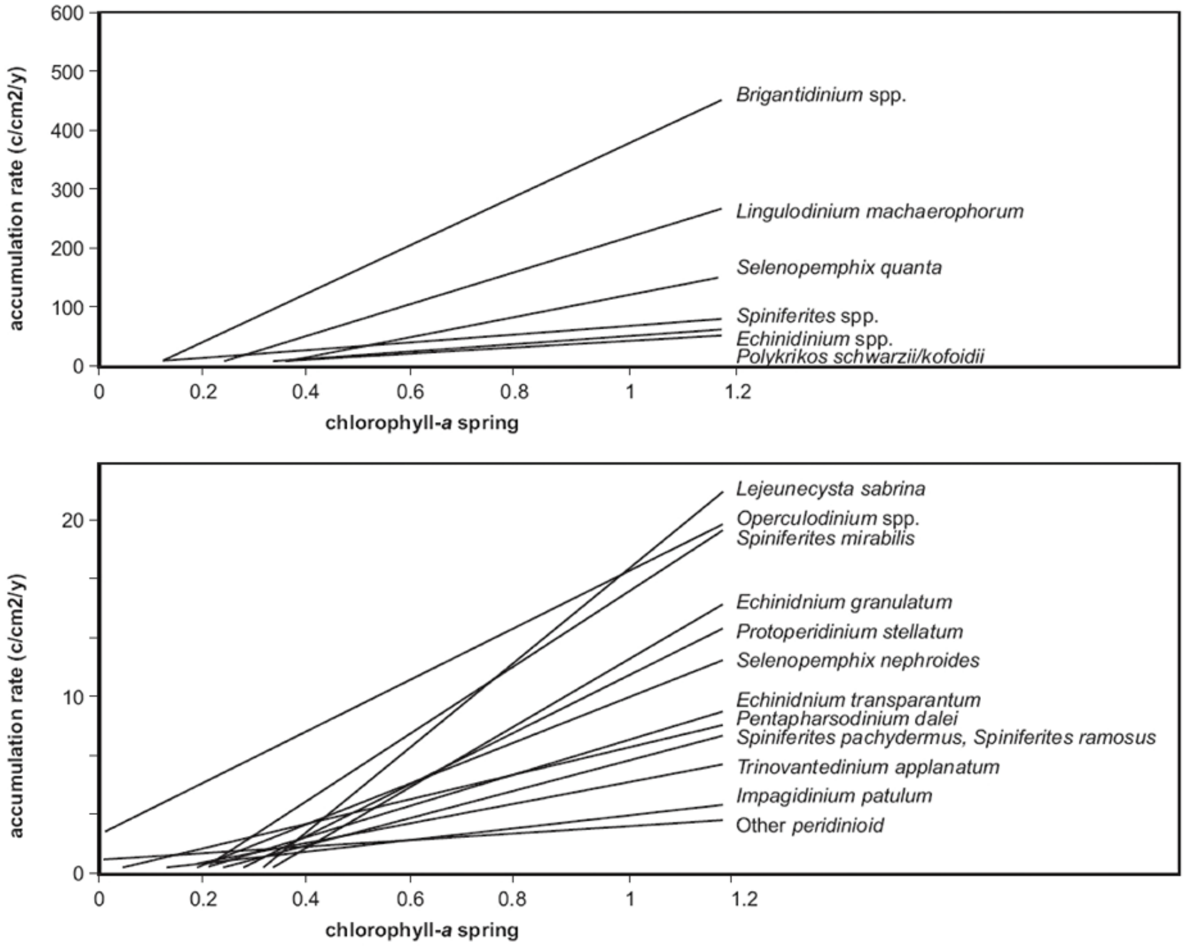


Fig. 15. Relationship between accumulation rates of individual cyst species and chlorophyll-a concentrations in the upper waters in spring.

The RDA analysis plots *Impagidinium aculeatum, Impagidinium sphaericum, Impagidinium paradoxum, Impagidinium* spp., *Nematosphaeropsis labyrinthus, Operculodinium israelianum* and *Quinquecuspis concreta* in the center of the diagram (Fig. 5). This indicates that either the highest production of these species corresponds to intermediate values of the studied gradients or that production rates do not change with the changing environmental gradients studied. The latter is probably the case for *Impagidinium sphaericum, Impagidinium paradoxum, Impagidinium* spp., *Nematosphaeropsis labyrinthus* and *Quinquecuspis concreta* which occur in such low amounts that no ecological interpretation can be made based on this dataset (Fig. 11).

Ecological studies based on relative abundance datasets generally suggest *Impagidinium aculeatum* and *Impagidinium patulum* to be characteristically produced in oligotrophic environments and as such they are often characterized as oligotrophic species.

However, the cyst production of these species is often extremely low as registered by sediment trap studies in both eutrophic and oligotrophic regions (Dale, 1992). In our study we also do not find a negative relationship between the accumulation rates of these species and chlorophyll-*a* concentration. On the contrary, the sites of our accumulation rates data are all located within the river-discharge plume where eutrophic conditions in surface waters occur. We even find a positive relationship between cyst accumulation rates of *I. patulum* and the chlorophyll-*a* concentrations in surface waters (Figure 15). The only species that is sometimes registered in higher abundances in sediment trap studies is *Impagidinium aculeatum.* This species shows enhanced cyst production during the upwelling season in the Arabian Sea.

The shortness of information about the production of cyst species in relationship to upper oceanic environmental conditions emphasizes the urgent need for further studies. Our study shows that valuable ecological information can be obtained when accumulation rates rather than relative abundances are studied. We therefore invite the dinoflagellate cyst research community to invest some time and money in dating of the sediments on the study sites so that we can establish accurate ecological concepts of the individual cyst species in future.

Conclusions

The dinoflagellate cyst association reflects both upper and bottom water circulation. Based on the relative abundance data four associations can be distinguished that are characteristic for the major oceanographic settings in the region. (1) River discharge association. This association consists of *Echinidinium* spp., *Lejeunecysta sabrina, Lingulodinium machaerophorum, Polykrikos* cysts of *Protoperidinium stellatum, Selenopemphix quanta* and reworked cysts. These species have high relative abundances in sites where bottom waters are low in oxygen and upper waters are influenced by river discharge waters that are characterized by high productivity and relative low salinity. (2) Warm water association. This association consists of *Spiniferites mirabilis, Spiniferites pachydermus, Spiniferites ramosus* and *Spiniferites* spp. which have their highest relative abundances in the sites that are characterized by relative warm upper waters with intermediate chlorophyll-a concentrations. (3) Oxygenated bottom water group. Species of this group; *Impagidinium aculeatum, Impagidinium patulum, Impagidinium sphaericum, Operculodinium centrocarpum* and *Operculodinium israelianum* have their highest relative abundance at sites where bottom waters are well oxygenated and formed by ADW or EMDW. (4) Golfo di Taranto group consisting of round brown cysts produced by *Protoperidinium* species (grouped as *Brigantedinium* spp.). These species have their highest relative abundances in the Golfo di Taranto that is characterized by enhanced primary production in winter.

The variation in accumulation rates can be related to gradiental changes in the trophic state of the surface waters linked to river outflow. Most species show a positive relationship between cyst production and nutrient/trace element availability in upper waters. No negative correlation between cyst production and nutrient/trace element availability could be documented so that we can not define so called oligotrophic cyst species.

Production of *Brigantidinium* spp., *Echinidinium* spp., *Lejeunecysta Sabrina, Lingulodinium machaerophorum, Polykrikos kofoidii/schwarzii, spiniferites* spp.*, Spiniferites mirabilis* and *Selenopemphix quanta* shows the most pronounced increase with increasing nutrient/trace element availability and as such might be valuable indicators for reconstructing changes in the trophic state of the upper waters within the Po-river area in palaeo-environmental studies. There are strong indications that the production of several *Brigantidinium* spp. and *Echinidinium* spp. species are steered by an endogenic rhythm as well. The current study suggests that the production of *Spiniferites mirabilis* is not steered by temperature.

Acknowledgements

We thank the captain Schneider and the R.V. POSEIDON crew members for the professional and kind help of collecting the samples during the CAPPUCINO cruise. This study has been carried out in the German Science foundation (DFG) sponsored International Graduate college EUROPROX and ISF project MOCCHA through financing of the shiptime and the position of Liang Chen. The Humbold Foundation is thanked for making a stay of Magdy Mahmoud in july – September at the University of Bremen possible. We thank the two reviewers and the editor for their constructive remarks that improved the paper.

References

Azanza, R. V., Siringan, F. P., Diego-Mcglone, M. L., Yniguez, A. T., Macalalad, N. H., Zamora, P. B., Agustin, M. B., and Matsuoka, K., 2004. Horizontal dinoflagellate cyst distribution, sediment characteristics and benthic flux in Manila Bay, Philippines. Phycological Research 52, 376-386.

Behrenfeld, M. J., Boss, E., Siegel, D. A., and Shea, D. M., 2005. Carbon-based ocean productivity and phytoplankton physiology from space. Global Biochemical Cycles 19, GB1006-1-GB1006-14.

Belmonte, G., Castello, P., Piccinni, M. R., Quarta, S., Rubino, F., Geraci, S., and Boero, F., 1993. Resting stages in marine sediments off the Italian coast. Eleftheriou, A., Ansell, A. D., and Smith, C. J. Biology and Ecology of Shallow Coastal Waters.Proceedings of the 28th European Marine Biology Symposium, IMBC,Hersonissos, Crete, 1993. 53-58. 1995. Fredensborg, Denmark, Olson and Olson.

Blanco, J., 1995. The distribution of dinoflagellate cysts along the Galician (NW Spain) coast. Journal of Plankton Research 17, 283-302.

Bockelmann, F.-D., Zonneveld, K. A. F., and Schmidt, M., 2007. Assessing environmental control on dinoflagellate cyst distribution in surface sediments of the Benguela upwelling region (eastern South Atlantic). Limnology and Oceanography 52, 2582-2594.

Boldrin, A., Langone, L., Miserocchi, S., Turchetto, M. M., and Acri, F., 2005. Po River plume on the Adriatic continental shelf: dispersion and sedimentation of dissolved and suspended matter during different river discharge rates. Marine Geology 222-223, 135-158.

Boldrin, A., Miserocchi, S., Rabitti, S., Turchetto, M. M., Balboni, V., and Socal, G., 2002. Particulate matter in the southern Adriatic and Ionian Sea: characterisation and downward fluxes. Journal of Marine Systems 33-34, 389-410.

Boni, L., Ceredi, A., Guerrini, F., Milandri, A., Pistocchi, R., Poletti, R., and Pompei, M., 2000. Toxic *Protoceratium reticulatum* (Peridiniales, Dinophyta) in the north-western Adriatic Sea (Italy). In 'Harmfull Algal Blooms, Proceedings of the IX international conference on harmfull algal blooms.'. pp. 137-40. (UNESCO: Paris.)

Boni, L., Mancini, L., Milandri, A., Poletti, R., Pompei, M., and Viviani, R., 1992. First cases of diarrhoetic shellfish poisening in the Northern Adriatic Sea (Italy). In 'Marine Coastal Eutrophication'. (Eds. R. A. Vollenweiler, R. Marchetti, and R. Viviani. Elsevier: Amsterdam.

Boni, L., Pompei, M., and Reti, M., 1986. Maree colorate e fioriture algali lungo le coste dell'Emilia-Romagna dal 1982 al 1985con particolare riguardo alla comparsa di *Protogonyaulax tamarensis*. Nova Thalassia 8, 237-245.

Borel, C. M., Cervellini, P. M., and Guerstein, G. R., 2006. Quistes de dinoflagellados de sedimentos Holocenos y dinoflagellados modernos del Estuario de Bahía Blanca, Argentinia. Geoacta 31, 23-31.

Boudena, M., 2004. Sea surface temperature of the central mediterranean during the last Millenium. Thesis Università degli studi di Torino, pp. 64.

Campbell, J., Antoine, D., Armstrong, R., Arrigo, K., Balch, W., Barber, R., Behrenfeld, M., Bidigare, R., Bishop, J., Carr, M. E., Esaias, W., Falkowski, P., Hoepffner, N., Iverson, R., Kiefer, D., Lohrenz, S., Marra, J., Morel, A., Ryan, J., Vedernikov, V., Waters, K., Yentsch, C., Yoder, J., Antoine, J.-M., Armstrong, R., Arrigo, K., Balch, W., and Barber, R., 2002. Comparison of algorithms for estimating ocean primary production from surface chlorophyll, temperature, and irradiance. Global Biogeochemical Cycles 16, 74-75.

Caroppo, C., Turicchia, S., and Margheri, M. C., 2006. Phytoplankton assemblages in coastal waters of the northern Ionian Sea (eastern Mediterranean), with special reference to cyanobacteria. Journal of the Marine Biology Association of the United Kingdom 86, 927-937.

Casotti, R., Landolfi, A., Brunet, C., D'Ortenzio, F., Mangoni, O., and Ribera d' Alcalà, M., 2003. Composition and dynamics of the phytoplankton of the Ionian Sea (eastern Mediterranean). Journal of Geophysical Research 108, 8116.

Cho, H.-J., Kim, C.-H., Moon, C.-H., and Matsuoka, K., 2003. Dinoflagellate cysts in recent sediment from the southern coastal waters of Korea. Botanica Marina 46, 332-337.

Cho, H.-J. and Matsuoka, K., 2000. Distribution of dinoflagellate cysts in surface sediments from the Yellow Sea and East China Sea. Marine Micropaleontology 42, 103-123.

Cini Castagnoli, G., Bonino, G., Della Monica, P., and Taricco, C., 1997. The solar-irradiance variability recorded by thermo-luminescence in shallow Ionian Sea sediments. In 'Past and Present Variability of the Solar-Terrestrial System: Measurement Data Analysis and Theoretical Models'. (Eds. G. Cini Castagnoli and A. Provenzale.) pp. 59-69. (IOS Press: Amsterdam.)

Cini Castagnoli, G., Bonino, G., Della Monica, P., Taricco, C., and Bernasconi, S. M., 1999. Solar activity in the last millennium recorded in the d^{18}O profile of planktonic foraminifera of a shallow water Ionian Sea core. Solar Physics 188, 191-202.

Combourieu-Nebout, N., Paterne, M., Turon, J-L. and Siani, G., 1998. A high-resolution record of the Last Deglaciation in the central Mediterranean sea. palaeovegetation and palaeohydrological evolution. Quaternary Science Reviews 17, 303-317.

Cremer, H., Sangiorgi, F., Wagner-Cremer, F., McGee, V., Lotter, A. F., and Visscher, H., 2007. Diatoms (Bacillariophyceae) and dinoflagellate cysts (Dinophyceae) from Rookery Bay, Florida, U.S.A. Carribbean Journal of Science 43, 23-58.

D'Ortenzio, F., Ragni, M., Marullo, S., and Ribera d' Alcalà, M., 2003. Did biological activity in the Ionian Sea change after the Eastern Mediterranean Transient? Results from the analysis of remote sensing observations. Journal of Geophysical Research 108, 8113.

Dale, A. L. and Dale, B., 1992. Dinoflagellate contributions to the open ocean sediment flux. In 'Dinoflagellate Contributions to the Deep Sea'. (Eds. B. Dale and A. L. Dale.) pp. 45-73. (Woods Hole Oceanographic Institution: Woods Hole.)

Dale, B., 1976. Cyst formation, sedimentation, and preservation: factors affecting dinoflagellate assemblages in recent sediments from Trondheimsfjord. Norway. Review of Palaeobotany and Palynology 22, 39-60.

Dale, B., 1986. Life cycle strategies of oceanic dinoflagellates. UNESCO Technical Papers in Marine Science 49, 65-72.

Dale, B., 1992. Dinoflagellate contributions to the open ocean sediment flux. In 'Dinoflagellate Contributions to the Deep Sea'. (Eds. B. Dale and A. L. Dale.) pp. 1-23. (Woods Hole Oceanographic Institution: Woods Hole.)

Dale, B., 1996. Dinoflagellate cyst ecology: modeling and geological applications. In 'Palynology: Principles and Applications'. (Eds. J. Jansonius and D. C. McGregor.) pp. 1249-75. (AASP Foundation: Salt Lake City.)

Dale, B., 2008. Eutrohication signals in the sedimentary record of dinoflagellate cysts in coeastal waters. Journal of Sea Research , 1-11.

Dale, B., Dale, A. L., and Jansen, J. H. F., 2002. Dinoflagellate cysts as environmental indicators in surface sediments from the Congo deep-sea fan and adjacent regions. Palaeogeography, Palaeoclimatology, Palaeoecology 185, 309-338.

Dale, B. and Fjellså, A., 1994. Dinoflagellate cysts as paleoproductivity indicators: state of the art, potential, and limits. In 'Carbon Cycling in the Glacial Ocean: Constraints on the Ocean's Role in Global Change'. (Eds. R. Zahn, T. F. Pedersen, M. A. Kaminski, and L. Labeyrie.) pp. 521-37. (Springer: Berlin.)

Dale, B., Thorsen, T. A., and Fjellså, A., 1999. Dinoflagellate cysts as indicators of Cultural eutrophication in the Oslofjord, Norway. Estuarine Coastal and Shelf Science 48, 371-382.

de Vernal, A., Eynaud, F., Henry, M., Hillaire-Marcel, C., Londeix, L., Mangin, S., Matthiessen, J., Marret, F., Radi, T., Rochon, A., Solignac, S., and Turon, J.-L., 2005. Reconstruction of sea surface conditions at middle to high latitudes of the Northern Hemisphere during the Last Glacial Maximum (LGM) based on dinoflagellate cyst assemblages. Quaternary Science Reviews 24, 897-924.

de Vernal, A., Matthiessen, J., Mudie, P. J., Rochon, A., Boessenkool, K. P., Eynaud, F., Grøsfjeld, K., Guiot, J., Hamel, D., Harland, R., Head, M. J., Kunz-Pirrung, M., Loucheur, V., Peyron, O., Pospelova, V., Radi, T., Turon, J.-L., and Voronina, E., 2001. Dinoflagellate cyst assemblages as tracers of sea-surface conditions in the northern North Atlantic, Arctic and sub-Arctic seas: the new "n-677" data base and its application for quantitative paleoceanographic reconstruction. Journal of Quaternary Science 16[7], 681-698.

de Vernal, A., Rochon, A., Turon, J.-L., and Matthiessen, J., 1998. Organic-walled dinoflagellate cysts: palynological tracers of sea-surface conditions in middle to high lattitude marine environments. Geobios 30, 905-920.

Devillers, R. and de Vernal, A., 2000. Distribution of dinoflagellate cysts in surface sediments of the North Atlantic in relation to nutrient content and productivity in surface waters. Marine Geology 166, 103-124.

Esper, O. and Zonneveld, K. A. F., 2007. The potential of organic-walled dinoflagellate cysts for the reconstruction of past sea-surface conditions in the Southern Ocean. Marine Micropaleontology 65, 185-212.

Filipsson, H. L., Björk, G., Harland, R., McQuoid, M. R., and Nordberg, K. A., 2004. major change in the phytoplankton of a Swedish sill fjord - a consequence of engeneering work? Estuarine Coastal and Shelf Science 63, 551-560.

Frignani, M., Langone L., Ravaioli M., Sorgente D., Alvisi F. and Albertazzi S., 2005. Fine-sediment mass balance in the western Adriatic continental shelf over a century time scale. Marine Geology 222–223, 113– 133

Giannakourou, A., Orlova, T. Y., Assimakopoulou, G., and Pagou, K., 2005. Dinoflagellate cysts in recent marine sediments from Thermaikos Gulf, greece: effects of resuspension events on vertical cyst distribution. Continental Shelf Research 25, 2585-2596.

Godhe, A., Norén, F., Kulenstierna, M., Ekberg, C., and Karlson, B., 2001. Relationship between planktonic dinoflagellate abundance, cysts recovered in sediment traps and environmental factors in the Gullmar Fjord, Sweden. Journal of Plankton Research 23, 923-938.

Grbec, B., Vilibic, I., Morovic, M., Paklar, G. B., Matic, F., and Dadic, V., 2007. Response of the Adriatic Sea to the atmospheric anomaly in 2003. Annales Geophysicae 25, 835-846.

Grill, S. C. and Guerstein, G. R., 1995. Estudio palynologico de sedimentos superficiales en el estuario de Bahia blanca, Buenos Aires (Argentinia). Polen 7, 40-49.

Hainbucher, D., Rubino, A., and Klein, B., 2006. Water mass characteristics in the deep layers of the western Ionian Basin observed during May 2003. Geophysical Research Letters 33, 1-4.

Harland, R., 1983. Distribution maps of recent dinoflagellate cysts in bottom sediments from the North Atlantic Ocean and adjacent seas. Palaeontology 26, 321-387.

Harland, R., Nordberg, K., and Filipsson, H. L., 2004. The seasonal occurence of dinoflagellate cysts in surface sediments from Koljö Fjord, west coast of Sweden - a note. Review of Palaeobotany and Palynology 128, 107-117.

Harland, R., Nordberg, K., and Filipsson, H. L., 2006. Dinoflagellate cysts and hydrological change in Gullmar Fjord, west coast of Sweden. Science of the total environment 355, 204-231.

Harland, R. and Pudsey, C. J., 1999. Dinoflagellate cysts from sediment traps deployed in the Bellinghausen, Weddell and Scotia Seas, Antarctica. *Marine Micropaleontology* **37**, 77-99.

Holzwarth, U., Esper, O., and Zonneveld, K., 2007. Distribution of organic-walled dinoflagellate cysts in shelf surface sediments of the Benguela upwelling system in relationship to environmental conditions. Marine Micropaleontology 64, 91-119.

Ishikawa, A. and Taniguchi, A., 1996. Contribution of benthic cysts to the population dynamics of *Scrippsiella* spp. (Dinophyceae) in Onagawa Bay, northeast Japan. Marine Ecology Progress Series 140, 169-178.

Jansen, E., Overpeck, J., Briffa, K. R., Duplessy, J.-C., Joos, F., Masson-Delmotte, V., Olago, D. O., Otto-Bliesner, B., Peltier, W. R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba, R., and Zhang, D., 2007. Palaeoclimate. In 'Climate Change 2007: The physical science basis. Contribution of working group I to the fourth report of the intergovernemental panel on climate change'. (Eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller.) pp. 434-97. (Cambridge University Press: Cambridge, UK.)

Jeong, H. J., Kim, S. K., Kim, J. S., Kim, J. T., Yoo, Y. D., and Yoon, J. H. Growth and grazing rates of heterotrophic dinoflagellate *Polykrikos kofoidii* on Red-Tide and toxic dinoflagellates. Journal of Eukaryotic Microbiology 48[3], 298-308. 2001.

Jongman, R. H. G., ter Braak, C. J. F., and Van Tongeren, O. F. R., 1987. 'Data Analysis in Community and Landscape Ecology.' (Cent. Agric. Publ. Doc. (Pudoc): Wageningen.)

Kobayashi, S., Matsuoka, K., and Iizuka, S., 1986. Distribution of dinoflagellate cysts in surface sediments of Japanese coastal waters. I Omura Bay, Kyushu. Bulletin of Plankton Society of Japan 33[2], 81-93.

Kodranz-Nsiah, M., Zonneveld, K. A. F., and de Lange, G. J., in press. Species-selective aerobic degradation of dinoflagellate cysts - results of a natural exposure experiment. Marine Micropaleontology.

Kremp, A. and Heiskanen, A.-S., 1999. Sexuality and cyst formation of the spring-bloom dinoflagellate *Scrippsiella hangoei* in the coastal northern Baltic Sea. Marine Biology 134, 771-777.

Larrazabal, M. E., Lassus, P., Maggi, P., and Bardouil, M., 1990. Kystes modernes de dinoflagellés en Baie de Villaine-Bretagne sud (France). Cryptogamie et Algologie 11, 171-185.

Lee, C. M., Orlic, M., Poulain, P.-M., and Cushman-Roisin, B., 2007. Introduction to special section: Recent advances in oceanography and marine meteorology of the Adriatic Sea. Journal of Geophysical Research, C 112.

Lewis, J., 1988. Cysts and sediments: *Gonyaulax polyedra* (*Lingulodinium machaerophorum*) in Loch Ceran. Journal of the Marine Biology Association of the United Kingdom 68, 701-714.

Lewis, J. and Hallett, R., 1997. *Lingulodinium polyedrum* (*Gonyaulax polyedra*) a blooming dinoflagellate. Oceanography and Marine Biology: an Annual Review 35, 97-161.

Margalef, R., 1978. Life forms of phytoplankton as survival alternatives in an unstable environment. Oceanologica Acta 1, 493-509.

Marret, F., Eiríksson, J., Knudsen, K. L., Turon, J.-L., and Scourse, J., 2004. Distribution of dinoflagellate cyst assemblages in surface sediments from the northern and western shelf of Iceland. Review of Palaeobotany and Palynology 128, 35-53.

Marret, F., Mudie, P. J., Aksu, A. E., and Hiscott, R. N., 2008. A Holocene dinocyst record of a two step transformation of the Neoeuxinian brackish water lake into the Black Sea. Quaternary International , 1-15.

Marret, F., Scourse, J., Versteegh, G., Jansen, J. H. F., and Schneider, R., 2001. Integrated marine and terrestrial evidence for abrupt Congo River palaeodischarge fluctuations during the last deglaciation. Journal of Quaternary Science 16, 761-766.

Marret, F. and Zonneveld, K. A. F., 2003. Atlas of modern organic-walled dinoflagellate cyst distribution. Review of Palaeobotany and Palynology 125, 1-200.

Matsuoka, K., 1987. Organic-walled dinoflagellate cysts from surface sediments of Akkeshi Bay and Lake Saroma, North Japan. Bulletin of the Faculty of Liberal Arts, Nagasaki University, Natural Science 28, 35-123.

Matsuoka, K., Joyce, L. B., Kotani, Y., and Matsuyama, Y., 2003. Modern dinoflagellate cysts in hypertrophic coastal waters of Tokyo Bay, Japan. Journal of Plankton Research 25, 1461-1470.

Matsuoka, K. and Lee, J.-B., 1994. Dinoflagellate cysts in surface sediments of Aso Bay and Mine Bay in Tsushima Island, West Japan. Bulletin of the Faculty of Liberal Arts, Nagasaki University, Natural Science 34, 121-132.

Matsuoka, K., Saito, Y., Katayama, H., Kanai, Y., Chen, J., and Zho, H., 1999. Marine palynomorphs found in surface sediments and a core sample collected from off Chanjang River, western part of the East China Sea. *Proceedings of the Second International Workshop on Oceanography and Fisheries in the East China Sea* 195-207.

Matthiessen, J. and Brenner, W., 1995. Orgenic-walled microfossils in Holocene sediments from Neustadt Bay, western Baltic Sea. Zeitblätter der Geologie und Paläontologie, Teil I 1/2, 67-81.

Matthiessen, J. and Brenner, W., 1996. Chlorococcalalgen und Dinoflagellaten-Zysten in rezenten Sedimenten des Greifswalder Boddens (südliche Ostsee). Senkenbergiana Maritima 27, 33-48.

Matthiessen, J., de Vernal, A., Head, M., Okolodkov, Y. B., Ángel, P., Zonneveld, K. A. F., and Harland, R. 2005. Modern organic-walled dinoflagellate cysts in Arctic marine environments and their (paleo-) environmental significance. Paläontologische Zeitschrift 79, 3-51.

Milligan, T. G. and Cattaneo, A., 2007. Sediment dynamics in the western Adriatic Sea: from transport to stratigraphy. Continental Shelf Research 27, 287-295.

Montresor, M., Zingone, A., and Sarno, D., 1998. Dinoflagellate cyst production at a coastal Mediterranean site. Journal of Plankton Research 20, 2291-2312.

Morquecho, L. and Lechuga-Devéze, C. H., 2004. Seasonal occurrence of planktonic dinoflagellates and cyst production in relationship to environmental variables in subtropical Bahía Concepción, Gulf of California. Botanica Marina 47, 313-322.

Mouw, C. B. and Yoder, J. A., 2005. Primary production calculations in the Mid-Atlantic Bight, including effects of phytoplankton community size structure. Limnology and Oceanography 50, 1232-1243.

Nittrouer, C. A., Miserocchi, S., and Trincardi, F., 2004. The PASTA project; investigation of Po and Apennine sediment transport and accumulation. Oceanography 17, 46-57.

Novichkova, E. A. and Polyakova, E. I., 2007. Dinoflagellate cysts in the surface sediments of the White Sea. Marine Biology 47, 709-719.

Orlova, T. Y., Morozova, T. V., Gribble, K. E., Kulis, D. M., and Anderson, D. M., 2004. Dinoflagellate cysts in recent marine sediments from the east coast of Russia. Botanica Marina 47, 148-201.

Palinkas, C. M. and Nittrouer, C. A., 2006. Clinoform sedimentation along the Apennine shelf, Adriatic Sea. Marine Geology 234, 245-260.

Penna, N., Capellacci, S., and Ricci, F., 2004. The influence of the Po River discharge on phytoplankton bloom dynamics along the coastline of Pesaro (Italy). Marine Pollution Bulletin 48, 321-326.

Persson, A. and Rosenberg, R., 2003. Impact of grazing and bioturbation of marine benthic deposit feeders on dinoflagellate cysts. Harmful Algae 2, 43-50.

Pfiester, L. A. and Anderson, D. M., 1987. Dinoflagellate life-cycles and their environmental control. In 'The biology of dinoflagellates'. (Ed. F. J. R. Taylor.) pp. 611-48. (Blackwell Scientific Publishers: Oxford.)

Pospelova, V., Chmura, G. L., Boothman, W. S., and Latimer, J. S., 2005. Spatial distribution of modern dinoflagellate cysts in polluted estuarine sediments from Buzzards Bay (Massachusetts, USA) embayments. Marine Ecology Progress Series 292, 23-40.

Pospelova, V., Chmura, G. L., and Walker, H. A., 2004. Environmental factors influencing the spatial distribution of dinoflagellate cyst assemblages in shallow lagoons of southern New England (USA). Review of Palaeobotany and Palynology 128, 7-34.

Pospelova, V., de Vernal, A., and Pedersen, T. F., 2008. Distribution of dinoflagelate cysts in surface sediments from the northeastern Pacific Ocean (43-25°N) in relation to sea-surface temperature, salinity, productivity and coastal upwelling. Marine Micropaleontology , 1-56.

Pospelova, V., Pedersen, T. F., and de Vernal, A., 2006. Dinoflagellate cysts as indicators of climatic and oceanographic changes during the past 40 kyr in the Santa Barbara Basin, southern California. Paleoceanography 21, 1-16.

Radi, T. and de Vernal, A., 2004. Dinocyst distribution in surface sediments from the northeast Pacific margin (40-60°N) in relation to hydrographic conditions, productivity and upwelling. Review of Palaeobotany and Palynology 128, 169-193.

Radi, T., Pospelova, V., de Vernal, A., and Barrie, J. V., 2007. Dinoflagellate cysts as indicators of water quality and productivity in British Columbia estuarine environments. Marine Micropaleontology 62, 269-297.

Reichart, G. J. and Brinkhuis, H., 2003. Late Quaternary *Protoperidinium* cysts as indicators of paleoproductivity in the northern Arabian Sea. Marine Micropaleontology 937, 1-13.

Reid, P. C., Balch, W. M., Surey-Gent, S. C., and John, A. W. G., 1981. Resuspension of dinoflagellate cysts during 1980 from bottom muds in Plymouth Sound. British Phycological Journal 16, 134.

Rochon, A., de Vernal, A., Turon, J.-L., Matthiessen, J., and Head, M., 1999. Distribution of Recent dinoflagellate cysts in surface sediments from the North Atlantic Ocean and adjacent seas in relation to sea-surface parameters. American Association of Stratigraphic Palynologists Contribution Series 35, 1-150.

Rochon, A. and Marret, F., 2004. Middle latitude dinoflagellates and their cysts: increasing our understanding on their distribution. Review of Palaeobotany and Palynology 128, 1-5.

Roether, W. and Putzka, A., 1996. Transient-tracer information on ventilation and transport of South Atlantic Waters. In 'The South Atlantic'. (Eds. G. Wefer, W. H. Berger, G. Siedler, and D. J. Webb.) pp. 45-62. (Springer-Verlag: Berlin,Heidelberg.)

Rossi, S., Auroux, C., and Mascle, J., 1983. The Gulf of Taranto (Southern Italy): seismic stratigraphy and shallow structure. Marine Geology 51, 327-346.

Rubino, F., Belmonte, G., Miglietta, A. M., Geraci, S., and Boero, F., 2000. Resting stages of plankton in recent North Adriatic sediments. Marine Ecology 21, 263-286.

Rubino, F., Belmonte, G., Todaro, M., and Boero, F., 1997. Cisti di protisti nei sedimenti del Golfo di Taranto. Biologia Marina Mediterranea 4, 612-614.

Rubino, F., Moscatello, S., Saracino, O. D., Fanelli, G., Belmonte, G., and Boero, F., 2002. Plankton-derived resting stages in marine coastal sediments along the Salenta Peninsula (Apulia, South-Eastern Italy). Marine Ecology Supplement 23, 329-339.

Rubino, F., Saracino, O. D., Fanelli, G., Belmonte, G., Miglietta, A., and Boero, F., 1998. Life cycles and pelagos-benthos interactions. Biologia Marina Mediterranea 5, 253-257.

Sangiorgi, F., Capotondi, L., and Brinkhuis, H., 2002. A centennial scale organic-walled dinoflagellate cyst record of the last glaciation in the south adriatic sea (Central Mediterranean). Palaeogeography Palaeoclimatology Palaeoecology 186, 199-216.

Sangiorgi, F. and Donders, T. H., 2004. Reconstructing 150 years of eutrofication in the north-western Adriatic Sea (Italy) using dinoflagellate cysts, pollen and spores. Estuarine Coastal and Shelf Science 60, 69-79.

Sangiorgi, F., Fabbri, D., Comandini, M., Gabbanelli, G., and Tagliavini, E., 2005. The distributin of sterols and organic-walled dinoflagellate cysts in surface sediments of the North-western Adriatic sea (Italy). Estuarine Coastal and Shelf Science 64, 395-406.

Santoleri, R., Banzon, V., Marullo, S., Napolitano, E., D'Ortenzio, F., and Evans, R., 2003. Year-to-year variability of the phytoplankton bloom in the southern Adriatic Sea (1998-2000): Sea-viewing Wide Field-of-view Sensor observations and modeling study. Journal of Geophysical Research 108, 8122.

Sellschopp, J. and Álvarez, A., 2003. Dense low-salinity outflow from the Adriatic Sea under mild (2001) and strong (1999) winter conditions. Journal of Geophysical Research, C 108[9], 8104.

Siringan, F. P., Azanza, R. V., Macalalad, N. H., Zamora, P. B., and Maria, M. Y. Y. S., 2008. Temporal changes in cyst densities of *Pyrodiniumbahamense* var. *compressum* and other dinoflagellates in the Manila Bay, Philippines. Harmful Algae , 1-31.

Smayda, T. J. and Reynolds, C. S., 2003. Strategies of marine dinoflagellate survival and some rules of assembly. Journal of Sea Research 49, 95-106.

Socal, G., Boldrin, A., Bianchi, F., Civitarese, G., De Lazzari, A., Rabitti, S., Totti, C., and Turchetto, M. M., 1999. Nutrient, particulate matter and phytoplankton variability in the photic layer of the Otranto strait. Journal of Marine Systems 20, 381-398.

Spatharis, S., Tsirtsis, G., Danielidis, D. B., DoChi, T., and Mouillot, D., 2007. Effects of pulsed nutrient inputs on phytoplankton assemblage structure and blooms in an enclosed coastal area. Estuarine Coastal and Shelf Science 73, 807-815.

Sprangers, M., Dammers, N., Brinkhuis, H., van Weering, T. C. E., and Lotter, A. F., 2003. Modern organic-walled dinoflagellate cyst distribution offshore NW Iberia; tracing the upweling system. Review of Palaeobotany and Palynology 2560, 1-3.

Susek, E., Zonneveld, K. A. F., Fischer, G., Versteegh, G. J. M., and Willems, H., 2005. Organic-walled dinoflagellate cyst production related to variations in upwelling intensity and lithogenic influx in the Cape Blanc region (off NW Africa). Phycological Research 53, 97-112.

Taylor, F. J. R.,1987. 'The Biology of Dinoflagellates.' (Blackwell Scientific Publications: Oxford.) ter Braak, C. J. F. and Smilauer, P.,1998. 'Canoco 4.' (Centre for Biometry: Wageningen.)

Turchetto M., Boldrin A., Langone L., Miserocchi S., Tesi T. and Foglini F., 2007. Particle transport in the Bari Canyon (southern Adriatic Sea). Marine Geology 246, 231–247.

Wall, D. and Dale, B., 1968. Modern dinoflagellate cysts and the evolution of the Peridinales. Micropaleontology 14, 265-304.

Wang, Z., Matsuoka, K., Qi, Y. Z., Chen, J. F., and Lu, S. H., 2004. Dinoflagellate cyst records in recent sediments from Daya Bay, South China Sea. Phycological Research 52, 396-407.

Zonneveld, C. A. F., Bockelmann, F.-D., and Holzwarth, U., 2007. Selective preservation of organic walled dinoflagellate cysts as a tool to quantify past net primary production and bottom water oxygen concentrations. Marine Geology 237, 109-126.

Zonneveld, K., Emeis, K.-C., Holzwarth, U., Kniebel, N., Möbius, J., Ní Fhlaithearta, S., Schmiedl, G., Versteegh, G., and Welti, R., 2008a. Report and preliminary results of the R/V POSEIDON cruise P339, Piräus - Messina, 16 June - 2 July 2006, CAPPUCCINO - Calabrian and Adriatic palaeoproductivity and climatic variability in the last two millenia. Berichte aus dem Fachbereich Geowissenschaften der Universität Bremen 268, 1-75. 2008a.

Zonneveld, K. A. F., 1997. Dinoflagellate cyst distribution in surface sediments of the Arabian Sea (Northwestern Indian Ocean) in relation to temperature and salinity gradients in the upper water column. Deep-Sea Research II 44, 1411-1443.

Zonneveld, K. A. F. and Brummer, G. A., 2000. Ecological significance, transport and preservation of organic walled dinoflagellate cysts in the Somali Basin, NW Arabian Sea. Deep-Sea Research II 47, 2229-2256.

Zonneveld, K.A.F., 1996. Palaeoclimatic reconstruction of the last deglaciation (18 ka. BP. - 8 ka. BP.) In the Adriatic Sea region: a land-sea correlation based on palynological evidence. Palaeogeography Palaeoclimatology Palaeoecology 122, 89-106.

Zonneveld, K. A. F., Versteegh, G. J. M., and de Lange, G. J., 1997. Preservation of organic walled dinoflagellate cysts in different oxygen regimes: a 10,000 years natural experiment. Marine Micropaleontology 29, 393-405.

Zonneveld, K. A. F., Versteegh, G. J. M., and de Lange, G. J., 2001. Palaeoproductivity and post-depositional aerobic organic matter decay reflected by dinoflagellate cyst assemblages of the Eastern Mediterranean S1 sapropel. Marine Geology 172, 181-195.

Zonneveld, K., Emeis, K., Holzwarth, U., Kniebel, N., Kuhnt, T., Möbius, J., Ní Fhlaithearta, S., Schmiedl, G., Versteegh, G. and Welti, R., 2008a. report and preliminary results of the R/V POSEIDON Cruise P339, Piräus - Messina, 16 June - 2 July 2006. CAPPUCCINO - Calbrian and Adriatic palaeoproductivity and climatic variability in the last two millenia. Berichte aus dem Fachbereich Geowissenschaften der Universität Bremen, 268, 1 - 61.

Zonneveld, K. A. F., Versteegh, G. J. M., and Kodranz-Nsiah, M., 2008b. Preservation of Late Cenozoic organic-walled dinoflagellate cysts; a review. Marine Micropaleontology 68, 179-197.

Appendix. Original counts of organic walled dinoflagellate cysts.

Sample	10701	10702	10703	10704	10705	10706	10707	10708	10709	10710	10711	10712	10713	10714	10715	10716	10717	10718	10719	10720	10721	10722	10723
Bitectatodinium tepekiense	1	0	0	0	0	1	2	4	4	0	2	1	0	1	0	4	2	4	7	4	0	0	2
Brigentedinium spp.	92	84	103	118	78	74	38	85	103	84	17	85	53	64	42	17	45	110	32	5	45	64	58
Pentapharsodinium dalei	5	4	1	0	0	11	8	2	6	10	9	3	1	2	6	10	2	27	7	4	8	7	2
Polykrikos kofoidii	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Polykrikos schwarzii	1	0	0	0	1	3	0	1	1	3	0	1	0	3	1	0	1	2	0	0	0	0	0
Protoperidinium stellatum	1	2	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	0	1	0	0	0	0
Echinidinium granulatum	0	0	0	2	1	1	1	0	0	0	0	1	1	0	0	1	1	3	0	0	1	0	0
Echinidinium spp.	2	0	5	6	2	6	0	2	4	6	0	2	3	6	0	0	4	10	0	1	1	0	0
Echinidinium transparantum	0	0	2	1	2	2	1	3	3	1	0	1	0	0	0	1	0	6	7	2	0	1	0
Impagidinium aculeatum	16	4	1	1	0	1	6	1	0	2	12	3	1	0	8	24	1	5	8	8	3	3	4
Impagidinium paradoxum	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	2	0
Impagidinium patulum	3	0	0	0	0	0	2	0	1	2	1	2	0	0	1	4	0	0	0	5	1	2	1
Impagidinium spp.	1	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2
Impagidinium sphaericum	5	0	0	0	0	0	2	3	0	2	2	4	0	1	2	10	0	0	1	5	2	1	1
Lejeunecysta sabrina	0	2	2	0	0	4	0	2	0	1	0	1	0	0	0	0	0	0	1	0	0	0	1
Lingulodinium machaerophorum	12	20	27	36	23	39	23	10	31	10	9	23	6	13	4	7	13	28	14	5	1	19	10
Nematosphaeropsis labyrinthus	1	0	0	0	0	0	0	1	1	0	0	0	1	1	2	0	1	0	2	5	0	0	0
Operculodinium centrocarpum	38	53	65	85	21	57	40	65	80	19	58	62	20	25	55	52	13	35	20	40	25	75	30
operculodinium israelianum	10	3	8	10	4	4	5	5	3	1	2	6	1	2	5	4	3	2	0	4	1	7	1
Operculodinium spp.	1	0	1	4	1	1	0	0	0	1	0	0	1	1	0	0	1	2	1	0	0	9	6
Quinquecuspis concreta	1	1	0	1	2	2	0	1	2	0	0	0	1	3	0	0	0	0	0	0	0	0	2
Selenopemphic nephroides	5	2	7	3	0	2	2	4	2	3	0	1	1	0	1	4	0	1	0	1	1	0	1
Selenopemphix quanta	2	7	7	18	3	17	3	7	10	5	1	7	4	1	1	0	3	18	2	1	1	1	4
Spiniferites mirabilis	3	2	3	12	0	10	2	5	14	0	5	3	1	6	4	6	3	10	10	3	1	1	1
Spiniferites pachyderma	0	4	0	0	0	0	3	0	0	2	1	3	0	1	0	1	0	0	6	0	0	1	0
Spniniferites ramosus	2	12	9	12	0	11	2	2	2	1	1	2	1	5	2	11	2	11	11	0	5	5	3
Spiniferites spp.	26	24	17	45	21	26	20	33	26	8	29	20	7	10	3	20	10	39	44	7	10	36	16
Trinovantedinium applanatum	0	1	0	1	1	0	0	1	0	0	0	1	1	0	1	0	0	1	0	0	0	0	1
other Peridinioid	1	0	5	7	2	3	2	1	1	2	0	0	0	2	0	0	0	0	0	0	1	0	2
reworked	0	0	0	1	0	2	0	0	0	0	0	0	0	0	1	6	0	1	0	1	0	1	1
total cysts	229	227	264	363	162	278	162	239	294	164	149	232	105	148	140	183	106	314	174	102	107	235	148
Lycopodium counts	2418	1466	2143	2190	1230	2555	3333	1983	3010	4644	5241	2643	3620	2174	4865	8395	4330	3185	2434	3155	2891	2844	2179
Weight processed (9)	0.8257	0.8255	0.8373	0.832	0.8373	0.8016	0.8316	0.8309	0.8339	0.8339	0.831	0.8289	0.8235	0.8607	1.558	1.951	0.8326	0.8468	0.8468	0.8264	0.9978	0.9862	0.988

Continued

Sample	10724	10725	10727	10729	10730	10731	10732	10733	10734	10735	10736	10737	10738	10739	10740	10741	10742	10743	10744	10746	10747	10748	10749
Bitectatodinium tepekiense	0	0	0	1	0	0	3	0	1	1	1	0	0	3	2	3	1	3	0	1	0	1	0
Brigentedinium spp.	36	45	76	97	145	83	113	77	61	291	90	96	131	97	57	107	63	76	105	83	62	46	42
Pentapharsodinium dalei	0	1	2	4	2	1	2	2	1	5	3	0	0	2	0	1	5	2	7	1	6	4	1
Polykrikos kofoidii	0	1	0	0	0	0	2	6	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Polykrikos schwarzii	0	0	0	0	0	0	6	13	6	0	3	2	2	1	2	2	0	2	2	1	0	0	0
Protoperidinium stellatum	1	1	0	0	0	1	0	5	1	1	0	1	2	0	1	0	0	1	1	1	0	0	0
Echinidinium granulatum	0	0	0	0	0	0	1	1	4	0	0	0	0	0	0	0	0	0	1	0	0	2	0
Echinidinium spp.	4	7	6	1	0	10	8	21	3	4	3	4	7	5	1	1	1	2	11	3	3	5	1
Echinidinium transparantum	1	3	1	1	0	2	3	0	2	1	0	2	2	4	2	2	4	2	0	0	0	1	0
Impagidinium aculeatum	0	1	3	5	0	1	1	0	0	10	2	1	0	6	0	0	4	2	4	1	2	3	1
Impagidinium paradoxum	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
Impagidinium patulum	0	0	2	0	0	0	4	0	0	2	1	0	1	1	0	0	1	1	1	0	0	1	2
Impagidinium spp.	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	1	2	0	0	0	0
Impagidinium sphaericum	0	0	0	0	0	1	0	0	0	4	0	0	2	2	1	2	2	3	2	1	1	2	0
Lejeunecysta sabrina	0	1	0	0	0	2	0	3	5	0	5	0	6	0	1	0	0	5	0	0	0	0	0
Lingulodinium machaerophorum	16	38	29	2	3	22	32	44	46	7	11	31	20	7	7	13	5	16	29	19	27	21	10
Nematosphaeropsis labyrinthus	0	2	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
Operculodinium centrocarpum	12	22	41	19	12	32	27	18	13	41	15	21	18	24	11	24	20	40	60	12	27	15	31
operculodinium israelianum	1	1	1	3	1	0	0	0	1	2	1	3	2	3	0	0	3	1	3	1	0	6	3
Operculodinium spp.	6	5	7	11	2	9	8	4	1	3	2	4	0	4	0	3	2	4	10	2	2	4	6
Quinquecuspis concreta	0	0	0	0	0	0	0	0	1	0	0	0	1	1	2	2	0	0	0	0	0	0	0
Selenopemphic nephroides	0	0	0	0	1	5	6	0	2	1	2	2	2	2	0	3	1	2	3	3	0	3	1
Selenopemphix quanta	11	18	10	1	1	16	26	18	25	0	5	22	16	4	1	4	3	2	11	1	0	3	0
Spiniferites mirabilis	0	8	0	0	0	3	4	3	3	1	1	6	1	3	1	1	3	2	6	2	2	7	1
Spiniferites pachyderma	2	0	0	1	1	0	1	3	0	0	0	0	0	0	0	0	0	1	0	0	1	2	1
Spniniferites ramosus	1	1	5	0	0	0	1	2	6	2	0	1	2	2	0	0	0	0	4	1	3	0	1
Spiniferites spp.	17	33	20	2	6	20	7	11	16	8	8	15	15	23	3	13	15	29	47	15	23	22	14
Trinovantedinium applanatum	0	0	0	0	0	2	4	1	0	0	0	1	1	0	0	1	0	1	0	0	0	0	0
other Peridinioid	0	1	0	0	0	0	3	0	0	0	0	4	1	2	2	0	1	5	0	4	0	0	0
reworked	0	1	3	1	0	0	0	0	3	0	0	0	1	0	4	1	0	0	2	0	0	4	0
total cysts	108	189	204	148	174	211	262	232	199	386	153	216	234	198	98	182	134	203	310	154	159	152	115
Lycopodium counts	1403	1545	5142	6284	5282	2195	1839	988	1453	1566	1347	1389	1859	1684	2235	1251	2449	2032	1915	2520	2422	6798	4595
Weight processed (9)	0.9902	0.9861	1.503	1.0084	1.0069	0.9934	0.9899	0.9971	0.9845	0.9943	0.9919	0.9925	0.9947	0.9994	1.923	1.0021	0.9903	0.9961	0.9872	0.9825	1.0002	1.491	1.617

5. Rapid fluctuations of the central Mediterranean environment during the last 400 years – human or naturally induced ?

Liang Chen,[1, *] Karin Zonneveld,[1,2] and Gerard Versteegh[2]

[1] Fachbereich Geowissenschaften, Universität Bremen, Postfach 330440, D-28334 Bremen, Germany
[2] MARUM, Universität Bremen, Leobenerstraße, D-28359 Bremen, Germany

* Corresponding author.

To be submitted to *The Holocene*, 2011

Abstract

Dinoflagellate cysts from marine sediments in the southern Adriatic area (Central Mediterranean) were used in a high resolution reconstruction of environmental and climatic change in order to investigate possible natural/anthropogenic forcing over the last 400 years. Rapid fluctuations of sea surface temperature (SST), precipitation and trophic conditions in the Gulf of Taranto area were recorded by individual dinoflagellate species, the overall association, and the freshwater species *Concentricystes* spp. The eutrophication reflected by *Lingulodinium machaerophorum* started around 1880 AD and has evolved with industrial and agricultural development as well as population growth in Italy. *Concentricystes* based precipitation variations are consistent with instrumental and documentary records in the Mediterranean region, and show a positive correlation with solar activity between 1700 and 1900 AD. We found that temperature increased after 1860 AD, which could correspond to global warming. Our reconstructed SST is also comparable to other proxy and instrumental records, although the magnitude and timing of temperature change are not always uniform within different locations. Naturally occurring cyclical changes of SST and precipitation signals may be connected with solar activity and the North Atlantic Oscillation (NAO), especially during the period of 1750-1940 AD. Furthermore, we suggest that the anthropogenic activity might have disturbed the climate rhythm after 1940 AD in the Southern Adriatic area.

1. Introduction

Rapid fluctuations of climate over Earth's history has attracted worldwide concern and led to significant scientific discussions during the past decades since it has strong environmental and socioeconomic impacts on society (e.g. Alley et al., 2003; IPCC, 2007). One of the most intriguing examples is the "global warming" issue during the past century where human activity has been suggested to be a main contributor for this phenomenon (e.g. Crowley, 2000; Jones and Mann, 2004; Mann et al., 1999). However, the question remains as to what extent human induced changes are responsible for the current global warming? The difficulty of this question is mainly due to the scarcity of exact climate forcing mechanisms, one feasible approach is to carry out the high fidelity reconstructions on past climatic change, for example last 400 years that covers both industrial and preindustrial periods can supply us more insights into this question.

Climate change of the Mediterranean has been studied by various proxies and climate models for several decades (e.g. Castagnoli et al., 1995; Gibelin and Deque, 2003; Schilman et al., 2001). The Mediterranean is located between low and mid-latitudes, and is highly sensitive to upper air circulation variations like the North Atlantic Oscillation (NAO). For example, recent studies have shown that sea surface temperatures (SST) in the Eastern Mediterranean were influenced by solar forcing over a centennial scale before anthropogenic interference (Versteegh et al., 2007). SST and primary productivity changes during the last deglaciation in the South Adriatic Sea have also been shown in the organic walled dinoflagellate cyst (dinocyst) records (Sangiorgi et al., 2002). However, little information exists on high resolution climate reconstructions on a decadal or even higher scale over the last 400 years. Furthermore, it is not known how dinoflagellate species might react to the rapid environmental transitions of global warming.

In this paper we investigate high frequency environmental and climatic variability through the use of dinocyst assemblages and the freshwater algal species *Concentricystes* spp. in the southern Adriatic Sea (Central Mediterranean). We show information on past trophic states in the upper water column through dinocyst evidence and provide more insight into the anthropogenic influence on marine ecosystems during last 200 years. The rapid climatic fluctuations are probably related to both solar activity and the NAO. Furthermore, the trends of observed SST and precipitation signals are discussed to both improve our knowledge on how dinoflagellates might react to anthropogenic disturbance and to describe how natural/anthropogenic activity can induce climate change in the study area.

2. Regional setting

The climate in the Mediterranean regions is strongly linked to the position of the westerlies which in turn is largely related to the North Atlantic climate modes, for example

North Atlantic Oscillation (NAO) (e.g. Hurrell and VanLoon, 1997; Vignudelli et al., 1999). The NAO represents a dipole-like pressure gradient between the Azores (high) and Iceland (low) (Hurrell, 1995). When NAO is in its positive phase (+NAO, strong pressure gradient between Iceland and Azores), northern Europe experiences excess precipitation. A negative phase (-NAO, weak pressure gradient between Iceland and Azores) brings enhanced precipitation and temperature in southern Europe and Mediterranean area (Baldini et al., 2008; Giorgi and Lionello, 2008; Lionello and Sanna, 2005). As a result, changes in NAO will have strong influence on the rainfall in the Italian regions, and the varied precipitation with river discharge will cause more or less freshwater entering into the Adriatic Sea along the coast to the Gulf of Taranto area which presented as Adriatic Surface Waters (ASW) (see details in Chen et al., 2011; Zonneveld et al., 2011). In the study location, ocean circulation is largely influenced by the river discharge waters which can be traced along the entire Italian eastern coast. Po-the largest Italian river drains the southern part of the Alps and the northern part of Italy forms one of the main source of surface freshwaters. It supplies a great deal of nutrients into the northwestern Adriatic Sea (e.g. Boldrin et al., 2005). Italian local eastern rivers also join these river discharge waters on their way southeastwardly. Meanwhile, Ionian Sea Waters (ISW) which is characterized by relatively high temperature and salinity and low nutrients enters the Gulf of Taranto region from the eastern side, these waters mix with ASW gradually in the Golf area (Boldrin et al., 2005; Socal et al., 1999). Furthermore, Levantine Intermediate Water (LIW) which comes from the Levantine basin and Adriatic Deep Water (ADW) which below 600 m depth can also be detected in the study area (e.g. Hainbucher et al., 2006; Sellschopp and Alvarez, 2003).

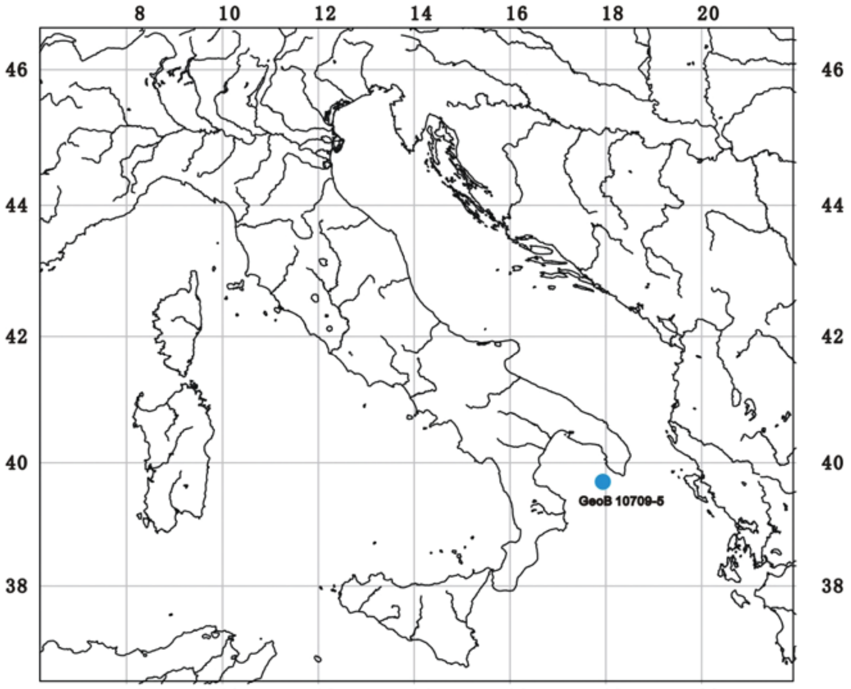


Figure 1. Research area, bule dot shows the core location.

3. Materials and sample preparation

Multicore GeoB 10709-5 was collected during the R.V. Poseidon cruise P339 “Cappuccino” in June 2006 at 39°45.39'N and 17°53.57'E from a water depth of 172.3m (Fig1) (Zonneveld, 2008). Direct after recovery, the complete multicore was stored at -20°C. The temperature of frozen material was enhanced to -4°C and the core was carefully sliced in parts of 2.5 mm, with exception of the lower 5 cm of the core that was left in one piece.

1 ml of each sample was dried overnight at 60 ^{o}C and weighted to determine the dry bulk density. Successively the material was brought into suspension in tap water and sieved over a 100 μm sieve. The material of size > 100 μm was dried and stored for future study. The remnant material <100 μm was treated using standard palynological preparation techniques according to the aliquot method as described by Zonneveld et al. (2009). No oxidative agents or heavy liquid separation has been preformed to avoid selective cyst degradation during sample preparation. Taxonomy is according to Marret and Zonneveld (2003). Round, brown colored cyst were grouped as *Brigantedinium spp.*. The classification of the species *Polykrikos kofoidii* and *P. schwarzii* are according to Matsuoka et al. (2009). Apart from organic walled dinoflagellate cyst (dinocyst), land derived pollen and spores and remains of the fresh water algal species *Concentricystes spp.* were distinguished.

4. Stratigraphic framework

The stratigraphic framework of the core is based on measurement of ^{210}Pb which is a natural radionuclide ($T_{1/2}$ = 22.26 yr) by product of ^{226}Ra decay. 11 samples of the core GeoB 10709-5 have been selected and measured for the ^{210}Pb content at the Institute of Environmental Physics, University of Bremen (Pittauerova and Fischer, 2009). For determination of excess-^{210}Pb activity (^{210}Pbxs), ^{210}Pb-supported activity was subtracted from the ^{210}Pb-total signal. Besides, ^{137}Cs, a fallout product of nuclear testing was also measured to detect its distribution in the sediments. We assume the upper 7 cm materials have been bioturbated and based on the constant flux constant sedimentation model (CFCS), it allows a sedimentation rate of 1.17 mm/y of the core 10709-5, the bottom of the core therefore can be dated back to 1664 AD (see description in Zonneveld et al., 2011).

5. Paleoenvironmental indicators

5.1 Anthropogenic induced eutrophication

Dinoflagellate species and associations have been suggested as a good eutrophication indicators (Dale, 2009). In many different estuarine basins, dinoflagellate species *Lingulodinium machaerophorum* and heterotrophic taxa were observed largely related to human induced waste discharge and industrial pollution (Dale et al., 1999; Harland et al., 2006; Pospelova et al., 2002; Pospelova and Kim, 2010; Radi et al., 2007). It is noticeable however that the sediments of our studied core might suffered organic matter degradation (Zonneveld et al., 2011). We therefore only use the autotrophic species *L. machaerophorum* to trace potential human induced eutrophication in the study area.

5.2 Local precipitation indicator

The freshwater alga *Concentricystes spp.* is used here to indicate the river discharge and precipitation in Southern Adriatic area. *Concentricystes* is restricted to the freshwater environments but can be transported into the marine waters by river discharge (Sánchez-Goñi et al., 1999). The concentration of this palynomorph can therefore indicate the river discharge waters which amount is largely subject to the local precipitation change.

5.3 Past sea surface temperature (SST)

Qualitative estimation of the past sea surface temperatures are based on the following formula:

$W/C = W_n / (W_n + C_n)$

where n = number of specimens counted, W = warm water species, C = cold water species. W = *Spiniferites mirabilis*, *Operculodinium israelianum*, *Impagidinium aculeatum,* Impagidinium patulum, *Impagidinium paradoxum* and *Polysphaeridium zoharyi.* C = *Bitectatodinium tepikiense* and *Spiniferites elongates.*

Species selection is according to the global distribution of organic walled dinoflagellate cysts (e.g. Marret and Zonneveld, 2003).

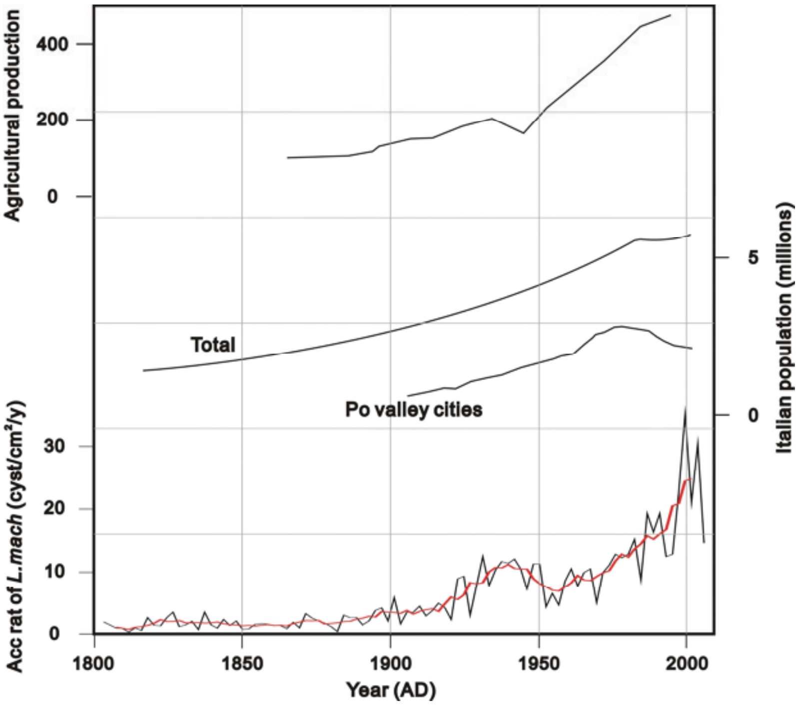


Figure 2. Accumulation rates of *L.machaerophorum* and comparison with Italian agricultural production (Federico and Malanima, 2004) and population variation. After Zonneveld (2011).

5. 4 Frequency analysis

Continuous Wavelet Transform (CWT) is used to show the cyclic characters of reconstructed SST and precipitation signal and inspect the temporal cyclicity distribution throughout the study period (Grinsted et al., 2004). Since our time series is unevenly distributed at the bottom of the core, we applied linear interpolation to our dataset before wavelet analysis is carried out.

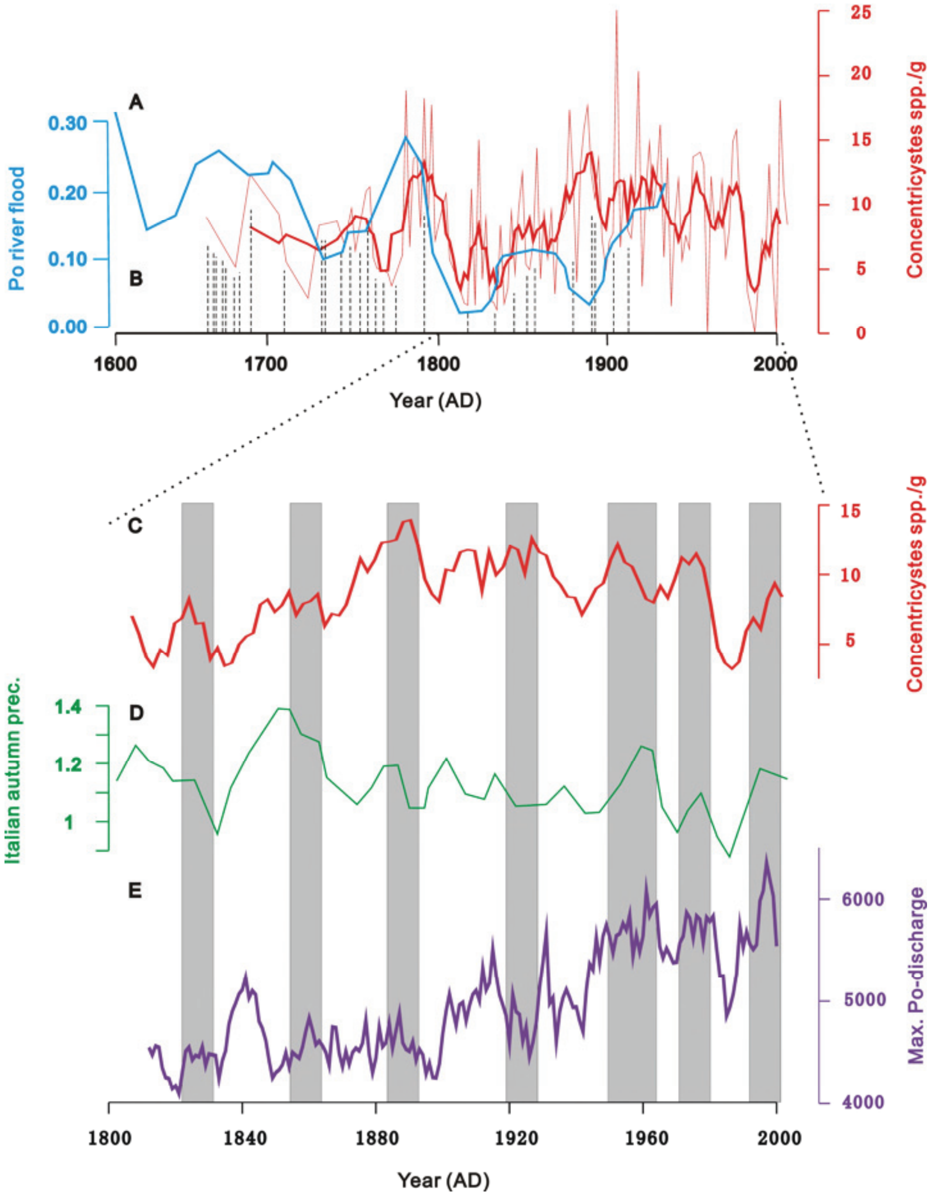


Figure 3. Concentration of *concentricystes* and comparison with A. Po river floods index (Camuffo and Enzi, 1995). B. Droughts records in Sicily (1565-1915 AD) (Piervitali and Colacino, 2001). D. Italian mean precipitation in autumn (Brunetti et al., 2006). E. Daily maximum Po discharge (m^3) (Zanchettin et al., 2008).

6. Results and discussions

6. 1 Human disturbance on marine trophic status

Autotrophic dinoflagellate species *L. machaerophorum* is used here to indicate human induced eutrophication history in our study area. We observe a gradual and slow increment of the accumulation rate of *L. machaerophorum* between 1880 and 1920 AD (Fig 2). Historical reports that the Italian industrial development starts at 1870 AD after the unification of the country (e.g. Collantes, 2006), indicating that this might have caused the initial increase of the accumulation rate of *L. machaerophorum* (Zonneveld et al., 2011). The accumulation rate of *L. machaerophorum* shows an abrupt increase from 1920 AD that ends at 1950 AD, this period corresponds well to the gross agricultural production in central and north Italy (Federico and Malanima, 2004) (Fig 2). Moreover, our results is comparable to the Northern Adriatic results which show the clear shift of *L. machaerophorum* at 1930 AD (Sangiorgi and Donders, 2004). Afterwards, *L. machaerophorum* continues to increase until reaching the maximum value between 1981-1991 AD which points to the highest eutrophication level, this hypertrophication can be interpreted by either agricultural development or population increase in Northern Italy (see details in Zonneveld et al., 2011). Notably, eutrophication seems to ameliorate after 1991 AD which means an improved water quality due to a ban of phosphorus in artificial fertilizer and washing products by the Italian government since 1979 AD. However, another increase trend of *L. machaerophorum* has been registered after 1995 AD which imply the ecosystem has not yet restored to the natural level.

6. 2 Local precipitation reconstructions in Southern Italy area

The concentration of *Concentricystes* has been used to trace the past freshwater variations in our study area (Chen et al., 2011), the amount of freshwater in Adriatic Sea is subject to the Italian river discharge waters which are largely related to the Italian precipitation, therefore we suggest that *Concentricystes* can be used here to reflect Italian local precipitation change in Southern Adriatic area. *Concentricystes* shows relatively low values between 1680 and 1840 AD, and an abrupt rise can be observed after 1840 AD. Its variation shows coherent patterns with both maximum daily po river discharge amount (Zanchettin et al., 2008b) and instrumental Italian average autumn precipitation (Brunetti et al., 2006) (Fig 3). Studies shows that po river has maximum discharge waters in spring and autumn due to enhanced meltwater of Alps and precipitation of Italy (e.g. Cattaneo et al., 2003). We therefore suggest the *Concentricystes* species might reflect the environmental signal during the autumn period. The good matching between concentration of *Concentricystes* and historical po river floods during 1680-1860 AD (Camuffo and Enzi, 1995) and documentary drought occurrence in Sicily during 1565-1915 AD (Piervitali and Colacino, 2001) confirms further that *Concentricystes* is a reliable proxy for Italian local precipitation variation (Fig 3). Particularly, the reconstructed precipitation series is consistent with recorded sunspot numbers between 1700 and 1900 AD, which active sun (maximum sunspot) corresponding to enhanced precipitation (Eddy, 1976). The positive correlations between floods (droughts) and maximum (minimum) solar activity have been established in Tagus basin (Central Spain) (Vaquero, 2004) and Sicily area respectively (Piervitali and Colacino, 2001), and in the Po basin (Northern Italy), the connection between NAO and po discharge is suggested to be modulated by solar activity (Zanchettin et al., 2008a). We therefore suggest that similar solar-river discharge/precipitation relationships might also exist in Southern Italian regions. However, clear discrepancy between solar activity and concentration of *Concentricystes* can be observed after 1860 AD (Fig 5), indicating the temporal heterogeneity of local precipitation under natural forcings such as solar activity and NAO, therefore more studies are required to explore this consequence in future. Another possible interpretation could be due to the anthropogenic influence, as we discussed above that human activity through industrial and agricultural development has disturbed the marine ecological system in our study area since 1895 AD, therefore the concentration of *Concentricystes* might have shown the response to this environmental change although the mechanism remains unclear.

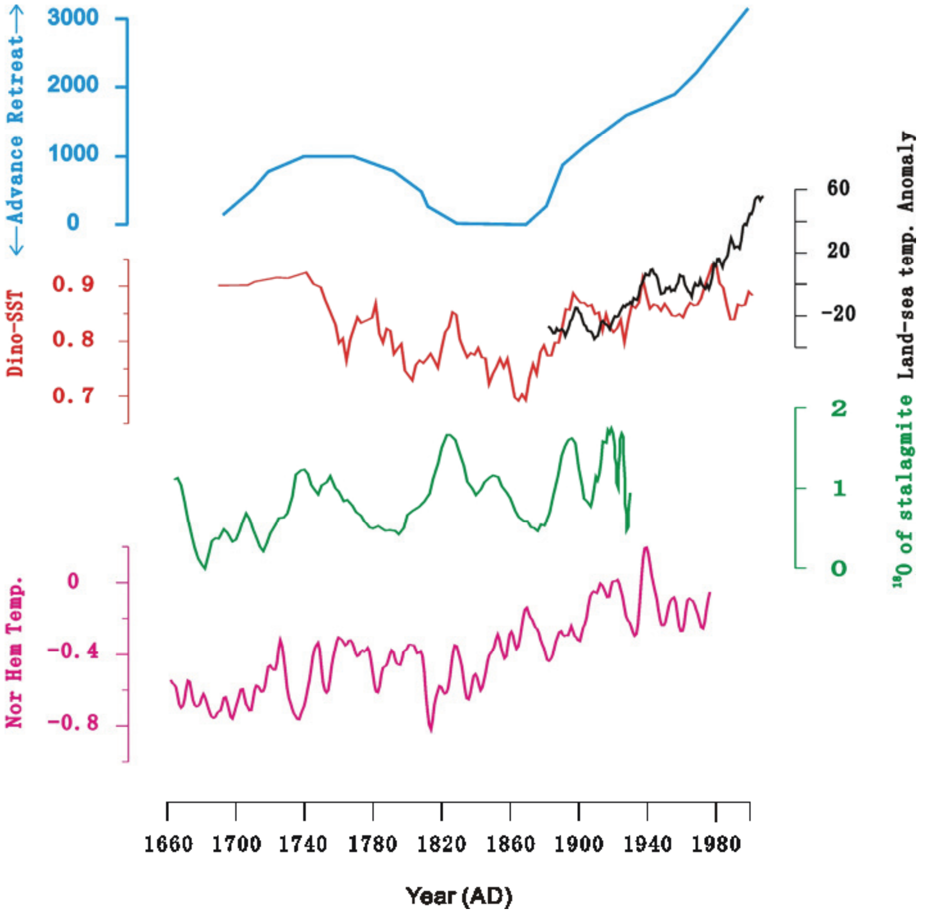


Figure 4. Reconstructed SST and compare with Alps glacial records (Haeberli and Holzhauser, 2003), speleothem records (Mangini et al., 2005), global land-sea temperature anomalies (Hansen et al., 2010) and Northern Hemisphere temperatures (Moberg et al., 2005).

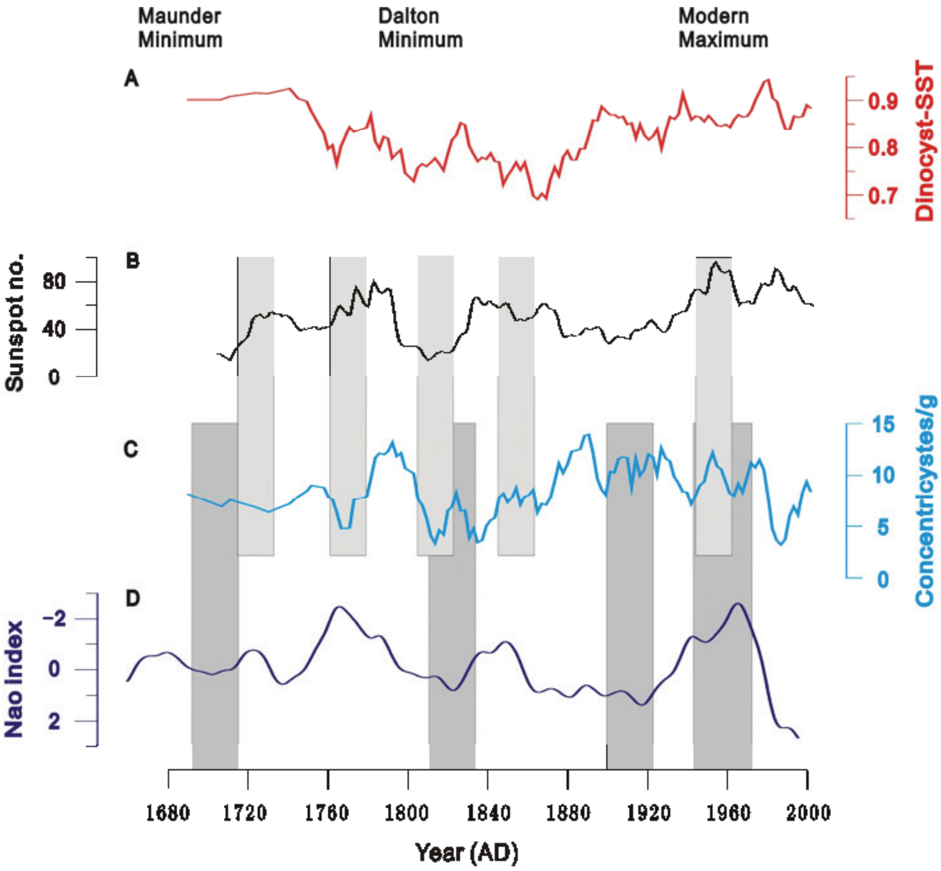


Figure 5. Dino-SST (A) and B. Sunspot numbers (Eddy, 1976). C. Concentration of *concentricystes*. D. NAO index (Trouet et al., 2009).

6. 3 Temperature perturbations during past 400 years

Dinocyst derived sea surface temperature (SST) presents a gradual decrease trend between 1660 and 1860 AD, and an abrupt rise of temperature can be observed after 1860 AD (Fig 4). The SST variations in the study area have been closely related to air temperatures (Chen et al., 2011; Versteegh et al., 2007), we therefore assume the dinocyst derived SST can be indicative of air temperature variability in southern Adriatic area. The abrupt increase of SST from 1860 AD could be well corresponding to the 20th global warming although the amplitude of increase is smaller than that is observed with continued fast climate warming since 1985 AD (Fig 4). By comparing with instrumental seasonal temperatures of Southern Italian cities, Zonneveld et al. (2011) found that dinocyst derived SST reveals coherency with autumn and a less extent spring air temperatures than summer and winter temperature. Besides, the temperature reconstructed during last 400 years by dinocyst evidence is also comparable with temperature records which have been carried out in other Europe-Mediterranean regions, for example $\delta^{18}O$ records of stalagmite (Mangini et al., 2005) and documentary glacier records in the Alps regions (Haeberli and Holzhauser, 2003). Our result is furthermore in agreement with global land-ocean temperature anomalies although divergency appears after 1985 AD where dinocyst-SST shows decline trend while global temperature still keeps increasing (Hansen et al., 2010) (Fig 4). However, our reconstructed SST is not synchronous with calibrated Northern Hemisphere temperatures which shows 50 years earlier of the initial climate warming during the 300 years (Moberg et al., 2005) (Fig 4), indicating that Mediterranean climate might show more local climate characters than large scale temperature variability. Solar activity has been suggested as a main forcing for the past climate change, our data shows a minimal W/C values around 1800 AD that can corresponding to Dalton solar minimum, and high temperature during the second half of 20th century is associated with modern solar maximum. We therefore suggest that solar forcing might play an important role in regulating the Southern Adriatic temperature change. However, there is no response of dinoflagellate temperature indicative species to the Maunder Minimum occurred during 1650-1700 AD (Fig 5), this inconsistency can be explained by either low sample resolution between 1660 and 1750 AD or relatively low dinocyst concentrations during this period.

6. 4 Natural versus anthropogenic influence on local climatic conditions

It is suggested that North Atlantic Oscillation (NAO) and solar activity exert significant effect on past climatic change in central Mediterranean area (e.g. Chen et al., 2011). Meanwhile, we found the trophic status in Southern Adriatic area has been largely disturbed by anthropogenic activity since 1895 AD. However, it is ambiguous whether the human activity has also influenced the natural climate rhythm since that time. To this end, we perform the continuous wavelet analysis on reconstructed SST and local precipitation/river discharge series to determine the temporal distribution of cyclicities and discuss how human/natural element might have influenced the local climate. We excluded the data prior to 1750 AD to avoid unrealistic signal as the study resolution is much lower between 1660 and 1750 AD than the later time interval. There are multi-cycles of about 8-10, 6-7 years and to a less extent 15-18 years shown from the reconstructed SST series between 1750 and 1940 AD (Fig 6), which might indicate the influence of different natural forcing factors on local climate change, for example NAO and solar activity which has typical periodicity of 7-8 and 11 years respectively. Interestingly, there is no clear cycle of the SST data especially after 1940 AD which time period is characterized by great human release of greenhouse gases (Fig 6). We therefore speculate that such activity might have destroyed the naturally cyclic occurred temperature tempo. The wavelet spectral presents 4-8 years cycles during 1750-2000 AD on local precipitation signal again stress the influence of NAO (Fig 6). It is demonstrated that the negative phase of NAO index brings enhanced precipitation and temperature in southern Europe and Mediterranean area (Lionello and Sanna, 2005). Therefore we would expect to see the contemporaneous changes in local SST and precipitation change in the study area, our data shows the good matching between W/C ratio, concentration of *concentricystes spp.* and reconstructed NAO index (Trouet et al., 2009) confirms this assumption (Fig 5). However, the gap between these two curves becomes larger after 1890 AD, it might also indicate the intensified anthropogenic influence on local climate. Furthermore, we notice that the cycles of temperature and precipitation sequence are discontinuous throughout the study period, this might indicate the existence of complex interaction of different factors influence on climate variability in Central Mediterranean region. Therefore more studies are required to better pinpoint to what extent natural/anthropogenic activity can be responsible for the recent climate change.

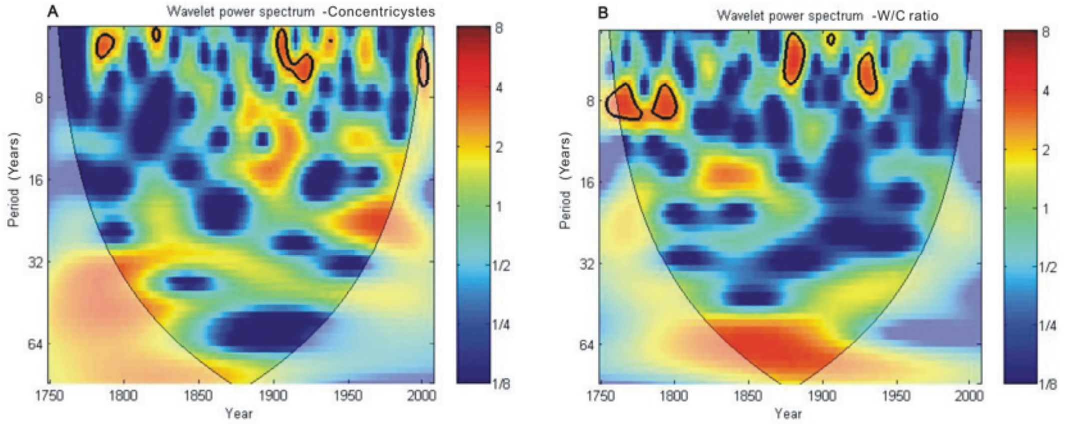


Figure 6. Wavelet analysis of A. Concentration of *Concentricystes* and B. W/C ratio.

7. Conclusions

The high resolution environmental change in Southern Adriatic Sea during last 400 years has been achieved mainly by organic walled dinocyst species and associations. The accumulation rates of autotrophic dinoflagellate species *L. machaerophorum* shows the evolution of eutrophication status in the Gulf of Taranto area, the initial increase of *L. machaerophorum* between 1880 and 1920 AD can be corresponding to the industrial development in Italy which starts at more or less the same time. The persistent fast increase of *L. machaerophorum* during 1920-1991 AD is highly related to the agricultural development and population growth in northern Italy. Trophic status seems to ameliorate after 1991 AD which indicate the improved water quality due to Italian pollution control regulations. However, another increase trend of *L. machaerophorum* observed after 1995 AD which means the ecosystem has not yet restored to the natural level.

We show *Concentricystes* based precipitation change is consistent with other instrumental and documentary records in Mediterranean region, indicating that *Concentricystes* to be a reliable indicator for local precipitation change. The reconstructed precipitation sequence can be related to documented sunspot numbers between 1700 and 1900 AD, which active sun (maximum sunspot) corresponding to enhanced precipitation. We therefore suggest that solar-precipitation relationship might exist in Southern Italian regions under the mediation of NAO. However, more studies are needed to validate this connection.

Dinocyst derived SST presents an abrupt temperature increase after 1860 AD which can be corresponding to the occurring global warming. Our data shows that the SST is comparable to other proxy and instrumental records although the variation patterns are not always synchronous. It is suggested that solar activity might be related to some of the climate trend during past 400 years.

Cycles of 4-8 and 8-12 years are prominent in the reconstructed local temperature and precipitation signals especially between 1750 and 1940 AD, these naturally cyclic variations are suggested to be related to NAO and solar activity. However, there is no clear cycle of the SST and precipitation data especially after 1940 AD which time period is characterized by great human release of greenhouse gases. We therefore speculate that apart from natural forcing, anthropogenic activity might also have influenced the climate change that disturbed the naturally cyclic occurred temperature and to a less extent precipitation perturbations. However, many more studies are required to understand better to what extent and how natural/anthropogenic activity can cause climate perturbation.

Acknowledgements

We thank DFG/ESF for the financial support of the MOCCHA project (Multidisciplinary study of continental/ocean climate dynamics using high-resolution records from the eastern Mediterranean). Malin Holler and Mirja Hoins are acknowledged for processing the samples. All the group members in Historical Geology and Palaeontology, Bremen University are thanked for the laboratory help and fruitful discussions. Kara is thanked for correcting the English. Furthermore, we would like to thank Daniela Pittaurova and Dr. Helmut Fischer (IUP-Bremen) for dating of the core.

References

Alley, R. B., Marotzke, J., Nordhaus, W. D., Overpeck, J. T., Peteet, D. M., Pielke, R. A., Pierrehumbert, R. T., Rhines, P. B., Stocker, T. F., Talley, L. D., and Wallace, J. M. (2003). Abrupt climate change. *Science* **299,** 2005-2010.

Baldini, L. M., McDermott, F., Foley, A. M., and Baldini, J. U. L. (2008). Spatial variability in the European winter precipitation delta O-18-NAO relationship: Implications for reconstructing NAO-mode climate variability in the Holocene. *Geophysical Research Letters* **35**.

Boldrin, A., Langone, L., Miserocchi, S., Turchetto, M., and Acri, F. (2005). Po River plume on the Adriatic continental shelf: Dispersion and sedimentation of dissolved and suspended matter during different river discharge rates. *Marine Geology* **222,** 135-158.

Brunetti, M., Maugeri, M., Monti, F., and Nannia, T. (2006). Temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series. *International Journal of Climatology* **26,** 345-381.

Camuffo, D., and Enzi, S. (1995). The analysis of two bi-millenary series: Tiber and Po River floods. *In: P. D. Jones, R. S. Bradley, and J. Jouzel (Eds) Climatic Variations and Forcing Mechanisms of the Last 2000 Years.* **Springer Verlag, Stuttgart, Vol. 41,** p433-450.

Castagnoli, G. C., Bonino, G., and Taricco, C. (1995). Similar response to climate stage 3 (20-62ky BP) in Mediterranean and Bahama carbonate records. *Nuovo Cimento Della Societa Italiana Di Fisica C-Geophysics and Space Physics* **18,** 575-582.

Cattaneo, A., Correggiari, A., Langone, L., and Trincardi, F. (2003). The late-Holocene Gargano subaqueous delta, Adriatic shelf: Sediment pathways and supply fluctuations. *Marine Geology* **193,** 61-91.

Chen, L., Zonneveld, K. A. F., and Versteegh, G. J. M. (2011). Short term climate variability during "Roman Classical Period" in the Eastern Mediterranean. *Quaternary Science Reviews* **doi: 10.1016/j.quascirev.2011.09.024**.

Collantes, F. (2006). Farewell to the peasant republic: marginal rural communities and European industrialisation, 1815-1990. *Agricultural History Review* **54,** 257-273.

Crowley, T. J. (2000). Causes of climate change over the past 1000 years. *Science* **289,** 270-277.

Dale, B. (2009). Eutrophication signals in the sedimentary record of dinoflagellate cysts in coastal waters. *Journal of Sea Research* **61,** 103-113.

Dale, B., Thorsen, T. A., and Fjellsa, A. (1999). Dinoflagellate cysts as indicators of cultural eutrophication in the Oslofjord, Norway. *Estuarine Coastal and Shelf Science* **48,** 371-382.

Eddy, J. A. (1976). Maunder Minimum. *Science* **192,** 1189-1202.

Federico, G., and Malanima, P. (2004). Progress, decline, growth: product and productivity in Italian agriculture, 1000-2000. *Economic History Review* **57,** 1-437.

Gibelin, A. L., and Deque, M. (2003). Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. *Climate Dynamics* **20,** 327-339.

Giorgi, F., and Lionello, P. (2008). Climate change projections for the Mediterranean region. *Global and Planetary Change* **63,** 90-104.

Grinsted, A., Moore, J. C., and Jevrejeva, S. (2004). Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics* **11,** 561-566.

Haeberli, W., and Holzhauser, H. (2003). Alpine Glacier Mass Changes During the Past Two Millennia. *PAGES News* **11,** 13-15.

Hainbucher, D., Rubino, A., and Klein, B. (2006). Water mass characteristics in the deep layers of the western Ionian Basin observed during May 2003. *Geophysical Research Letters* **33,** 4.

Hansen, J., Ruedy, R., Sato, M., and Lo, K. (2010). Global Surface Temperature Change. *Reviews of Geophysics* **48,** 29.

Harland, R., Nordberg, K., and Filipsson, H. L. (2006). Dinoflagellate cysts and hydrographical change in Gullmar Fjord, west coast of Sweden. *Science of the Total Environment* **355,** 204-231.

Hurrell, J. W. (1995). Decadal Trends in the North-Atlantic Oscillation - Regional Temperatures and Precipitation. *Science* **269,** 676-679.

Hurrell, J. W., and VanLoon, H. (1997). Decadal variations in climate associated with the north Atlantic oscillation. *Climatic Change* **36,** 301-326.

IPCC. (2007). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. **IPCC, Geneva, Switzerland,** 104pp.

Jones, P. D., and Mann, M. E. (2004). Climate over past millennia. *Reviews of Geophysics* **42,** 42.

Lionello, P., and Sanna, A. (2005). Mediterranean wave climate variability and its links with NAO and Indian Monsoon. *Climate Dynamics* **25,** 611-623.

Mangini, A., Spotl, C., and Verdes, P. (2005). Reconstruction of temperature in the Central Alps during the past 2000 yr from a delta O-18 stalagmite record. *Earth and Planetary Science Letters* **235,** 741-751.

Mann, M. E., Bradley, R. S., and Hughes, M. K. (1999). Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26,** 759-762.

Marret, F., and Zonneveld, K. A. F. (2003). Atlas of modern organic-walled dinoflagellate cyst distribution. *Review of Palaeobotany and Palynology* **125,** 1-200.

Matsuoka, K., Kawami, H., Nagai, S., Iwataki, M., and Takayama, H. (2009). Re-examination of cyst-motile relationships of Polykrikos kofoidii Chatton and Polykrikos schwartzii Butschli (Gymnodiniales, Dinophyceae). *Review of Palaeobotany and Palynology* **154,** 79-90.

Moberg, A., Sonechkin, D. M., Holmgren, K., Datsenko, N. M., and Karlen, W. (2005). Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433,** 613-617.

Piervitali, E., and Colacino, M. (2001). Evidence of drought in western Sicily during the period 1565-1915 from liturgical offices. *Climatic Change* **49,** 225-238.

Pittauerova, D., and Fischer, H. W. (2009). Report: Test measurements for sediment chronology, core GeoB 10709-5. *Institute of Environmental Physics, University of Bremen.*

Pospelova, V., Chmura, G. L., Boothman, W. S., and Latimer, J. S. (2002). Dinoflagellate cyst records and human disturbance in two neighboring estuaries, New Bedford Harbor and Apponagansett Bay, Massachusetts (USA). *Science of the Total Environment* **298,** 81-102.

Pospelova, V., and Kim, S. (2010). Dinoflagellate cysts in recent estuarine sediments from aquaculture sites of southern South Korea. *Marine Micropaleontology* **76,** 37-51.

Radi, T., Pospelova, V., de Vernal, A., and Barrie, J. V. (2007). Dinoflagellate cysts as indicators of water quality and productivity in British Columbia estuarine environments. *Marine Micropaleontology* **62,** 269-297.

Sánchez-Goñi, M. F., Eynaud, F., Turon, J. L., and Shackleton, N. J. (1999). High resolution palynological record off the Iberian margin: direct land-sea correlation for the Last Interglacial complex. *Earth and Planetary Science Letters* **171,** 123-137.

Sangiorgi, F., Capotondi, L., and Brinkhuis, H. (2002). A centennial scale organic-walled dinoflagellate cyst record of the last deglaciation in the South Adriatic Sea (Central Mediterranean). *Palaeogeography Palaeoclimatology Palaeoecology* **186,** 199-216.

Sangiorgi, F., and Donders, T. H. (2004). Reconstructing 150 years of eutrophication in the north-western Adriatic Sea (Italy) using dinoflagellate cysts, pollen and spores. *Estuarine Coastal and Shelf Science* **60,** 69-79.

Schilman, B., Bar-Matthews, M., Almogi-Labin, A., and Luz, B. (2001). Global climate instability reflected by Eastern Mediterranean marine records during the late Holocene. *Palaeogeography Palaeoclimatology Palaeoecology* **176,** 157-176.

Sellschopp, J., and Alvarez, A. (2003). Dense low-salinity outflow from the Adriatic Sea under mild (2001) and strong (1999) winter conditions. *Journal of Geophysical Research-Oceans* **108,** 12.

Socal, G., Boldrin, A., Bianchi, F., Civitarese, G., De Lazzari, A., Rabitti, S., Totti, C., and Turchetto, M. M. (1999). Nutrient, particulate matter and phytoplankton variability in the photic layer of the Otranto strait. *Journal of Marine Systems* **20,** 381-398.

Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., and Frank, D. C. (2009). Persistent Positive North Atlantic Oscillation Mode Dominated the Medieval Climate Anomaly. *Science* **324,** 78-80.

Vaquero, J. M. (2004). Solar signal in the number of floods recorded for the Tagus river basin over the last millennium. *Climatic Change* **66,** 23-26.

Versteegh, G. J. M., de Leeuw, J. W., Taricco, C., and Romero, A. (2007). Temperature and productivity influences on U-37(K') and their possible relation to solar forcing of the Mediterranean winter. *Geochemistry Geophysics Geosystems* **8**.

Vignudelli, S., Gasparini, G. P., Astraldi, M., and Schiano, M. E. (1999). A possible influence of the North Atlantic Oscillation on the circulation of the Western Mediterranean Sea. *Geophysical Research Letters* **26,** 623-626.

Zanchettin, D., Rubino, A., Traverso, P., and Tomasino, M. (2008a). Impact of variations in solar activity on hydrological decadal patterns in northern Italy. *Journal of Geophysical Research-Atmospheres* **113**.

Zanchettin, D., Traverso, P., and Tomasino, M. (2008b). Po River discharges: a preliminary analysis of a 200-year time series. *Climatic Change* **89,** 411-433.

Zonneveld, K. A. F. (2008). Report and preliminary results of R/V POSEIDON Cruise P339, Piräus - Messina, 16 June - 2 July 2006. CAPPUCCINO - Calabrian and Adriatic palaeoproductivity and climatic variability in the last two millenia. *Berichte, Fachbereich Geowissenschaften, Universität Bremen* **No. 268,** 61.

Zonneveld, K. A. F., Chen, L., Elshanawany, R., Fischer, H. W., Hoins, M., Ibrahim, M. I., Pittaurova, D., and Versteegh, G. J. M. (2011). The use of dinoflagellate cysts to separate human induced and natural variability in the trophic state of the Po-river discharge plume during the last two centuries. *Marine Pollution Bulletin* **in press**.

Zonneveld, K. A. F., Chen, L., Möbius, J., and Mahmoud, M. (2009). Environmental significance of dinoflagellate cysts from the proximal part of the Po-river discharge plume (off southern Italy, Eastern Mediterranean) *Journal of Sea Research.* **62,** 189-213.

6. Paleoclimate of the Southern Adriatic Sea region during the Medieval Climate Anomaly reflected by organic walled dinoflagellate cysts

Liang Chen,[1,*] Karin Zonneveld,[1,2] and Gerard Versteegh[2]

[1] Fachbereich Geowissenschaften, Universität Bremen, Postfach 330440, D-28334 Bremen, Germany
[2] MARUM, Universität Bremen, Leobenerstraße, D-28359 Bremen, Germany

* Corresponding author.

Submitted to *Palaeoceanography*, Oct. 2011

Abstract

To obtain insight into the way climate changed during the Medieval Classical Period and to infer what forcings might have driven the climate anomaly during this time, high temporal resolution marine sediments from the Gulf of Taranto are analyzed on their dinoflagellate cyst content. The high sedimentation rate at the core location enables the establishment of a paleoclimate and paleoceanography reconstruction at a 3-4 years resolution between 990 and 1200 AD (Medieval Climate Anomaly). The reconstructed sea surface temperature (SST) appears to be lower in the Medieval Period compared to those of today. We observe clear 11.4 years cyclicity in the reconstructed SST series during Medieval Period. Furthermore, there is a good matching between SST and global ^{14}C anomalies. This suggests that solar activity might have played an important role influencing the local climate during medieval time. Short-term fluctuations in accumulation rates of the river discharge species and species resistant to aerobic degradation provide information on past river discharge and upper water nutrient availability. Results indicate that the trophic state of the upper waters is closely linked to the variations of river discharge which in turn is strongly related to precipitation in Italy. We reconstruct low river discharge/precipitation in Adriatic area during studied interval synchronous to widespread drought events in other subtropical regions. We argue this to be influenced by NAO and ENSO related large scale ocean-atmosphere circulation shifts during the Medieval Period. Furthermore, we suggest that volcanic eruptions might have influenced the local temperatures upper water nutrient conditions.

1. Introduction

Within the scope of the current debate about to what extent anthropogenic activities and natural forcings are responsible for the current global rise in temperature, it is of strong interest to obtain insight into the relationship between potential natural forcings and climate change in pre-industrial time intervals of warm climate conditions. One of this time intervals is the Medieval Classical Period (MCP) (800-1200 AD) as there are many studies that suggest that climate conditions in this time interval might have been equivalent or warmer than today (e.g. Filippi et al., 1999; 2001; Lamb, 1965). However, an increasing number of studies argue about how warm this period was and there are even discussion about if such a “warm” period have existed at all in this time interval (e.g. Bradley et al., 2003; Crowley and Lowery, 2000; Goosse et al., 2006; Hughes and Diaz, 1994; Jones and Mann, 2004). Apart from the different opinions about the rate of the temperature anomaly, it is today far from clear in how far forcings such as volcanism and/or solar activity might have steered the climate anomaly. One of the reasons for this is the limited amount of records available that are characterized by an excellent stratigraphic framework and have a temporal resolution on annual scale that allows the recognition of short term cyclic variability on “solar” time-scales. Here we intend to contribute to this discussion by establishing a detailed high temporal resolution paleoclimate and –environmental reconstruction of the Eastern Mediterranean region, notably the Gulf of Taranto for the time interval between 990-1200 AD. For this we studied fossil dinoflagellate cysts from marine sediments that are characterized by minimal bioturbation and high sedimentation rates. We interpret changes in the accumulation rates of dinoflagellate species and associations with specific environmental preferences in terms of the past environmental signals of sea surface temperatures (SST), local river discharge, precipitation and upper water nutrient concentrations. By comparing our results with climate forcing factors like solar activity and volcanism, we discuss potential forcing mechanisms that might have influenced the climate fluctuations of Southern Adriatic area during the Medieval Period.

2. Oceanographic and climatic setting

The circulation of Gulf of Taranto is strongly influenced by river discharge waters which can be traced along the whole eastern Italian coast. The main source of these waters is the Po-river which is the largest river in Italy with a length of about 673 km (Fig 1). It supplies high amount fresh water with ample nutrients and suspended matter into the northwestern Adriatic (Boldrin et al., 2005; Degobbis et al., 1986). These waters are traditionally classified as the Adriatic Surface Waters (ASW). The cyclonic surface currents of the Adriatic Sea induced by Coriolis forcing presses against the western coastal margin of the Adriatic Sea (Lee et al., 2007). On their way southeastward, the ASW are spiced by discharge waters of local eastern Italian rivers draining the eastern side of the Apennine mountains. The ASW can be traced along the whole western Adriatic Sea flowing through the western part of the Strait of Otranto, into the Gulf of Taranto. The circulation of the Gulf of Taranto is cyclonic as well. Additionally, Ionian Sea Waters (ISW) which are characterized by relatively high temperature, salinity and low suspended matter and nutrients enter the Gulf of Taranto at the eastern side where they gradually mix with ASW (Caroppo et al., 2006; Socal et al., 1999). Within the Gulf, intermediate water is formed by Levantine Intermediate Waters (LIW) that can be observed between 150 and 600 m water depth. A shift towards much cooler waters of the dense Adriatic Deep Water (ADW) can be observed below 600 m water depth (e.g. Hainbucher et al., 2006; Sellschopp and Alvarez, 2003).

The Mediterranean Sea which is almost enclosed by land covers an approximate area of 3.5 million km^2 (Saliot, 2005). It is located between low and mid-latitudes and its climate is therefore highly sensitivity to upper air circulation variations (e.g. Cassou et al., 2004; Hurrell and VanLoon, 1997). One of the most prominent climate modes influencing the Mediterranean climate is the so-called North Atlantic Oscillation (NAO) which represents the dipole-like pressure gradient between the Azores (high) and Iceland (low) (Hurrell, 1995). When the NAO index is in positive phase, northern Europe experiences excess precipitation. In turn, its negative phase brings excess precipitation and high temperatures in southern Europe and Mediterranean area (Lionello and Sanna, 2005). Consequently, variations of NAO have strong effects on the Italian precipitation, with enhanced precipitation resulting in excess discharge of the Po and Apennine rivers into the Adriatic Sea. In turn this results in an extension of the ASW "plume" and enhanced inflow of ASW into the Gulf of Taranto.

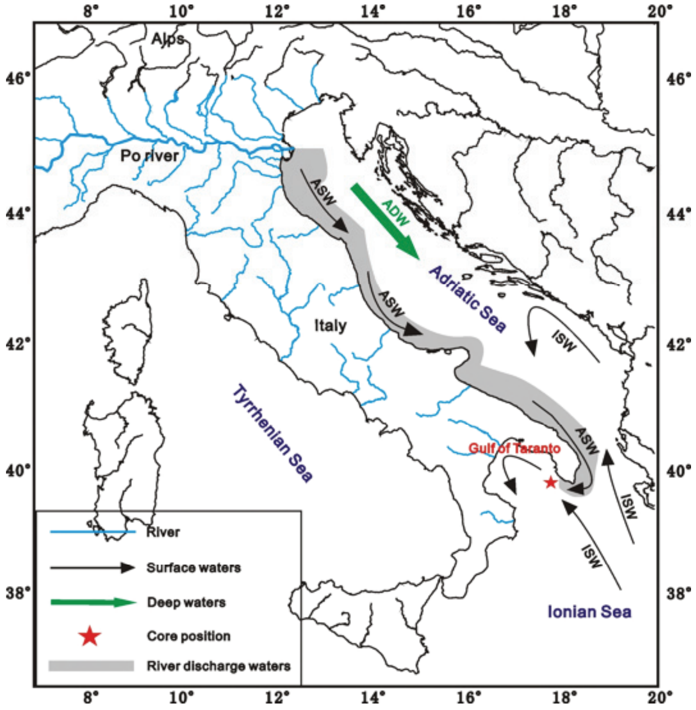


Fig 1. Study location and ocean circulation. ASW - Adriatic Surface Water, ISW - Ionian Sea Water, ADW - Adriatic Deep Water.

During winter time, cold and dry Bora winds blow from the northeastern in strong pulses over the study region. This results in sea level fluctuates in downwind and upwind regions as result of the wind-curl effects on the ocean current system. (Orlic et al., 1994). These sea level fluctuations vary in intensity as a result of maxima and minima in Bora strength.

Apart from this the ocean current system and the oceanographic environmental conditions can be strongly influenced by northward blowing Sirocco winds that origin in the Sahara and that bring warm and humid air into the region (Cavaleri et al., 1997; Pasaric et al., 2007). It is suggested that strong Sirocco wind may reverse the currents that are observed along the Adriatic coast (Orlic et al., 1994). Therefore both Bora and Sirocko can play an important role on regulating the oceanographic system in the research area despite the fact that they only last several days during the year.

3. Material

3. 1 Sample preparation

The studied core was retrieved during the RV Pelagia, DOPPIO cruise, 2008 (39° 50.07' N, 17°48.05' E, water depth 270 m) (Fig 1) (De Lange, 2008). The analyzed samples have been retrieved from the section 8 (0-145 mm) of the piston core DP30PC. After subsampling this interval at every 2.5 mm, material was dried overnight at 60^{o}C and treated based on standard palynological preparation procedures according to the aliquot method as described by Zonneveld et al. (2009). Samples at depth of 15, 22.5, 35, 42.5 and 57.5 mm were not included in the analysis due to very low abundance of dinoflagellate cysts. Taxonomy of dinoflagellate species is according to that cited in Marret and Zonneveld (2003) and Radi and de Vernal (2008). Round, brown cyst with a smooth cell wall without ornamentation were grouped as *Brigantedinium spp.*. The classification of the species *Polykrikos kofoidii* and *P. schwarzii* is according to Matsuoka et al. (2009).

3. 2 Age model

The chronological framework of the studied core is based on AMS (Accelerator Mass Spectrometry) ^{14}C measurements on bulk planktic foraminifera that have been prepared at the Geological Institute, ETH Zurich and measured at the AMS Radiocarbon Dating Laboratory at ETH Zurich. The ^{14}C dates were calibrated with the program OxCal v3.10 (Bronk Ramsey, 2009), with the references of atmospheric data from Reimer et al. (2004) and the Curve marine04 with the marine data from Hughen et al. (2004) ($\Delta R=121\pm60$ years). The calibrated ages of the section are on top AD 1195±135 and on bottom BC 190±120. Linear interpolation between the data points reveals a constant sedimentation rate of 0.72 mm/y. This results in a temporal sample resolution of approximately 3-4 years (see details in Chen et al., 2011). Sedimentation rates are comparable to those registered for a nearby gravity core (GT89/3) that was retrieved 11 km southeastern of our core DP30PC (Castagnoli et al., 1990). The age model of the core GT89/3 is based on tephra chronology which is represented by 22 pyroxene peaks that are related to the outbreaks of the Vesuvius and the volcanos in the study region (Arno et al., 1987). Extensive surveys of numerous cores in this region have revealed that a constant sedimentation rate is characteristic in the whole Gallipoli terrace during last 2000 years (e.g. Bonino et al., 1993; Castagnoli et al., 1992).

4. Methods

4. 1 Aerobic degradation

The post-depositional degradation extent of dinoflagellate species is estimated by the dinoflagellate degradation index "kt" which is determined by the degradation constant "k" and reaction time "t", its calculated based on the following formula (Versteegh and Zonneveld, 2002)

$kt = \ln (X_i/X_f)$, with $X_i = 68 \times X_r$

X_i = initial cyst accumulation rates of sensitive cyst species (cysts/cm^2/y); X_f = final cyst accumulation rates of sensitive cysts (cysts/cm^2/y); X_r = cyst accumulation rates of resistent cyst species (cysts/cm^2/y).

The relationship between degradation sensitive and resistant dinoflagellate species is established empirically (Zonneveld et al., 2008). High kt values (3-4) indicate that degradation might have altered the initial dinoflagellate ecological signal.

4. 2 Sea surface temperature indicators

Qualitative estimation about variations in sea surface temperature is obtained using the following ratio:

$W/C = W_n / (W_n + C_n)$

where n = number of specimens counted, W = warm water species, C = cold water species. W = *Impagidinium aculeatum, Impagidinium paradoxum, Impagidinium patulum, Operculodinium israelianum, Polysphaeridium zoharyi, Spiniferites mirabilis*. C = *Bitectatodinium tepikiense* and *Spiniferites elongates.*

Species selection is based on the global geographic distribution of organic walled dinoflagellate cysts (e.g. Marret and Zonneveld, 2003)

4. 3 River discharge and local precipitation indicators

We use the sum of accumulation rates of cysts of the photosynthetic dinoflagellate *Lingulodinium machaerophorum* and the freshwater algae *Concentricystes spp.* as indicators for the presence of Adriatic surface waters. In the Eastern Mediterranean Sea and Adriatic Sea, *L. machaerophorum* is characteristically present in river discharge plumes (Elshanawany et al., 2010; Sangiorgi et al., 2002; Zonneveld et al., 2009). Its accumulation rates show a gradient from high to low values from the river mouths towards the distal parts of the plumes. A recent study on the hydrology of the Po-river discharge plume during the last 200 years shows that at in the research area site enhanced sedimentary concentrations of this species correspond to enhanced Po-river discharge influence (Zonneveld et al., 2011). The algal species *Concentricystes spp.* is restricted to fresh water environments. Its presence in marine sediments is therefore an indicator of fresh water reaching the deposition site. As such it can be used as a freshwater indicator (e.g. Horton et al., 2005; Mudie et al., 2002).

4. 4 Upper water trophic conditions

The variation of upper water nutrient availability is based on the accumulation rates of the nutrient sensitive-aerobic degradation resistant species which include *Impaginium aculeatum, Impagidinium paradoxum, Impagidinium patulum, Impagidinium plicatum, Impagidinium sphaericum, Impagidinium strialatum, Nematosphaeropsis labyrinthus* and *Pentapharsodinium dalei, Operculodinium israelianum* and *Polysphaeridium zoharyi* (Zonneveld et al., 2007). Accumulation rates of these species increase in the Mediterranean as well as open oceans when nutrient concentrations in upper waters increase (Elshanawany et al., 2010; Holzwarth et al., 2007; Zonneveld et al., 2009; Zonneveld et al., 2010) .

4. 5 Frequency analysis

To obtain information about cyclic variability in the W/C ratio and ASW curve, a red-noise spectrum analysis has been carried out using the program REDFIT. This method is particularly suitable for datasets that are characterized by an uneven temporal sample distribution (Schulz and Mudelsee, 2002).

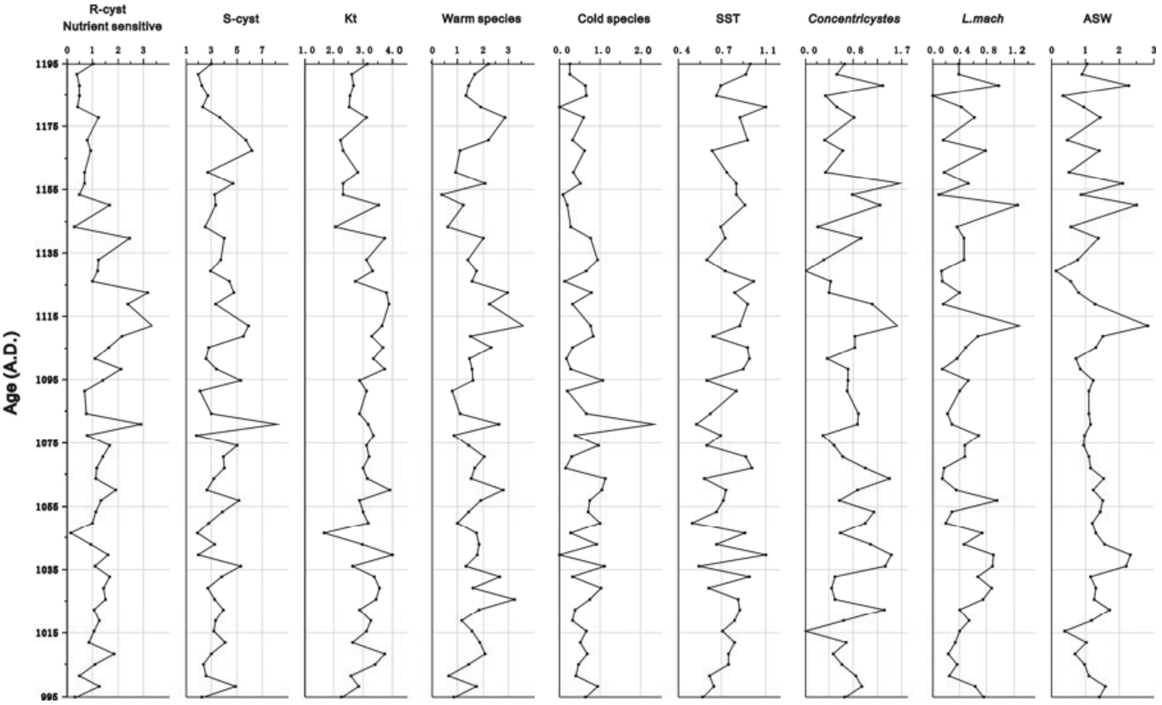


Fig 2. Diagram of dinoflagellate species, associations in accumulation rates (cyst/cm2/y) and kt index.

5. Results

The degradation index (kt) values are relatively constant throughout the sequence. However, it decreases sharply from 3.9 to 2.1 between 1119 and 1143 AD. The average kt value is 3.1 and minima can be observed at 1046 and 1143 AD (Fig 2).

Dinoflagellate cyst warm and cold species ratio during the Medieval Period (990 -1200 AD) shows a decreasing trend between 1022-1050 AD that overprinted by large fluctuations. Between 1050 and 1067 AD, the W/C value increases followed by a strong decrease until 1081 AD. From 1081 AD, an increasing trend is visible interrupted by short minima during 1133-1143 and around 1167 AD (Fig 2).

Accumulation rates of *L. machaerophorum* and *Concentricystes spp.* vary contemporaneously between 990 and 1200 AD (Fig 2). The accumulation rates of ASW varies from 2.53-53.19 cyst/cm^2/y and shows large fluctuations between 990 and 1200 AD with maxima at about 1022, 1039, 1064, 1112 and 1150-1157 AD. Minima can be observed at 1015, 1074, 1129, 1143 and between 1160-1185 AD.

The accumulation rates of nutrient sensitive-aerobic degradation resistant species fluctuate around a mean value of 1.26 cyst/cm^2/y between 990 and 1200 AD. No clear trend can be observed with exception of several peaks of high values during 1070-1140 AD (Fig 2). The influx of degradation sensitive species shows relatively constant variation during the study interval. The highest value is 8.15 cyst/cm^2/y that can be observed at 1081 AD (Fig 2).

The most predominant cycles are 11.4 years for the reconstructed sea surface temperatures, another cycle of 26.7 years is also observed with lower power throughout the time series. The reconstructed ASW record shows 9.3 and 13.8 years cycles during the studied time interval (Fig 3).

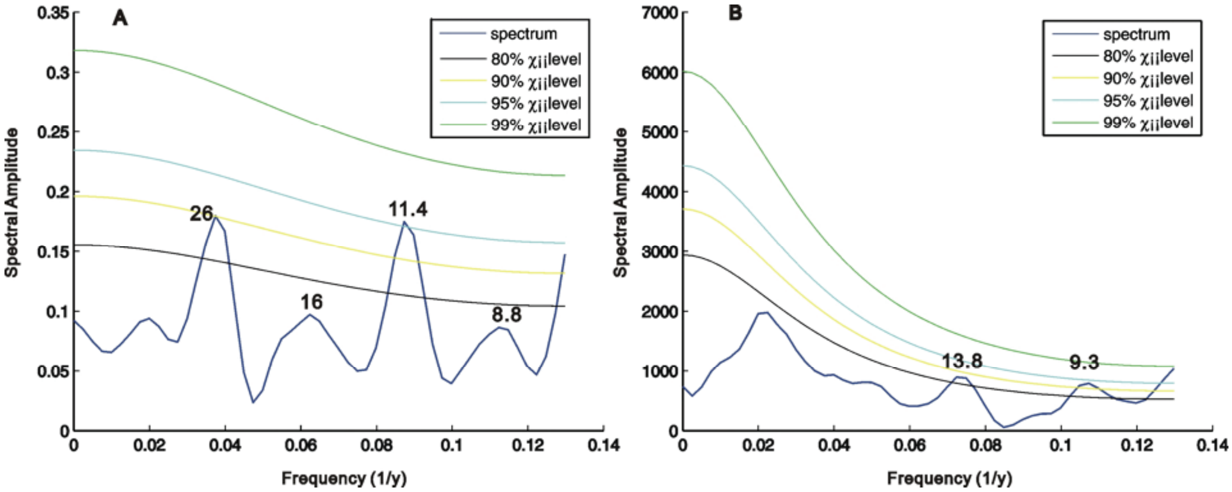


Fig 3. Spectral power of A Dino-W/C ratio, and B ASW indicator.

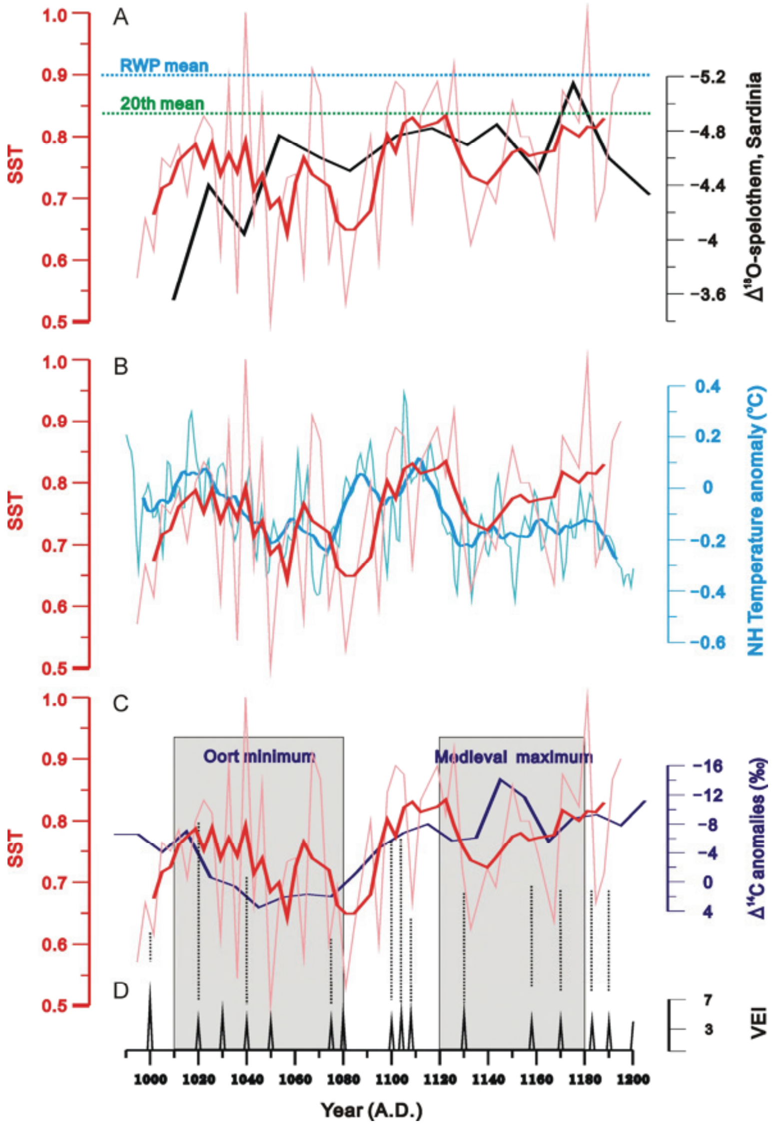


Fig 4. Dinoflagellate W/C derived SST and comparison with A δ^{18}O of spelothem from Sardinia (Antonioli, et al., 2003), Roman Warm Period (RWP) and 20th century mean value of W/C are based on Chen, et al. (2011) and Zonneveld, et al. (2011) respectively. B Northern Hemisphere temperature anomalies (Moberg, et al., 2005). C Global ^{14}C anomalies (Stuiver, et al., 1998). D global volcano eruption intensity (VEI) (Siebert and Simkin, 2002), thick line represents 5 point running average.

6. Discussion

6. 1. Preservation

During the last few decades it became clear that dinoflagellate cyst associations can be affected post-depositionally by species selective aerobic organic matter degradation that can severely alter the signal (e.g. Versteegh and Zonneveld, 2002). In the core section studied, the average degradation index (kt) is 3.1, indicating that the signal of degradation sensitive cysts especially *Brigantidinium* species might have been altered due to the degradation (Chen et al., 2011). Therefore we base our reconstructions exclusively on species that are known to be resistant to aerobic degradation and which sedimentary signal forms a reflection of upper water cyst production.

The studied core is retrieved from a shallow water depth of 270 m. Since dinoflagellate cysts are likely to sink as fecal pellets and phytoplankton aggregates with minimal sinking rates of about 274 m/day, the sedimentary dinoflagellate cyst can be considered to reflect oceanographic conditions in close vicinity to the sampling site (Zonneveld et al., 2010). We therefore assume that lateral translocation is unlikely to have influenced the dinoflagellate cyst associations.

6. 2. Sea surface temperature

The dinoflagellate cyst W/C ratio fluctuates strongly between 990 and 1200 AD. The W/C ratio can be used to trace changes in past sea surface temperatures (SST) in marine environments (Sangiorgi et al., 2002; Santarelli et al., 1998; Zonneveld et al., 2011). In Adriatic area, SST is shown to be strongly associated with the fluctuations of the local air temperature (Versteegh et al., 2007). We therefore assume that the W/C ratio can be used to reconstruct local air temperature during the Medieval Period.

We observe that W/C values in the MWP are generally lower compared to that of the last 100 years which suggest that air temperature might have been lower as well (Fig 3). This is consistent with several studies such as glacial records of the Alps that suggest the Medieval Warm Period to have been cooler than today (Giraudi, 2009; Holzhauser et al., 2005). Furthermore, based on records of chrysophyte cysts in lake sediments of the high Pyrenees (northwestern Mediterranean), Pla and Catalan (2005) reconstruct winter/spring temperatures that might have been about 0.5 °C – 1 °C colder than today between 1000 - 1200 AD. Also historical records report for cold spells in winter such as the so called “great winter” at 1076/1077 AD where even the Po and Tiber river became icebound (see overview in Pfister et al., 1998). However, our results are in contrast to other studies. For instance, based on pollen records from Lago Monticchio area (Southern Italy), Allen et al. (2002) reconstruct mean temperatures of the coldest month (MTCO) being as warm as or even warmer than today during 1000-1200 AD (Medieval Period). A compilation of tree ring records and pollen data, leads Guiot and Corona (2010) to reconstruct comparable to slightly warmer temperatures than today for southwestern Europe. One of the reasons for this discrepancy might be the dinoflagellate cysts being produced during spring and late summer/autumn and not in the winter time (e.g. Caroppo et al., 2006). As such, their signal reflects the environmental conditions in these seasons and not that of the coldest months in the year. Another explanation might be a difference in temporal resolution of the records. We observed large fluctuations in the temperature record with short pulses of warmer than today situations around 1067 and between 1102 - 1126, and 1171 - 1181 AD and cold spells between about 1075 - 1090 and

1130 – 1150 that are very consistent to variations in the $\delta^{18}O$ composition of stalagmites in Sardinia (Fig 3) (Antonioli et al., 2003). Consistent with our results, studies of tree rings suggest very cold climate conditions between 1000 and 1045 AD in northern Italy (Serrebachet, 1994). That temperatures might have fluctuated strongly during the MWP is confirmed by numerous studies in Northern Hemisphere region (e.g. Guiot and Corona, 2010; Guiot et al., 2005; Pfister et al., 1998). Pla and Catalan (2005) document for instance that the early MWP at about 900 AD might have been the warmest period of the whole latest Holocene whereas coldest conditions are being reconstructed between 1000 and 1200 AD. This has lead to the suggestion that the MWP might have been restricted to two-three short intervals of 20-30 years only where temperatures were comparable to the 20th conditions (Crowley and Lowery, 2000). This indicates that reconstructions with high temporal resolution are a requirement to understand the character and amplitude of the climate variability in heterogene time intervals as the MWP.

Our data is in good agreement with the composite Northern Hemisphere temperature anomalies during the Medieval Period although a clear discrepancy can be observed between 1070 and 1100 AD where low W/C ratios correspond to the maxima of the Northern Hemisphere temperature (Fig 3) (Moberg et al., 2005). This suggests that climate variations in Adriatic area might correspond to extra-hemispheric climate perturbations during the Medieval Classical Period. However, despite the coherence of our data with the compiled Northern Hemisphere Dataset, there is strong evidence that the MWP climate might have been prone to large regional differences. For instance, in the Sargasso Sea reconstructions suggest that sea surface temperatures to have been about 1 °C warmer than it is today in this time interval (Keigwin, 1996). Tree ring based study suggests that the Medieval warm period have been significantly warmer than the late 20th century in northern Fennoscandia region as well (Grudd, 2008). Therefore many records are required to obtain a comprehensive view of the magnitude and timing of climate variability during the Medieval Period.

Although the amplitude of the temperature fluctuation between Medieval Warm Period and 20th century appears to be similar to that of foraminiferal records in the Gulf of Taranto and central Adriatic area (Piva et al., 2008; Taricco et al., 2009), Taricco et al. (2009) came an opposite variation trend based on the $\delta^{18}O$ records in Gulf of Taranto. One of the reasons for this discrepancy might be that Taricco et al. (2009) did not take into account the fact that the core is located in the ASW influence area where varying amounts of fresh water cross the coring site, consequently ASW is likely to have influenced the ^{18}O signal.

6. 3. Nutrient availability and moisture anomaly

Studies on dinoflagellate cyst production show that increased production of dinoflagellate cyst occurs in oligotrophic and mesotrophic environments when nutrient concentrations in upper water increase (e.g. Holzwarth et al., 2007; Zonneveld et al., 2010). Zonneveld et al. (2009) and Elshanawany et al. (2010) document that this is also the case in Mediterranean region. There are several factors can influence the variation of phytoplankton production in Gulf of Taranto region. The most important factor is the river discharge waters which variation will result in more or less nutrient input at the core site (Boldrin et al., 2005; Degobbis et al., 1986). We observe that the accumulation rates of *L. machaerophorum* and *concentricystes* generally synchronous varies with the nutrient sensitive species.

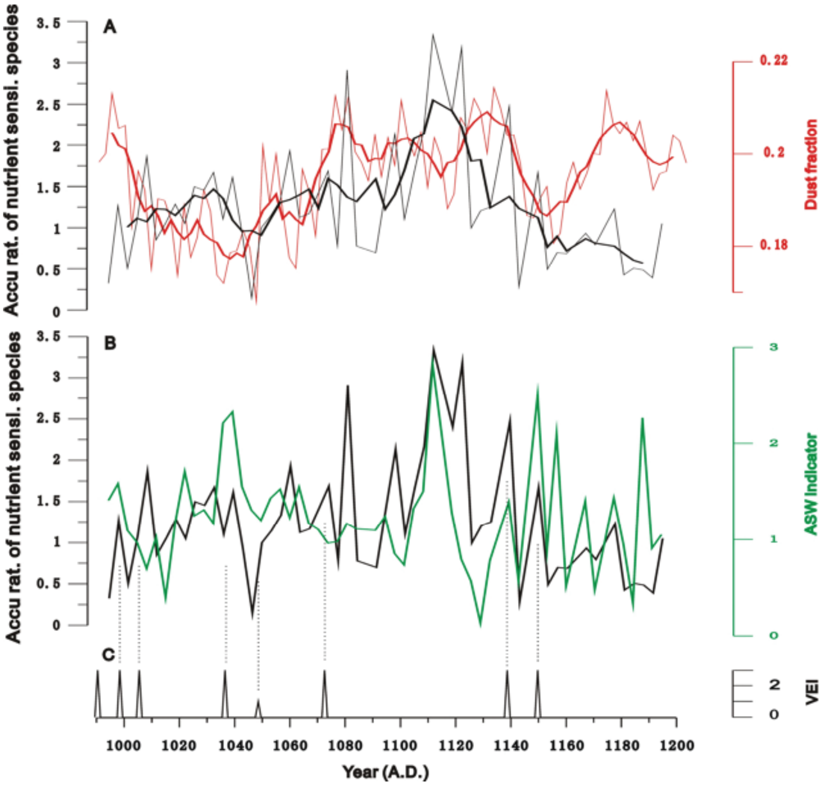


Fig 5. Comparison between accumulation rates of nutrient sensitive species (cyst/cm2/y) and A dust fraction from Northwest Africa (Mulitza, et al., 2010). B accumulation rates of ASW indicator species (cyst/cm2/y). C Historical Vesuvius eruptions (Siebert and Simkin, 2002), thick line represents 5 point running average.

Concentricystes is a typical fresh water algae that is transported into marine environments by river discharge waters (Goni et al., 1999). *L. machaerophorum* is often observed in high concentrations in sediments from river plumes areas (e.g. Lewis, 1988; Pospelova et al., 2005). In the eastern Mediterranean it is characteristically abundant in river plume waters (Elshanawany et al., 2010; Giannakourou et al., 2005). Studies show that this is also the case for the Po-river area that concentration of *L. machaerophorum* decreases with the increasing distance from the Po-river delta (e.g. Sangiorgi et al., 2005; Zonneveld et al., 2009). Relatively fresh water is transported into the Gulf of Taranto region in the form of ASW. In spring and autumn, when river discharge is at its maximum, as a result of melting of snow/ice in the Alps and Apennines and enhanced precipitation respectively, upper waters at the core position are formed by ASW (Boldrin et al., 2005). Our observation of contemporaneous variations in nutrient sensitive species and ASW species suggest therefore that the variation of upper water nutrient conditions can be largely ascribed to the river discharge fluctuations. However, nutrients and trace elements can also be transported into the study area by other mechanisms such as input of dust, volcanic ash and winter upwelling. Mineral dust from Sahara-Sahel region can be carried great distances away into Mediterranean Sea by wind (e.g. Dulac et al., 1996; Tafuro et al., 2006). It is suggested that the Sahara-Sahel dust can be transported not only to the northwest Africa margin but also to the Mediterranean area by different prevailing winds (Middleton and Goudie, 2001; Moulin et al., 1997). Our data shows that the accumulation rates of nutrient sensitive species show similar variation pattern with the dust deposition off northwest Africa especially during 1040-1110 AD and 1140-1200 AD (Fig 5) (Mulitza et al., 2010). This suggests that dust from Sahara-Sahel region might form an additional important source of nutrients in the Adriatic area.

Volcanic ash releases plentiful nutrients and trace metals that favor the marine phytoplankton growth (Jickells et al., 2005; Langmann et al., 2010). In our study area, the eruptions of the Italian volcano Vesuvius match often to high values of reconstructed nutrient availability during the study interval (Fig 5) (Siebert and Simkin, 2002). We therefore suggest that increased production of dinoflagellate cysts may also be partly caused by the released volcanic ash from Vesuvius.

Winter mixing promoted by Bora winds can also influence the nutrient availability in the Adriatic area (Orlic et al., 1994). The Bora originates from the Yugoslavian mountains that is characterized by a distinctive vegetation such as mesophilous taxa which in turn can well be traced by pollen records in marine sediments (Rizzi-Longo et al., 2007). For our study region and time interval, we can not find records that report variations of pollen influx in the research area from these source regions or from regions northeast of our research area (Combourieu-Nebout et al., 1998; Tinner et al., 2009). We therefore assume that enhanced nutrient variability is not induced by winter mixing.

The accumulation rates of ASW species *L. machaerophorum* and *Concentricystes* are shown to be highly related to the river discharge waters which variation of its amount will result in more or less fresh water inflowing into the Adriatic Sea. To date, surface waters at the sampling site are seasonally formed by ASW with minimal rates in summer and maximal in spring and late autumn. The extent of the ASW plume into the Gulf is strongly related to the amount of precipitation in the Alps and Apennines (Zanchettin et al., 2008). It therefore can be assumed that the accumulation rates of ASW species *L. machaerophorum* and *Concentricystes* can be used to indicate both river discharge and local precipitation. ASW concentration largely fluctuates during the study interval. Similar conclusions were drawn in a study of $\delta^{18}O$ of a varved lake sequence in Eastern Mediterranean area (Fig 6) (Jones et al., 2006), indicating that moisture conditions in Eastern Mediterranean might be similar to conditions that occurred in our study area. The observed accumulation rates of ASW are however lower than those found in sediments in the same core of the Roman Period which suggest that the local precipitation might have been lower as well.

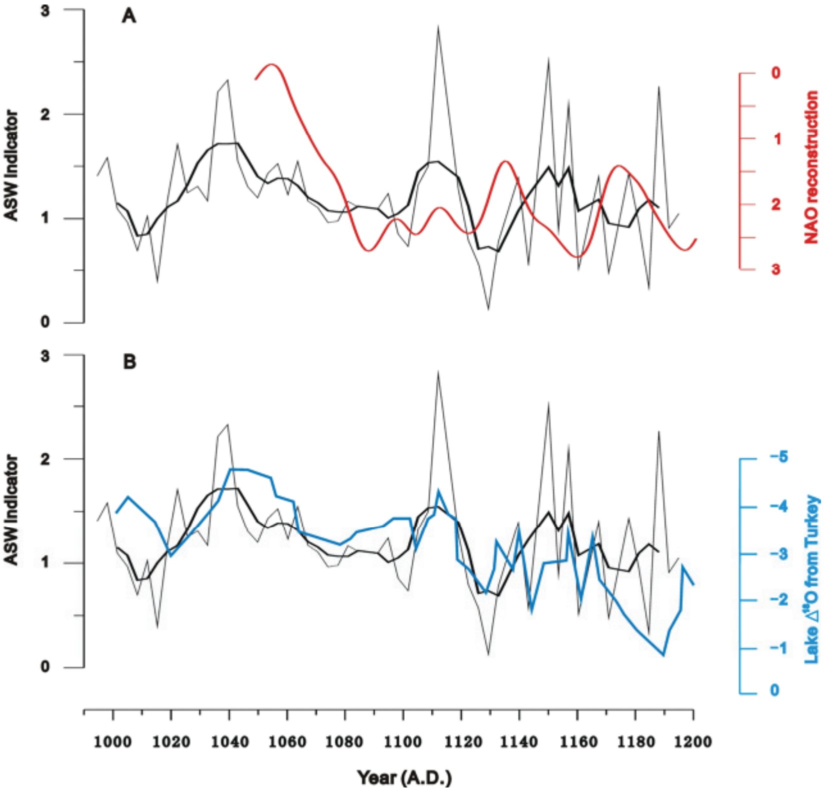


Fig 6. Accumulation rates of ASW indicator species (cyst/cm2/y) and comparison with A NAO index (Trouet, et al., 2009), and B Lake $\delta^{18}O$ records from Turkey (Jones, et al., 2006), thick line represents 5 point running average.

This is consistent to studies that reconstruct widespread hydrological anomalies in many different regions worldwide during the Medieval Period. For instance, based on pollen records in southern Sicily area, minima of *pistacia* shrubland was observed during the Medieval Period which might be caused by a decreased moisture availability (Tinner et al., 2009); Magny (2004) reconstruct based on multiproxy study of lacustrine sediments that there were many intervals during the Medieval Period when the lake level was low in the European Alpine regions; relatively low precipitation has also been indicated by geochemical proxy records of the southwestern Mediterranean (Martin-Puertas et al., 2010) and severe and persistent drought during the Medieval Period has been reconstructed based on tree ring records for Moroccan (Esper et al., 2007) and Californian regions (Graham and Hughes, 2007; Stine, 1994).

7. Forcing Mechanisms

Solar activity, volcanic activity and atmospheric circulation systems like NAO have been suggested to be important factors for the past climate variations of pre-industrial times in the research area (Chen et al., 2011; Taricco et al., 2009; Versteegh et al., 2007). In order to detect if these forcing factors might have influenced the climate perturbation reported in our study area during the Medieval Period, we have compared the reconstructed temperature curve with global $\triangle^{14}$C which is generally used as an indicator for solar activity and global volcanic activity (Stuiver et al., 1998). Our results show that variation in the W/C ratio can be closely linked to the $\triangle^{14}$C variability which low $\triangle^{14}$C values corresponding to high central Mediterranean temperatures, and vice versa. Particularly, the low temperatures during 990-1080 AD and high temperatures during 1100-1180 AD correspond well to the solar Oort Minimum (1010-1080 AD) and Medieval Maximum (1120-1180 AD) respectively (Fig 3). This suggests that solar activity might have influenced the local temperature during Medieval time. This is supported by the results of a frequency analysis where we observe a clear 11.4 year periodicity of the reconstructed SST series (Fig 6). We therefore assume that variations in solar activity form a major steering factor of the climate in the MWP.

It is well known that large volcanic eruptions can lower global temperature up to 0.5 ^{o}C during two to three years after the eruption (e.g. Crowley, 2000; Hegerl et al., 2003). Our record shows that several historical volcano eruptions during the Medieval Period correspond to short-term temperature perturbations recorded by the dinoflagellate cyst record (Fig 3). Consequently, volcanism might have influenced the local temperature during the study period as well. However, this conclusion has to be regarded with some caution as the exact timing of the outbreaks of most eruptions is rather unclear (Siebert and Simkin, 2002). Further studies are therefore required to confirm our hypothesis.

Another important factor which is known to influence both temperature and precipitation in Southern Europe and Mediterranean area is North Atlantic Oscillation (NAO). This climate mode represents the dipole-like pressure gradient between the Azores (high) and Iceland (low) (Hurrell, 1995). When the NAO index is in its positive phase, northern Europe experiences excess precipitation. In turn, a negative phase brings excess precipitation and high temperatures in southern Europe and Mediterranean area (Lionello and Sanna, 2005). When this climate mode would have had major influence on the climate in the research area during the MWP we expect to observed contemporaneous changes in temperature and precipitation in the region. Indeed we see a strong link between the reconstructed curves of temperature and river discharge supporting the hypothesis that the NAO might have influenced the local climate (Fig 2).

Recently it has been suggested that a strong and persistent positive NAO mode was present during the Medieval Warm Period (Fig 4) (Trouet et al., 2009). This is thought to have induced moisture deficiency in southern Europe and the Mediterranean area. It is consistent with our record that implies of relatively low precipitation as reflected by low mean concentrations of ASW indicative species throughout the interval. This is also supported by our frequency analysis results that show most prominent cycles found in the ASW accumulation rate fluctuations have frequencies of 9.3 and 13.8 years which are comparable to NAO variability with cycles of 8.2 and 13 years (Garcia et al., 2005). It has been suggested that NAO can be influenced by solar activity which maxima in solar activity promoting the occurrence of a positive NAO mode and an eastward extension of its influence (Boberg and Lundstedt, 2002; Gimeno et al., 2003; Ogi et al., 2003). We therefore assume that the moisture conditions in our study area might have been influenced by both NAO and solar activity.

Recent studies suggest that anomalous moisture conditions in the Mediterranean Region can also be linked to ENSO variability (e.g. Nazemosadat and Cordery, 2000). Although ENSO most prominently influences precipitation change in the Pacific tropics, effects can also be traced in the North Atlantic and Mediterranean regions (Rodo et al., 1997; Shaman and Tziperman, 2011). For instance, it is shown that the western Mediterranean region receives 10% more precipitation in the autumn preceding the mature phase of an El Nino event (Mariotti et al., 2002). As we discussed above the relatively low river discharge related to decreased precipitation reconstructed for the research area is synchronous to large-scale dryness events in differential subtropical areas during the Medieval Period. Interestingly, a major Holocene ENSO anomaly is reconstructed for the MWP which might be an indication of the climate perturbations reconstructed in this study interval, implying that these events might be teleconnected with ENSO being related to large scale atmosphere-ocean circulation shifts (Rein et al., 2004). We speculate that the relatively arid conditions in Gulf of Taranto area might therefore be partly influenced by ENSO anomalies during the Medieval Period as well. However, large uncertainties remain whether and to what extent ENSO can be responsible for precipitation change in the Mediterranean area and many more studies are required to provide a better understanding about the exact nature of such a teleconnection and to conform or reject our suggestion (Ropelewski and Halpert, 1987).

8. Conclusions

The dinoflagellate cysts based paleoclimate and paleoceanography reconstructions provide a high resolution detection of SST, river discharge/precipitation and upper water nutrient availability fluctuations during the Medieval Period. We show that reconstructed mean SST is lower in the Medieval Period compared to that of last 100 years and the Roman Warm Period although large short term fluctuations in temperature can be observed. It is consistent with other records that short pulses of warmer than today situations are being reconstructed around 1067 and during 1102 - 1126, and 1171 - 1181 AD and cold spells during about 1075 – 1090 and 1130 – 1150 AD.

River discharge waters with nutrients and trace elements transporting into the Southern Adriatic Sea is suggested to be a dominant factor for the variation in nutrient availability in the Gulf of Taranto. Apart from this, wind-driven Saharan-Sahel dust might have formed an additional nutrient/trace-element source. We observe that several volcanic eruptions occurred at times of maximum availability of nutrients (Fig 5), indicating that this might have promoted the production of dinoflagellate cysts as well.

We observe a clear 11.4 years solar cycles in the reconstructed SST series during the Medieval Period. Besides this, we document a good match between SST and the global $\triangle^{14}C$ anomaly signal. Our reconstructed temperature fluctuations vary in consistence with variations in solar activity such as for instance the Oort Minimum (1010-1080 AD) and Medieval Maximum (1120-1180 AD) of solar insolation. This suggests that solar activity played an important role influencing the local temperature during the Medieval time.

Accumulation rates of *L. machaerophorum* and *Concentricystes spp.* show similar variation patterns related to river discharge variability which can be subscribed to variations in local precipitation rates. We observe low precipitation in the Adriatic area during the study time interval, synchronous to other drought events in Europe and North America. We suggest that this can be related to the strong positive NAO mode and severe ENSO anomalous events that have been reconstructed for the Medieval Warm Period. We speculate that the relatively arid conditions in Gulf of Taranto area might have been influenced by NAO and ENSO related large scale ocean-atmosphere circulation shifts. However, more studies are required to verify these suggestions and to obtain more insights on how these factors might be teleconnected.

Acknowledgments

The study is funded by the DFG as part of the ESF/EuroMarc project MOCCHA (Multidisciplinary study of continental/ocean climate dynamics using high-resolution records from the eastern Mediterranean). We thank Caroline Clotten for processing the samples. All the group members in Historical Geology and Palaeontology, Bremen University are thanked for the laboratory help and fruitful discussions. We thank Anna-Lena Grauel, Stefano M. Bernasconi and the AMS ^{14}C Dating Laboratory at ETH Zurich for preparing, measuring and calibrating the AMS 14C-dates. We further would like to thank Arne Leider (MARUM Bremen), Marie-Louise Goudeau (Utrecht University) and Anna-Lena Grauel (ETH Zurich) for the core sub-sampling. Authors are grateful to Captains, Crew and Colleagues onboard RV Pelagia during the MOCCHA- Project Cruise (October-November 2008) under the coordination of Gert J. De Lange (Utrecht University).

References

Allen, J. R. M., Watts, W. A., McGee, E., and Huntley, B. (2002). Holocene environmental variability - the record from Lago Grande di Monticchio, Italy. *Quaternary International* **88,** 69-80.

Antonioli, F., Silenzi, S., Gabellini, M., and Mucedda, M. (2003). High resolution climate trend over the last 1000 years from a stalagmite in Sardinia (Italy). *Quaternaria Nova* **7,** 1-15.

Arno, V., Principe, C., Rosi, M., Santacroce, R., Sbrana, A., and Sheridan, M. F. (1987). Eruptive history, in Somma-Vesuvius, edited by R. Santacroce, Progetto Finalizzato Geodin. 114, Monogr. Finali, 8, Cons. Naz. delle Ric., Rome.: pp. 53-104.

Boberg, F., and Lundstedt, H. (2002). Solar wind variations related to fluctuations of the North Atlantic Oscillation. *Geophysical Research Letters* **29**.

Boldrin, A., Langone, L., Miserocchi, S., Turchetto, M., and Acri, F. (2005). Po River plume on the Adriatic continental shelf: Dispersion and sedimentation of dissolved and suspended matter during different river discharge rates. *Marine Geology* **222,** 135-158.

Bonino, G., Castagnoli, G. C., Callegari, E., and Zhu, G. M. (1993). Radiometric and Tephroanalysis Dating of Recent Ionian Sea Cores. *Nuovo Cimento Della Societa Italiana Di Fisica C-Geophysics and Space Physics* **16,** 155-162.

Bradley, R. S., Hughes, M. K., and Diaz, H. F. (2003). Climate in Medieval time. *Science* **302,** 404-405.

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbondates.

Caroppo, C., Turicchia, S., and Margheri, M. C. (2006). Phytoplankton assemblages in coastal waters of the northern Ionian Sea (eastern Mediterranean), with special reference to cyanobacteria. *Journal of the Marine Biological Association of the United Kingdom* **86,** 927-937.

Cassou, C., Terray, L., Hurrell, J. W., and Deser, C. (2004). North Atlantic winter climate regimes: Spatial asymmetry, stationarity with time, and oceanic forcing. *Journal of Climate* **17,** 1055-1068.

Castagnoli, G. C., Bonino, G., Caprioglio, F., Provenzale, A., Serio, M., and Zhu, G. M. (1990). The Carbonate Profile of 2 Recent Ionian Sea Cores - Evidence That the Sedimentation-Rate Is Constant over the Last Millennia. *Geophysical Research Letters* **17,** 1937-1940.

Castagnoli, G. C., Bonino, G., Provenzale, A., Serio, M., and Callegari, E. (1992). The Caco3 Profiles of Deep and Shallow Mediterranean-Sea Cores as Indicators of Past Solar-Terrestrial Relationships. *Nuovo Cimento Della Societa Italiana Di Fisica C-Geophysics and Space Physics* **15,** 547-563.

Cavaleri, L., Bertotti, L., and Tescaro, N. (1997). The modelled wind climatology of the Adriatic Sea. *Theoretical and Applied Climatology* **56,** 231-254.

Chen, L., Zonneveld, K. A. F., and Versteegh, G. J. M. (2011). Short term climate variability during "Roman Classical Period" in the Eastern Mediterranean. *Quaternary Science Reviews. in press*.

Combourieu-Nebout, N., Paterne, M., Turon, J. L., and Siani, G. (1998). A high-resolution record of the last deglaciation in the Central Mediterranean Sea: Palaeovegetation and palaeohydrological evolution. *Quaternary Science Reviews* **17,** 303-317.

Crowley, T. J. (2000). Causes of climate change over the past 1000 years. *Science* **289,** 270-277.

Crowley, T. J., and Lowery, T. S. (2000). How warm was the medieval warm period? *Ambio* **29,** 51-54.

De Lange, G. J. (2008). Report of DOPPIO cruise with R.V. PELAGIA to the MEDITERRANEAN.

Degobbis, D., Gilmartin, M., and Revelante, N. (1986). An annotated nitrogen budget calculation for the Northern Adriatic Sea. *Marine Chemistry* **20,** 159-177.

Dulac, F., Moulin, C., Lambert, C. E., Guillard, F., Poitou, J., Guelle, W., Quetel, C. R., Schneider, X., and Ezat, U. (1996). Quantitative remote sensing of African dust transport to the Mediterranean. *In* "Impact of Desert Dust across the Mediterranean." (S. Guerzoni, and R. Chester, Eds.), pp. 25-49. Environmental Science and Technology Library.

Elshanawany, R., Zonneveld, K., Ibrahim, M. I., and Kholeif, S. E. A. (2010). Distribution Patterns of Recent Organic-Walled Dinoflagellate Cysts in Relation to Environmental Parameters in the Mediterranean Sea. *Palynology* **34,** 233-260.

Esper, J., Frank, D., Buntgen, U., Verstege, A., and Luterbacher, J. (2007). Long-term drought severity variations in Morocco. *Geophysical Research Letters* **34,** 5.

Filippi, M. L., Lambert, P., Hunziker, J., Kubler, B., and Bernasconi, S. (1999). Climatic and anthropogenic influence on the stable isotope record from bulk carbonates and ostracodes in Lake Neuchatel, Switzerland, during the last two millennia. *Journal of Paleolimnology* **21,** 19-34.

Garcia, N. O., Gimeno, L., De la Torre, L., Nieto, R., and Anel, J. A. (2005). North Atlantic oscillation (NAO) and precipitation in Galicia (Spain). *Atmosfera* **18,** 25-32.

Giannakourou, A., Orlova, T. Y., Assimakopoulou, G., and Pagou, K. (2005). Dinoflagellate cysts in recent marine sediments from Thermaikos Gulf, Greece: Effects of resuspension events on vertical cyst distribution. *Continental Shelf Research* **25,** 2585-2596.

Gimeno, L., de la Torre, L., Nieto, R., Garcia, R., Hernandez, E., and Ribera, P. (2003). Changes in the relationship NAO-Northern Hemisphere Temperature due to solar activity. *Earth and Planetary Science Letters* **206,** 15-20.

Giraudi, C. (2009). Late Holocene glacial and periglacial evolution in the upper Orco Valley, northwestern Italian Alps. *Quaternary Research* **71,** 1-8.

Goni, M. F. S., Eynaud, F., Turon, J. L., and Shackleton, N. J. (1999). High resolution palynological record off the Iberian margin: direct land-sea correlation for the Last Interglacial complex. *Earth and Planetary Science Letters* **171,** 123-137.

Goosse, H., Arzel, O., Luterbacher, J., Mann, M. E., Renssen, H., Riedwyl, N., Timmermann, A., Xoplaki, E., and Wanner, H. (2006). The origin of the European "Medieval Warm Period". *Climate of the Past* **2,** 99-113.

Graham, N. E., and Hughes, M. K. (2007). Reconstructing the Mediaeval low stands of Mono Lake, Sierra Nevada, California, USA. *Holocene* **17,** 1197-1210.

Grudd, H. (2008). Tornetrask tree-ring width and density AD 500-2004: a test of climatic sensitivity and a new 1500-year reconstruction of north Fennoscandian summers. *Climate Dynamics* **31,** 843-857.

Guiot, J., and Corona, C. (2010). Growing Season Temperatures in Europe and Climate Forcings Over the Past 1400 Years. *Plos One* **5,** 15.

Guiot, J., Nicault, A., Rathgeber, C., Edouard, J. L., Guibal, F., Pichard, G., and Till, C. (2005). Last-millennium summer-temperature variations in western Europe based on proxy data. *Holocene* **15,** 489-500.

Hainbucher, D., Rubino, A., and Klein, B. (2006). Water mass characteristics in the deep layers of the western Ionian Basin observed during May 2003. *Geophysical Research Letters* **33**.

Hegerl, G. C., Crowley, T. J., Baum, S. K., Kim, K. Y., and Hyde, W. T. (2003). Detection of volcanic, solar and greenhouse gas signals in paleo-reconstructions of Northern Hemispheric temperature. *Geophysical Research Letters* **30,** 4.

Hiller, A., Boettger, T., and Kremenetski, C. (2001). Mediaeval climatic warming recorded by radiocarbon dated alpine tree-line shift on the Kola Peninsula, Russia. *Holocene* **11,** 491-497.

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

Holzwarth, U., Esper, O., and Zonneveld, K. (2007). Distribution of organic-walled dinoflagellate cysts in shelf surface sediments of the Benguela upwelling system in relationship to environmental conditions. *Marine Micropaleontology* **64,** 91-119.

Horton, B. P., Gibbard, P. L., Milne, G. M., Morley, R. J., Purintavaragul, C., and Stargardt, J. M. (2005). Holocene sea levels and palaeoenvironments, Malay-Thai Peninsula, southeast Asia. *Holocene* **15,** 1199-1213.

Hughen, K. A., Baillie, M. G. L., Bard, E., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Kromer, B., McCormac, G., Manning, S., Ramsey, C. B., Reimer, P. J., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J., and Weyhenmeyer, C. E. (2004). Marine04 marine radiocarbon age calibration, 0-26 cal kyr BP. *Radiocarbon* **46,** 1059-1086.

Hughes, M. K., and Diaz, H. F. (1994). Was There a Medieval Warm Period, and If So, Where and When. *Climatic Change* **26,** 109-142.

Hurrell, J. W. (1995). Decadal trends in the North-Atlantic Oscillation - Regional temperatures and precipitation. *Science* **269,** 676-679.

Hurrell, J. W., and VanLoon, H. (1997). Decadal variations in climate associated with the north Atlantic oscillation. *Climatic Change* **36,** 301-326.

Jickells, T. D., An, Z. S., Andersen, K. K., Baker, A. R., Bergametti, G., Brooks, N., Cao, J. J., Boyd, P. W., Duce, R. A., Hunter, K. A., Kawahata, H., Kubilay, N., laRoche, J., Liss, P. S., Mahowald, N., Prospero, J. M., Ridgwell, A. J., Tegen, I., and Torres, R. (2005). Global iron connections between desert dust, ocean biogeochemistry, and climate. *Science* **308,** 67-71.

Jones, M. D., Roberts, C. N., Leng, M. J., and Turkes, M. (2006). A high-resolution late Holocene lake isotope record from Turkey and links to North Atlantic and monsoon climate. *Geology* **34,** 361-364.

Jones, P. D., and Mann, M. E. (2004). Climate over past millennia. *Reviews of Geophysics* **42,** 42.

Keigwin, L. D. (1996). The Little Ice Age and Medieval warm period in the Sargasso Sea. *Science* **274,** 1504-1508.

Kim, J. H., Huguet, C., Zonneveld, K. A. F., Versteegh, G. J. M., Roeder, W., Damste, J. S. S., and Schouten, S. (2009). An experimental field study to test the stability of lipids used for the TEX86 and U-37(K ') palaeothermometers. *Geochimica Et Cosmochimica Acta* **73,** 2888-2898.

Lamb, H. H. (1965). The Early Medieval Warm Epoch and Its Sequel. *Palaeogeography Palaeoclimatology Palaeoecology* **1,** 13-37.

Langmann, B., Zaksek, K., Hort, M., and Duggen, S. (2010). Volcanic ash as fertiliser for the surface ocean. *Atmospheric Chemistry and Physics* **10,** 3891-3899.

Lee, C. M., Orlic, M., Poulain, P. M., and Cushman-Roisin, B. (2007). Introduction to special section: Recent advances in oceanography and marine meteorology of the Adriatic Sea. *Journal of Geophysical Research-Oceans* **112,** 3.

Lewis, J. (1988). Cysts and sediments: Gonyaulax polyedra (Lingulodinium machaerophorum) in Loch Ceran. *Journal of the Marine Biology Association of the United Kingdom* **68,** 701-714.

Lionello, P., and Sanna, A. (2005). Mediterranean wave climate variability and its links with NAO and Indian Monsoon. *Climate Dynamics* **25,** 611-623.

Magny, M. (2004). Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. *Quaternary International* **113,** 65-79.

Mariotti, A., Zeng, N., and Lau, K. M. (2002). Euro-Mediterranean rainfall and ENSO - a seasonally varying relationship. *Geophysical Research Letters* **29**.

Marret, F., and Zonneveld, K. A. F. (2003). Atlas of modern organic-walled dinoflagellate cyst distribution. *Review of Palaeobotany and Palynology* **125,** 1-200.

Martin-Puertas, C., Jimenez-Espejo, F., Martinez-Ruiz, F., Nieto-Moreno, V., Rodrigo, M., Mata, M. P., and Valero-Garces, B. L. (2010). Late Holocene climate variability in the southwestern Mediterranean region: an integrated marine and terrestrial geochemical approach. *Climate of the Past* **6,** 807-816.

Matsuoka, K., Kawami, H., Nagai, S., Iwataki, M., and Takayama, H. (2009). Re-examination of cyst-motile relationships of Polykrikos kofoidii Chatton and Polykrikos schwartzii Butschli (Gymnodiniales, Dinophyceae). *Review of Palaeobotany and Palynology* **154,** 79-90.

Middleton, N. J., and Goudie, A. S. (2001). Saharan dust: sources and trajectories. *Transactions of the Institute of British Geographers* **26,** 165-181.

Moberg, A., Sonechkin, D. M., Holmgren, K., Datsenko, N. M., and Karlen, W. (2005). Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433,** 613-617.

Moulin, C., Lambert, C. E., Dulac, F., and Dayan, U. (1997). Control of atmospheric export of dust from North Africa by the North Atlantic oscillation. *Nature* **387,** 691-694.

Mudie, P. J., Rochon, A., Aksu, A. E., and Gillespie, H. (2002). Dinoflagellate cysts, freshwater algae and fungal spores as salinity indicators in Late Quaternary cores from Marmara and Black seas. *Marine Geology*

190, 203-231.

Mulitza, S., Heslop, D., Pittauerova, D., Fischer, H. W., Meyer, I., Stuut, J. B., Zabel, M., Mollenhauer, G., Collins, J. A., Kuhnert, H., and Schulz, M. (2010). Increase in African dust flux at the onset of commercial agriculture in the Sahel region. *Nature* **466,** 226-228.

Nazemosadat, M. J., and Cordery, I. (2000). On the relationships between ENSO and autumn rainfall in Iran. *International Journal of Climatology* **20,** 47-61.

Ogi, M., Yamazaki, K., and Tachibana, Y. (2003). Solar cycle modulation of the seasonal linkage of the North Atlantic Oscillation (NAO). *Geophysical Research Letters* **30,** 4.

Orlic, M., Kuzmic, M., and Pasaric, Z. (1994). Response of the Adriatic Sea to the Bora and Sirocco Forcing. *Continental Shelf Research* **14,** 91-116.

Pasaric, Z., Belusic, D., and Klaic, Z. B. (2007). Orographic influences on the Adriatic sirocco wind. *Annales Geophysicae* **25,** 1263-1267.

Pfister, C., Luterbacher, J., Schwarz-Zanetti, G., and Wegmann, M. (1998). Winter air temperature variations in western Europe during the Early and High Middle Ages (AD 750-1300). *Holocene* **8,** 535-552.

Piva, A., Asioli, A., Trincardi, F., Schneider, R. R., and Vigliotti, L. (2008). Late-Holocene climate variability in the Adriatic sea (Central Mediterranean). *Holocene* **18,** 153-167.

Pla, S., and Catalan, J. (2005). Chrysophyte cysts from lake sediments reveal the submillennial winter/spring climate variability in the northwestern Mediterranean region throughout the Holocene. *Climate Dynamics* **24,** 263-278.

Pospelova, V., Chmura, G. L., Boothman, W. S., and Latimer, J. S. (2005). Spatial distribution of modern dinoflagellate cysts in polluted estuarine sediments from Buzzards Bay (Massachusetts, USA) embayments. *Marine Ecology-Progress Series* **292,** 23-40.

Radi, T., and de Vernal, A. (2008). Dinocysts as proxy of primary productivity in mid-high latitudes of the Northern Hemisphere. *Marine Micropaleontology* **68,** 84-114.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, G., Manning, S., Ramsey, C. B., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J., and Weyhenmeyer, C. E. (2004). IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP. *Radiocarbon* **46,** 1029-1058.

Rein, B., Luckge, A., and Sirocko, F. (2004). A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters* **31,** 4.

Rizzi-Longo, L., Pizzulin-Sauli, M., Stravisi, F., and Ganis, P. (2007). Airborne pollen calendar for Trieste (Italy), 1990-2004. *Grana* **46,** 98-109.

Rodo, X., Baert, E., and Comin, F. A. (1997). Variations in seasonal rainfall in southern Europe during the present century: Relationships with the North Atlantic Oscillation and the El Nino Southern Oscillation. *Climate Dynamics* **13,** 275-284.

Ropelewski, C. F., and Halpert, M. S. (1987). Global and Regional Scale Precipitation Patterns Associated with the El-Nino Southern Oscillation. *Monthly Weather Review* **115,** 1606-1626.

Saliot, A. (2005). The Mediterranean Sea. *Springer Verlag***,** p428.

Sangiorgi, F., Capotondi, L., and Brinkhuis, H. (2002). A centennial scale organic-walled dinoflagellate cyst record of the last deglaciation in the South Adriatic Sea (Central Mediterranean). *Palaeogeography Palaeoclimatology Palaeoecology* **186,** 199-216.

Sangiorgi, F., Fabbri, D., Comandini, M., Gabbianelli, G., and Tagliavini, E. (2005). The distribution of sterols and organic-walled dinoflagellate cysts in surface sediments of the North-western Adriatic Sea (Italy). *Estuarine, Coastal and Shelf Science* **64,** 395-406.

Santarelli, A., Brinkhuis, H., Hilgen, F. J., Lourens, L. J., Versteegh, G. J. M., and Visscher, H. (1998). Orbital signatures in a Late Miocene dinoflagellate record from Crete (Greece). *Marine Micropaleontology* **33,** 273-297.

Schulz, M., and Mudelsee, M. (2002). REDFIT: estimating red-noise spectra directly from unevenly spaced paleoclimatic time series. *Computers & Geosciences* **28,** 421-426.

Sellschopp, J., and Alvarez, A. (2003). Dense low-salinity outflow from the Adriatic Sea under mild (2001) and strong (1999) winter conditions. *Journal of Geophysical Research-Oceans* **108**.

Serrebachet, F. (1994). Middle-Ages Temperature Reconstructions in Europe, a Focus on Northeastern Italy. *Climatic Change* **26,** 213-224.

Shaman, J., and Tziperman, E. (2011). An Atmospheric Teleconnection Linking ENSO and Southwestern European Precipitation. *Journal of Climate* **24,** 124-139.

Siebert, L., and Simkin, T. (2002). Volcanoes of the World: an Illustrated Catalog of Holocene Volcanoes and their Eruptions. *Smithsonian Institution, Global Volcanism Program, Digital Information Series, GVP-3.*

Socal, G., Boldrin, A., Bianchi, F., Civitarese, G., De Lazzari, A., Rabitti, S., Totti, C., and Turchetto, M. M. (1999). Nutrient, particulate matter and phytoplankton variability in the photic layer of the Otranto strait. *Journal of Marine Systems* **20,** 381-398.

Stine, S. (1994). Extreme and Persistent Drought in California and Patagonia During Medieval Time. *Nature* **369,** 546-549.

Stuiver, M., Reimer, P. J., Bard, E., Beck, J. W., Burr, G. S., Hughen, K. A., Kromer, B., McCormac, G., Van der Plicht, J., and Spurk, M. (1998). INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. *Radiocarbon* **40,** 1041-1083.

Tafuro, A. M., Barnaba, F., De Tomasi, F., Perrone, M. R., and Gobbi, G. P. (2006). Saharan dust particle properties over the central Mediterranean. *Atmospheric Research* **81,** 67-93.

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

Tinner, W., van Leeuwen, J. F. N., Colombaroli, D., Vescovi, E., van der Knaap, W. O., Henne, P. D., Pasta, S., D'Angelo, S., and La Mantia, T. (2009). Holocene environmental and climatic changes at Gorgo Basso, a coastal lake in southern Sicily, Italy. *Quaternary Science Reviews* **28,** 1498-1510.

Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., and Frank, D. C. (2009). Persistent Positive North Atlantic Oscillation Mode Dominated the Medieval Climate Anomaly. *Science* **324,** 78-80.

Versteegh, G. J. M., de Leeuw, J. W., Taricco, C., and Romero, A. (2007). Temperature and productivity influences on U-37(K') and their possible relation to solar forcing of the Mediterranean winter. *Geochemistry Geophysics Geosystems* **8**.

Versteegh, G. J. M., and Zonneveld, K. A. F. (2002). Use of selective degradation to separate preservation from productivity. *Geology* **30,** 615-618.

Zanchettin, D., Traverso, P., and Tomasino, M. (2008). Po River discharges: a preliminary analysis of a 200-year time series. *Climatic Change* **89,** 411-433.

Zonneveld, K. A. F., Bockelmann, F., and Holzwarth, U. (2007). Selective preservation of organic-walled dinoflagellate cysts as a tool to quantify past net primary production and bottom water oxygen concentrations. *Marine Geology* **237,** 109-126.

Zonneveld, K. A. F., Chen, L., El-Shanawany, R., Fischer, H. W., Hoins, M., Ibrahim, M. I., Pittaurova, D., and Versteegh, G. (2011). The use of dinoflagellate cysts to separate human and natural induced variability in the trophic state of the Po-river discharge plume during the last two centuries. *Marine Pollution Bulletin. in press*.

Zonneveld, K. A. F., Chen, L., Mobius, J., and Mahmoud, M. S. (2009). Environmental significance of dinoflagellate cysts from the proximal part of the Po-river discharge plume (off southern Italy, Eastern Mediterranean). *Journal of Sea Research* **62,** 189-213.

Zonneveld, K. A. F., Susek, E., and Fischer, G. (2010). Seasonal Variability of the Organic-Walled Dinoflagellate Cyst Production in the Coastal Upwelling Region Off Cape Blanc (Mauritania): a Five-Year Survey. *Journal of Phycology* **46,** 202-215.

Zonneveld, K. A. F., Versteegh, G., and Kodrans-Nsiah, M. (2008). Preservation and organic chemistry of Late Cenozoic organic-walled dinoflagellate cysts: A review. *Marine Micropaleontology* **68,** 179-197.

7. Short term climate variability during "Roman Classical Period" in the Eastern Mediterranean

Liang Chen,[1, *] Karin Zonneveld,[1,2] and Gerard Versteegh[2]

[1] Fachbereich Geowissenschaften, Universität Bremen, Postfach 330440, D-28334 Bremen, Germany
[2] MARUM, Universität Bremen, Leobenerstraße, D-28359 Bremen, Germany

* Corresponding author.

***Quaternary Science Reviews*, in press, 2011, doi:10.1016/j.quascirev.2011.09.024**

Abstract

To obtain insight into character and potential forcing of short-term climatic and oceanographic variability in the southern Italian region during the "Roman Classical Period" (60 BC - AD 200), climatic and environmental reconstructions based on a dinoflagelate cyst record from a well dated site in the Gulf of Taranto located at the distal end of the Po-river discharge plume have been established with high temporal resolution. Short-term fluctuations in accumulation rates of the Adriatic Surface Water species *Lingulodinium machaerophorum*, the fresh water algae *Concentricystes* and species resistant to aerobic degradation indicate that fluctuations in the trophic state of the upper waters are related to river discharge of northern and eastern Italian rivers which in turn are strongly related to precipitation in Italy.

The dinoflagellate cyst association indicates that local sea surface temperatures which in this region are strongly linked to local air temperatures were slightly higher than today. We reconstruct that sea surface temperatures have been relatively high and stable between 60 BC - AD 90 and show a decreasing trend after AD 90. Fluctuations in temperature and river discharge rates have a strong cyclic character with main cyclicities of 7-8 and 11 years. We argue that these cycles are related to variations of the North Atlantic Oscillation climate mode. A strong correlation is observed with global variation in $\Delta^{14}C$ anomalies suggesting that solar variability might be one of the major forcings of the regional climate. Apart from cyclic climate variability we observed a good correlation between non-cyclic temperature drops and global volcanic activity indicating that the latter forms an additional major forcing factor of the southern Italian climate during the Roman Classical Period.

Keywords: Climate; Roman Classical Period; Dinoflagellate cysts; North Atlantic Oscillation

1. Introduction

The current abrupt rise in global temperature within the last century has resulted in major concern about future climate change (IPCC, 2007). Although it is obvious that anthropogenic activities influence climate, natural processes steer climate as well (Carslaw et al., 2002; Stott et al., 2000). This has resulted in intensive discussions in the academic community and general society alike about to what extent these natural processes might be responsible for the present change of climate. Unfortunately, to date, the character and influence of the natural forcing mechanisms are far from clear.

One of the most intriguing questions within the climate debate is if the present temperature rise is unique in the late Holocene or if there have been pre-industrial time intervals where comparable climatic perturbations occurred. One of these time intervals where historical records suggest that climate conditions might have been similar to today is the so called “Roman Warm Period” (≈BC 200 – AD 400) (Lamb, 1977). This period also referred to as the “Roman classical period” is known for the expansion of the Roman culture all around the Mediterranean region and throughout a large part of Europe. However, to date it is not clear if this period was warmer, comparable or cooler than today (Bianchi and McCave, 1999; deMenocal et al., 2000; Frisia et al., 2005; Giraudi, 2009; Taricco et al., 2009). Furthermore, it is not clear which forcing mechanisms steered the short-term climate fluctuations that are known for this time interval. Here we aim to obtain more insight into this by reconstructing past marine environment and climate variability in one of the central regions of the Roman occupation - southeastern Italy. For this we establish detailed reconstructions of past changes in climate and marine environment based on fossil sedimentary dinoflagellate cyst associations.

Dinoflagellates are primarily unicellular organisms with two distinctive flagella and a characteristic nucleus (Fensome et al., 1993). Together with diatoms and coccolithophorids, dinoflagellates constitute the majority of the marine eukaryotic phytoplankton. As part of their life cycle, many dinoflagellate species can produce cysts of which the walls have a high preservation potential. Organic walled dinoflagellate cysts (dinocysts) have been shown to be a suitable proxy for establishing environmental and climatic reconstructions as the cyst associations reflect even small changes in upper water conditions such as sea surface temperature (SST), salinity (SSS) and nutrient availability (Dale et al., 2002; De Vernal et al., 1997; Marret et al., 2001; Pospelova et al., 2006; Sangiorgi et al., 2002).

Here we present reconstructions that base on well dated marine sediments from the southeastern Gulf of Taranto which are characterized by high sedimentation rates and low bioturbation, the linear interpolation of the radiocarbon dates allows an approximately 4 year resolution detection of paleoenvironmental change. We show that changes in dinoflagellate associations reflect changes in past river discharge, upper water nutrient availability and SST. To obtain insight into the cause and origin of the variability of these signals, we compare our records with temperature and precipitation reconstructions from other lower resolution studies in the region based on e.g. pollen and speleothems. Furthermore, we compare them with climate forcing factors such as solar activity, volcanism and African dust input. By comparing our results with historical records we are able to speculate about the potential relationship between climate and cultural developments.

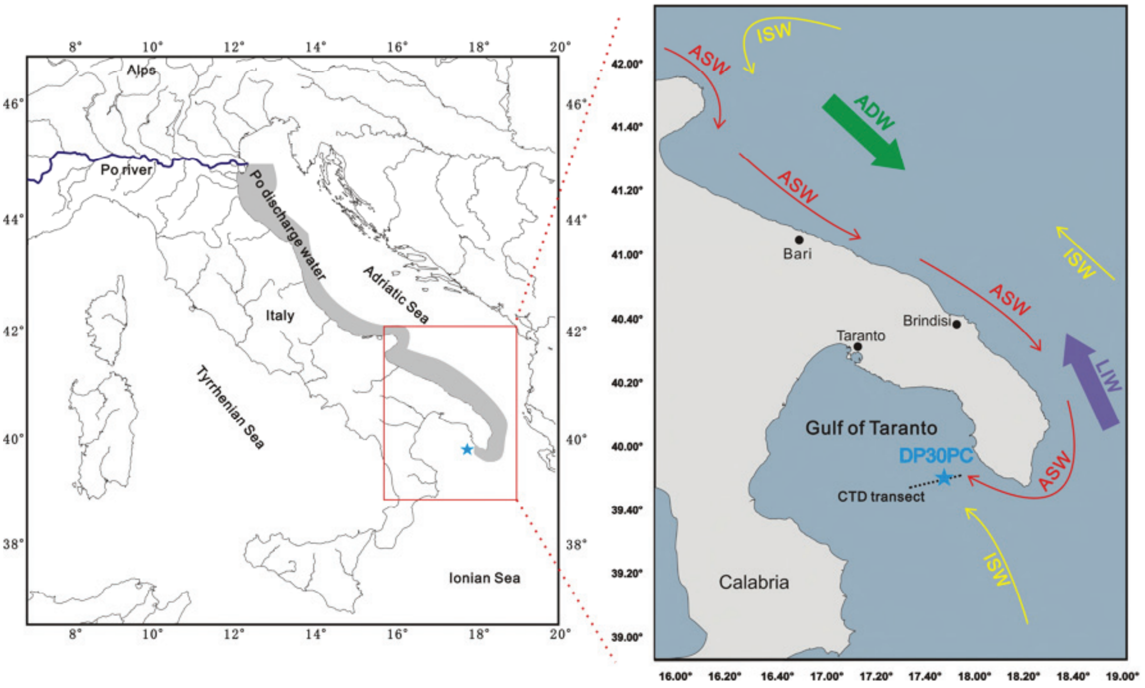


Fig 1. Study location and ocean circulation. ASW-Adriatic Surface Water, ISW-Ionian Sea Water, LIW-Levantine Intermediate Water, ADW-Adriatic Deep Water. Dotted line represents the transect where CTD was deployed.

2. Research area

2.1. Ocean circulation

The ocean circulation of Gulf of Taranto is strongly related to that of the Adriatic Sea. Surface waters in the southeastern part form the distal part “river-discharge” waters that can be traced along the whole eastern Italian coast. The main source of these waters is from the Po river (Fig 1). The Po river is the largest Italian river with a length of about 673 km that drains the southern part of the Alps and the northern part of Italy. It supplies high amounts of fresh water, nutrients and suspended matter into the northwestern Adriatic basin (Boldrin et al., 2005; Degobbis et al., 1986). These waters which are traditionally classified as the Adriatic

Surface Waters (ASW) are characterized by high chlorophyll-a concentrations (Fig 2). The cyclonic surface currents of the Adriatic Sea induced by Coriolis forcing press these southeastward flowing waters against the western coastal margin of the Adriatic Sea (Lee et al., 2007). Local eastern Italian rivers additionally spice these plume-waters on their way southeastward. However, the amounts of suspended matter and nutrients these local rivers discharge into the system are considerably less than the Po river discharge (Degobbis et al., 1986; Milligan and Cattaneo, 2007). Within the Gulf of Taranto, the circulation is generally cyclonic with ASW entering along the eastern part the basin. Additionally, Ionian Sea Waters (ISW) enters the Gulf of Taranto at the eastern side where these waters gradually mix with ASW (Fig 1). The ISW is characterized by relatively high temperature, high salinity, a low suspended matter load and low nutrients concentrations (Boldrin et al., 2005; Caroppo et al., 2006; Socal et al., 1999). Within the Gulf, intermediate water is formed by Levantine Intermediate Water (LIW) which originates from the Levantine basin (Greece), and can be observed between 150 and 600 m water depth. Below 600m depth a shift towards much cooler waters of the dense Adriatic Deep Water (ADW) can be observed (e.g. Hainbucher et al., 2006; Sellschopp and Alvarez, 2003).

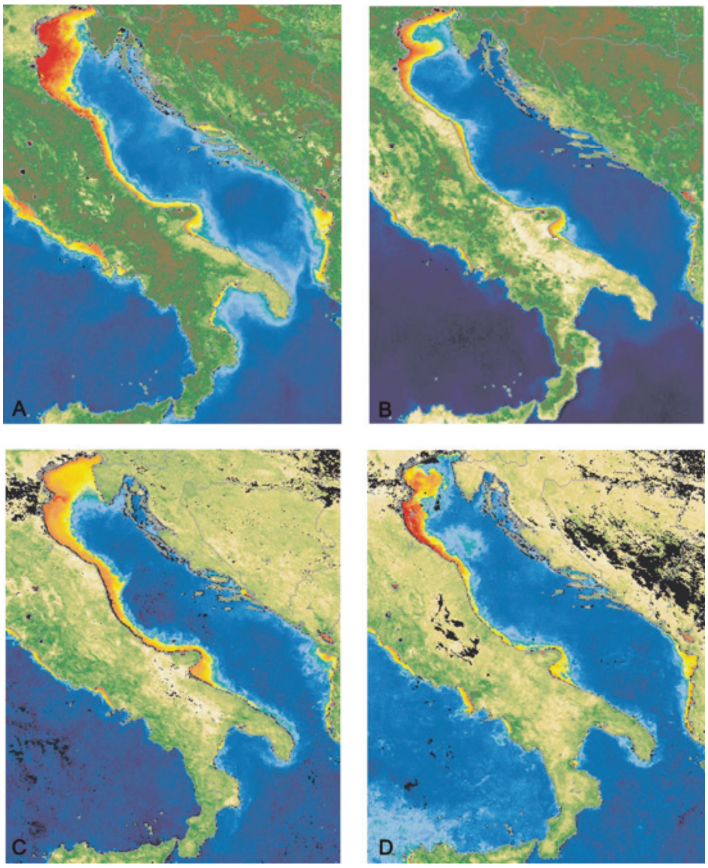


Fig 2. Seasonal chlorophyll-a image of upper ocean in (A) spring, (B) summer, (C) autumn, (D) winter, based on Zonneveld et al. (2009).

2.2. Climate

The Mediterranean climate is characterized by hot and dry summers and cool and relatively wet winters. It is strongly influenced by upper air circulation systems such as the Scandinavia pattern, East Atlantic (EA) pattern and North Atlantic Oscillation (NAO) (Cassou et al., 2004; Fil and Dubus, 2005; Hurrell and VanLoon, 1997). The most prominent climate mode, especially during the winter, is the NAO which represents the dipole-like pressure gradient between the Azores (high) and Iceland (low) (Hurrell, 1995). When the NAO index is in its positive phase, northern Europe experiences excess precipitation. In turn, a negative phase brings excess precipitation and high temperatures in southern Europe and Mediterranean (Lionello and Sanna, 2005). As a consequence, changes in NAO have their strong effects on the rainfall in the Italian region, with increasing rainfall resulting in excess discharge of the Po and other Italian rivers in the Adriatic and an increase in ASW entering the Gulf of Taranto (Fig 1). In winter, cold and dry winds typically blow from the northeast. This is the so called Bora which blows in strong pulses over Adriatic Sea (Orlic et al., 1994; Rachev and Purini, 2001). Anti-clockwise circulation induced by the Bora and Coriolis forcing presses the fresh, nutrient rich discharge waters from both the Po-River and Apennine rivers against the eastern coastal margin of Italy, driving Po river sediment southward along the eastern coast of the Adriatic Sea (Lee et al., 2007). A northward wind comes from the Sahara is named “Sirocco”. It brings warm and humid Mediterranean air into the Adriatic (Cavaleri et al., 1997; Pasaric et al., 2007). Although the Sirocco has no favored season, strong gale-forced Siroccos are most common during the spring (Sivall, 1957). The influence of strong Sirocco winds in the northern part of the Adriatic area can cause sea level rise and flooding of the northern Adriatic lowlands such as the region in the vicinity of Venice (Ferrarese et al., 2008; Jeromel et al., 2009). Although Bora and Sirocco only last several days, they can have an important influence on Adriatic sea level and circulation (Orlic et al., 1994).

3. Materials and methods

3.1. Material and sample preparation

Samples have been analysed from the section 8 (722-910 cm) of the piston core DP30PC which was retrieved during the RV Pelagia, DOPPIO cruise, 2008 (39° 50.07' N, 17°48.05' E, water depth 270 m). The core is located at the margin of the ocean where increased salinity in the water column can be observed along onshore-offshore transect (Fig 1, 3). The studied section of the piston core is composed of homogeneous olive-gray silt (Fig 4). Sediments were subsampled at every 2.5 mm. After subsampling, material was dried overnight at 60^{o}C, then treated based on standard palynological preparation procedures according to the aliquot method as described by Zonneveld et al. (2009). Taxonomy of dinoflagellate species is according to that cited in Marret and Zonneveld (2003) and Radi and de Vernal (2008).

Round, brown colored cyst were grouped as *Brigantedinium spp.*. The classification of the species *Polykrikos kofoidii* and *P. schwarzii* is according to Matsuoka, et al. (2009).

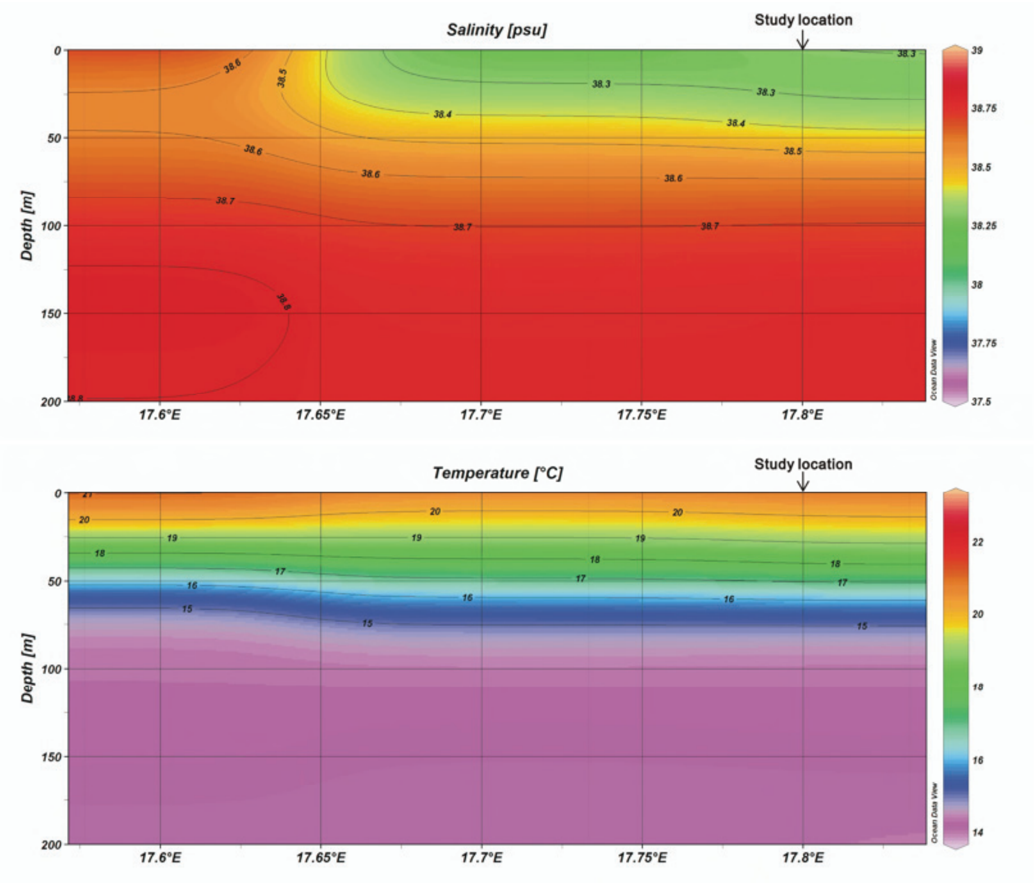


Fig 3. Salinity and temperature profile of the transect (Zonneveld et al., 2008b).

3.2. Age model

The age model of the studied core is based on AMS (Accelerator Mass Spectrometry) ^{14}C measurements on bulk planktic foraminifera that have been prepared at the Geological Institute, ETH Zurich and measured at the AMS Radiocarbon Dating Laboratory at ETH Zurich (Table 1). The ^{14}C dates were calibrated with the program OxCal v3.10 (Bronk Ramsey, 2009), with the references of atmospheric data from Reimer et al. (2004) and the Curve marine04 with the marine data from Hughen et al. (2004) ($\Delta R=121\pm60$ years). The chronological model of our studied interval has been derived by the linear interpolation between the radiocarbon dates which located above and below of the studied section. The age–depth relationship list takes into account the 2σ errors of the calibrated ^{14}C dates reveals a sedimentation rate of 0.7 mm/y (Fig 4). In the same study area, gravity core GT89/3 (39°45'43" N, 17°53'55" E, water depth 178 m) was retrieved around 11 km southeastern of our core DP30PC (Castagnoli et al., 1990). The chronological sequence of GT89/3 is based on tephra chronology. Although volcanic ash layers appear to be less than 1 mm in thickness and can not be traced visually in the cores of this region, 22 pyroxene peaks corresponding to outbreaks of the Vesuvius and the volcanos of the Campanian area could be determined in the core GT89/3 (Arno et al., 1987). The sedimentation rate of this core is constant with values of 0.6 mm/y (ca. 4 years temporal resolution of every 2.5 mm) during the last 2000 years. Extensive surveys on the sedimentary and elemental composition of numerous cores in the region have revealed that a constant sedimentation rate is characteristic for the whole Gallipoli terrace during the last 2000 years (e.g. Bonino et al., 1993; Castagnoli et al., 1990; Castagnoli et al., 1992).

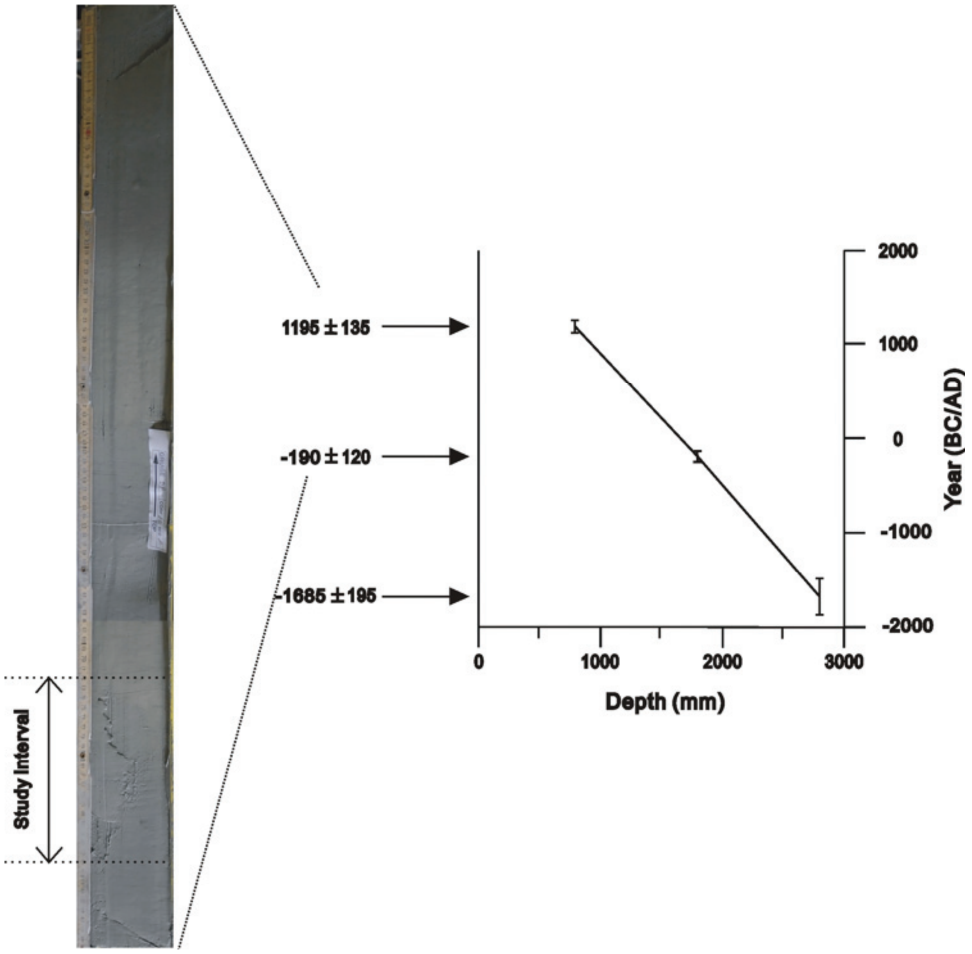


Fig 4. Radiocarbon dating and lithology of the sediments of DP30PC, 14C dates are present with 2s error bars and have converted to calibrated ages (BC/AD).

3.3. Paleoenvironmental indicators

3.3.1. Post depositional palynomorph degradation

Information about potential post-depositional aerobic degradation of palynomorphs is estimated by the dinoflagellate degradation index “kt” which depends on the degradation constant “k” and reaction time “t”, its calculated according to the formula (Versteegh and Zonneveld, 2002),

$kt = \ln(X_i/X_f)$, with $X_i = 68 \times X_r$

X_i = initial cyst accumulation rates of sensitive cyst species (cysts/cm^2/y); X_f = final cyst accumulation rates of sensitive cysts (cysts/cm^2/y); X_r = cyst accumulation rates of resistent cyst species (cysts/cm^2/y). Cyst accumulation rates is calculated according to the formula

Accumulation rates (cysts/cm^2/y) = Sedimentation rate (cm/y) x Dry bulk density (g/cm^3) x Cyst concentration (cyst/g)

The relationship between resistant and sensitive species is empirically determined based on sediment trap studies and geographical surveys (see overview in Zonneveld et al. (2008)). High kt values (3-4) suggest that post-depositional degradation might have overprinted the initial ecological signal.

3.3.2. River discharge

Here we use the sum of accumulation rates of cysts of the photosynthetic dinoflagellate *Lingulodinium machaerophorum* and the freshwater alga *Concentricystes spp.* as indicators for the presence of Adriatic surface waters. In the Eastern Mediterranean Sea and Adriatic Sea, *L. machaerophorum* is characteristically present in river discharge plumes (Elshanawany et al., 2010; Sangiorgi et al., 2002; Zonneveld et al., 2009). Its accumulation rates show a gradient from high to low values from the river mouths towards the distal parts of the plumes. Algal species *Concentricystes spp.* is a fresh-water species that is unable to survive in the marine environments. It can therefore be used as a freshwater indicator (e.g. Horton et al., 2005; Mudie et al., 2002).

3.3.3. Nutrient availability

Qualitative information about the trophic state of the upper waters is achieved by using an eutrophication index NA (nutrient availability):

NA = accumulation rates of the nutrient sensitive-aerobic degradation unsensitive species: *Impaginium aculeatum, Impagidinium paradoxum, Impagidinium patulum, Impagidinium sphaericum, Nematosphaeropsis labyrinthus, Operculodinium israelianum* and *Polysphaeridium zoharyi* (Zonneveld et al., 2007). Sediment trap studies and field surveys document that accumulation rates of these species increase in the Mediterranean as well as open oceans when phytoplankton production related nutrient concentrations in upper waters increase (Elshanawany et al., 2010; Holzwarth et al., 2007; Zonneveld et al., 2009; Zonneveld et al., 2010a).

3.3.4. Sea surface temperature

Qualitative information about variations in sea surface temperature is obtained using the following ratio:

$W/C = W_n / (W_n + C_n)$

where n = number of specimens counted, W = warm water species, C = cold water species. W = *Impagidinium aculeatum, Impagidinium paradoxum, Impagidinium patulum,* *Operculodinium israelianum, Polysphaeridium zoharyi, Spiniferites mirabilis*. C = *Bitectatodinium tepikiense*.

Species selection is based on the global geographic distribution of organic walled dinoflagellate cysts (e.g. Marret and Zonneveld, 2003).

3.4. Time series analysis

Frequency analysis of the above mentioned indices have been performed using the red-noise spectrum analysis of the program REDFIT which is based on Lomb periodogram and particularly suitable for unevenly spaced time series, the significance levels are presented to test reliability of periodicities as shown by spectral peaks (Schulz and Mudelsee, 2002). To validate if there is any spurious signal from REDFIT, we additionally performed an analysis using the multiTaper Method (MTM) of SSA-MTM Toolkit. This method can reduce the spectral leakage by using small tapers (Ghil et al., 2002). As spectrum analysis is unable to detect the temporal distribution of frequency signals, the matlab package of Continuous Wavelet Transform (CWT) which based on Morlet wavelet is included in this study to investigate the cyclic characters of the individual indicator properties throughout the sequence (Grinsted et al., 2004).

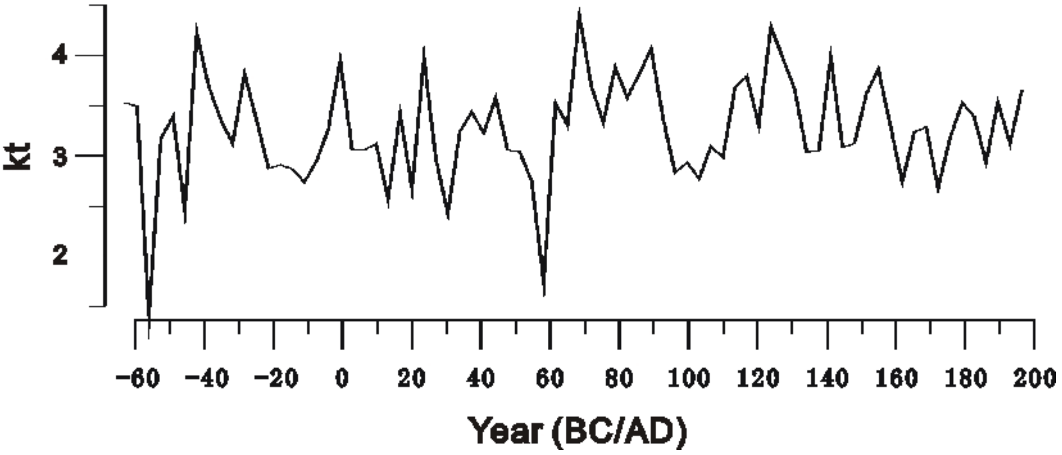


Fig 5. Degradation index (kt).

4. Results

The degradation index (kt) varies from 1.4 to 4.3 in the studied interval. It shows relatively low values between and BC 60 and 60 AD (Fig 5), and stays relatively stable throughout the whole sequence.

Accumulation rates of the dinoflagellate cyst *Lingulodinium machaerophorum* and freshwater alga *Concentricystes* show no increasing or decreasing trend through the studied interval but fluctuate around the mean of 8.6 cyst/cm^2/y and 0.8 cyst/cm^2/y respectively. Their accumulation rates fluctuate with strong cyclicities of 11 and 40 years and to a lesser extend of 8 and 18 years. Wavelet analyses reveal that the cyclicity is most pronounced during 0-120 AD (Fig 6).

The NA index is relatively steady throughout the sequence and ranges from 2.9 to 44.4 cyst/cm^2/y (Fig 7). The accumulation rates fluctuate with clear cyclicities of 7-8, 14 and 50 years based on spectral and wavelet analysis. The latter shows that the cycles are only clearly presented between 100 and 200 AD (Fig 6).

The dinocyst derived sea surface temperatures (SST) are stable during 60 BC and 90 AD with few exceptionally low values around 40 AD. After 90 AD, a clear decreasing trend is observed which characterized by large fluctuations (Fig 7 A). The association that is observed between 60 BC and 90 AD is equivalent to modern regions that are characterized by higher SST as the present day Gulf of Taranto. Predominant cycles of 7, 11 and 33 years are observed in the SST curve with different power throughout the time series but highest values during 80-200 AD.

5. Discussion

5.1. Preservation and relocation

During the last decade it has became clear that post-depositional aerobic organic matter (OM) degradation can severely alter the dinoflagellate cyst signal (Versteegh and Zonneveld, 2002; Zonneveld et al., 2010b). The reconstructed degradation index (kt) shows an average value of 3.3 indicating that the environmental signal from heterotrophic dinoflagellate cysts have been altered due to degradation. This implies that only the accumulation rates of cyst species that are resistant to aerobic degradation (autotrophic dinoflagellate cysts) reliably reflect upper water environmental changes (Kodrans-Nsiah et al., 2008). We therefore only use degradation resistant species to base our reconstruction on.

Another factor that can alter the fossil dinoflagellate cyst association is relocation of cysts. According to their size, dinoflagellate cysts belong to the silt fraction and traditionally it was assumed that they might be transported away long distances before they sink to the sea bottom (e.g. Dale, 1992). However, recent sediment trap studies show that the cysts sink like phytoplankton and fecal pellet aggregates with sinking rates of about 274 m/day, much faster than marine snow (Zonneveld and Brummer, 2000; Zonneveld et al., 2010a). Given the water depth of 270m on the core position, strong lateral translocation is unlikely. We therefore assume that the sedimentary dinoflagellate cyst association reflects local environmental conditions.

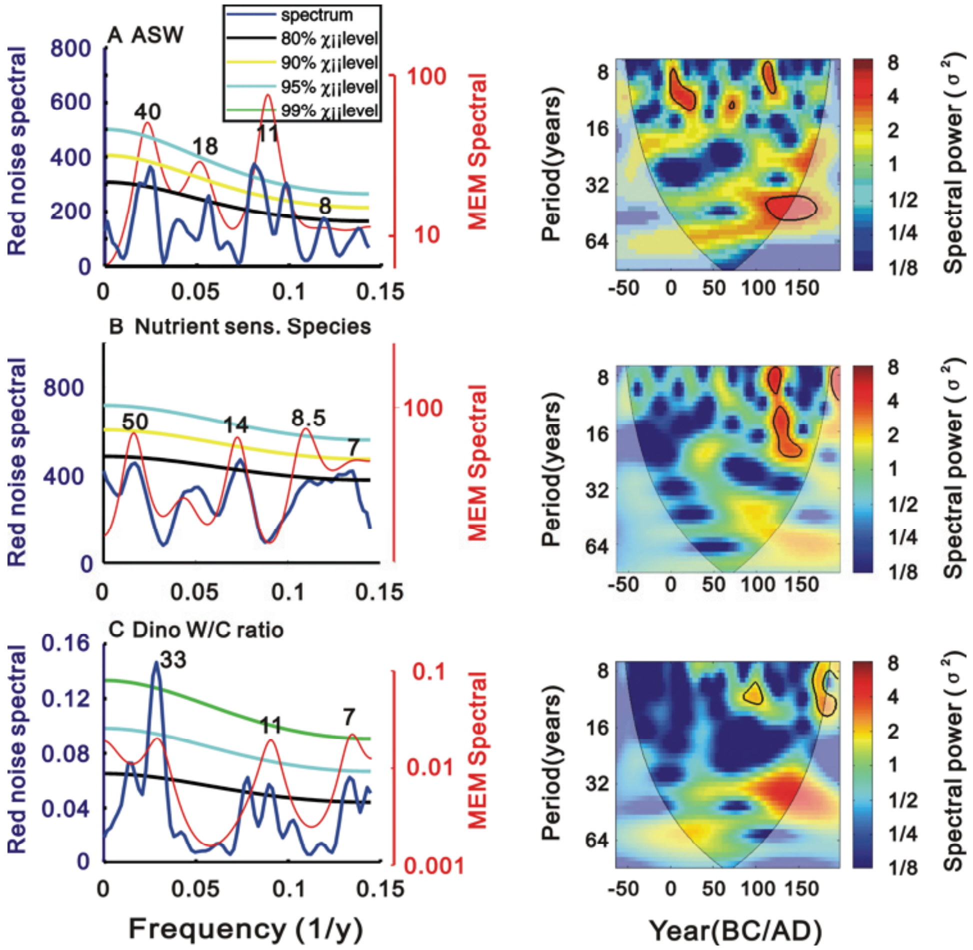


Fig 6. Spectral (Redfit and MEM) and wavelet power of Accumulation rates of A. ASW. B. NA. C. Dino-W/C ratio.

5.2. Upper water trophic conditions

Within this study, the total accumulation rates of degradation resistant species are used as upper-water nutrient indicators. This is based on sediment trap surveys that show that all dinoflagellate cyst species studied so far show increased cyst production (enhanced accumulation rates) when total upper water phytoplankton production increases (Montresor et al., 1998; Susek et al., 2005; Zonneveld et al., 2010a). That this holds as well for the research area is shown by a detailed survey of cyst production in the Po-river plume area (Zonneveld et al., 2009) as well as a broader survey in the whole Mediterranean Sea (Elshanawany et al., 2010) . Variation of upper water phytoplankton production in the Gulf of Taranto can be caused by several mechanisms. The majority of the nutrients and trace elements are brought into the research area by Adriatic Surface Waters (ASW). Changes in Po-river discharge rates and/or discharge rates of the Western Italian rivers will result in an extension of the “plume” length which in turn will result in more or less nutrient input at the core site (Boldrin et al., 2005; Degobbis et al., 1986). Consequently, an increase in accumulation rates of our nutrient sensitive species might be an indicator of enhanced river discharge. If this is the case, we would expect a contemporaneous increase in species that are characteristic for the ASW.

Concentricystes spp. is restricted to fresh water environments but can be transported into the marine realm by river waters (Sánchez-Goñi et al., 1999). The occurrence of this palynomorph in our record indicates that surface waters at the study site were influenced by river discharge. Here we also use the concentration of *Lingulodinium machaerophorum* as indicator for river discharge fluctuations. *L. mach* is often observed in high and sometimes overwhelming amounts in sediments from river plumes worldwide (e.g. Lewis, 1988; Dale and Fjellsa, 1994; Wang et al., 2004; Pospelova et al., 2005). This species is especially successful in the phytoplankton when a combination of environment factors of upper water column and the presence of high nutrient concentrations, such as is present in river plumes (Smayda and Trainer, 2010). In the eastern Mediterranean it is characteristically observed in river plumes (e.g. Giannakourou et al., 2005; Elshanawany et al., 2010). A change in cyst concentration can therefore be assumed to reflect changes in plume water influence at the sampling site. Our observation of enhanced accumulation rates of *L.mach* at times when fresh water must have reached the site confirms this assumption. This is also the case for the Po-river plume system where high concentration of this species are observed close to the Po-river delta with concentrations decreasing with increasing distance from the Delta (Rubino et al., 2000; Sangiorgi et al., 2002; Sangiorgi et al., 2005; Zonneveld et al., 2009). To date, surface waters at the sampling site are seasonally formed by ASW with minimal rates in summer when ASW has a more costal distribution and Ionian surface water flows over the core position. Maximal extension of the plume occurs in spring and late autumn. The extent of the ASW plume into the Gulf is strongly related to the amount of precipitation in the Alps and Apennines either in the form of snow in winter or rain in autumn (Zanchettin et al., 2008b). In the study region, cyst production is highest in autumn when ASW inflow is maximal, we can assume that the dinoflagellate cyst signal represents mainly autumn water conditions (Belmonte et al., 2001; Caroppo et al., 1999; Caroppo et al., 2006). The accumulation rates of Adriatic Surface Water species *L. machaerophorum* and *Concentricystes* generally match the accumulation rates of nutrient sensitive species throughout the whole period (Fig 7 B, C). It therefore can be assumed that the signal mainly reflects river discharge fluctuations. However, some discrepancies can be observed especially during BC 20 - AD 25 and 40 – 65 AD.

Other mechanisms that bring nutrients and trace elements into the research area are the deposition of volcanic ash, input of Sahara-Sahel dust or enhanced winter upwelling. It is suggested that volcanic ash releases large amounts of phosphate, iron, and other trace metals which can support microscopic biological life (Jickells et al., 2005; Langmann et al., 2010). Our study location is downwind of the Italian volcano Vesuvius. Therefore the oceanographic conditions in our study area might have been influenced by Vesuvius eruptions. However, we do not see a relationship between eruptions of the Vesuvius and changes in the NA index (Fig 7). We therefore assume that the volcanic ash input did not affect cyst association.

Several studies document that Sahara-Sahel mineral dust can be carried great distances away into Mediterranean area by wind (Dulac et al., 1996; Santese et al., 2010; Tafuro et al., 2006). By comparing monitored daily Saharan dust input in the northeastern Mediterranean Sea with observed chlorophyll *a* and nutrients data between 2000 and 2001, Eker-Develi et al. (2006) conclude that dust transport events increased phytoplankton abundance and biomass in autumn when water column stratification is at its peak. Geochemical records on the flux of Saharan dust in Eastern Mediterranean Sea suggest that the dust flux might have been higher 2000 years ago (Roman Classical Period) compared to the mean Holocene conditions (Box et al., 2008). For evaluation of the relationship between nutrients in Adriatic Sea and dust output from Sahara-Sahel region, we compared the NA index with the record of dust deposition off northwest Africa (Mulitza et al., 2010), however, no clear correlation can be observed throughout the series (Fig 7 C, D), therefore it is not able to interpret the cyst production of our “nutrient sensitive species” by the dust from Africa during the “Roman Classical Period”.

To date, the nutrient availability in the study area is also influenced by winter mixing between surface and intermediate waters promoted by cold Bora winds (Asioli et al., 2001; Orlic et al., 1994). The Bora originates from the northeastern area which has a characteristic vegetation. Consequently, fluctuations in Bora influence in the region are well traceable in pollen records (e.g. Di Rita and Magri, 2009). However, so far there is no indication of a changed pollen association suggesting enhanced influx of Northern regions in the research area and investigated time interval that can account for potential enhanced winter mixing during the last 2000 years (e.g. Combourieu-Nebout et al., 1998; Noti et al., 2009; Tinner et al., 2009). We therefore can not interpret our signal in terms of winter mixing, but can not exclude this factor to have influenced our signal. The fact that in the region cyst production does not take place in winter makes this however rather unlikely.

Sample ID	Depths (mm)	Year AD/BC	±95% confidence	Sedimentation Rate(mm/y)
Section 8 TOP	789	1195	135	0.97
Section 8 Bottom	1792	-190	120	0.72
Section 7 Bottom	2794	-1685	195	0.67

Table 1. Radiocarbon dates of core DP30PC.

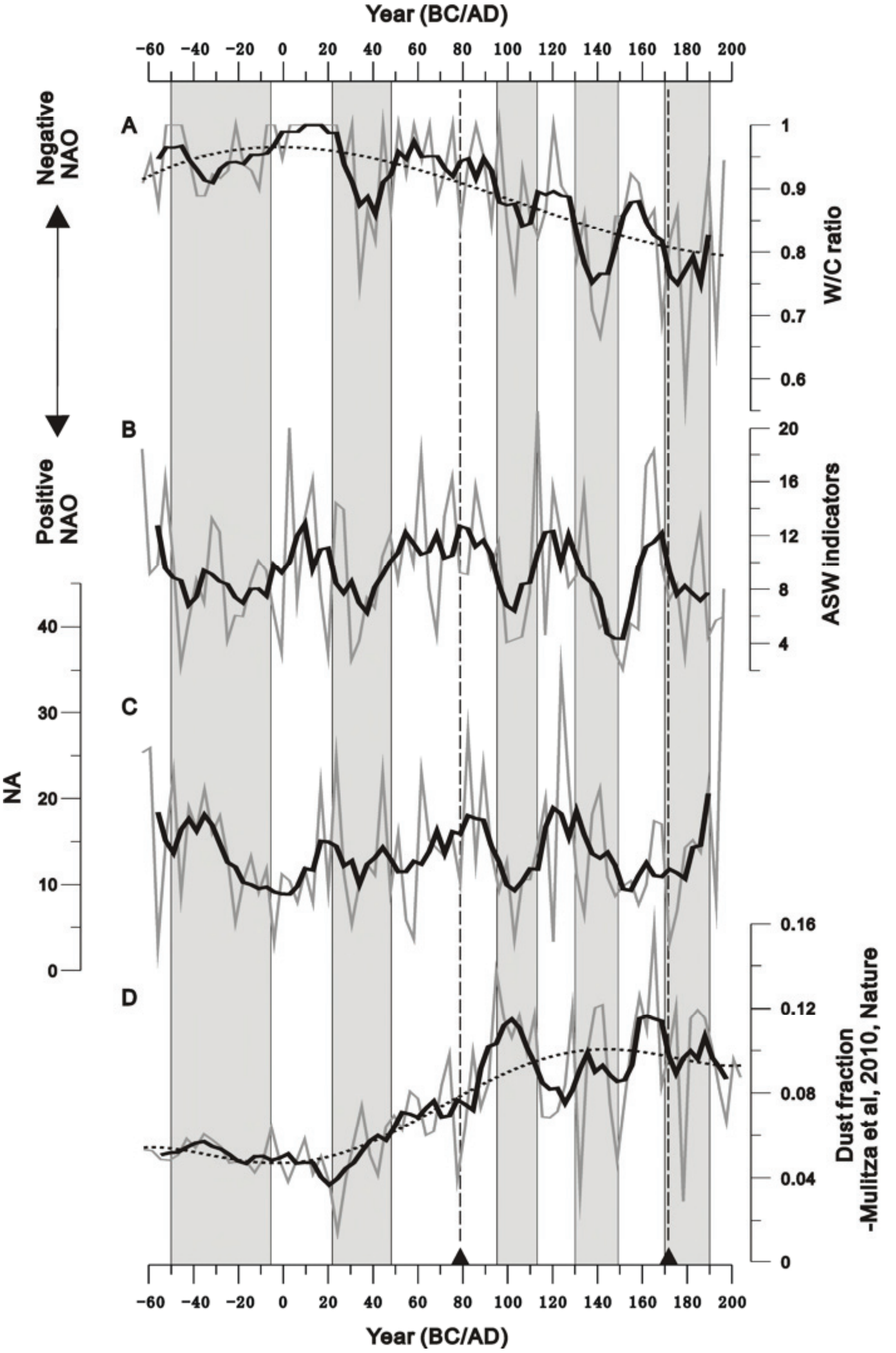


Fig. 7. Comparison of A. W/C ratio, B. ASW indicators (cyst/cm^2/y), C. NA index (cyst/cm^2/y) and D. dust fraction, thick line represents 5 point running average, dotted line indicates five order polynomial fit (A, D).

5.3. Sea surface temperature

The dinoflagellate cyst warm/cold ratio suggests that SST is relatively high and stable between 60 BC and 90 AD followed by a decreasing trend between 90 and 200 AD. When comparing the W/C ratio of 60 BC to 200 AD to the present day situation, the dinoflagellates suggest slightly higher SST than today (Fig 8). Recently Versteegh et al (2007) showed that

SST in the region is strongly related to local air temperature, we therefore assume that air temperature might have been warmer during the Roman Period as well. Similar results of ameliorative climate conditions during Roman Period have also been suggested by other studies in the Mediterranean region. For example, based on investigation of stalagmites in SE Alps, Frisia et al (2005) conclude that the "Roman Classical Period" temperatures were similar or slightly higher than those of today with the highest temperatures reached between around 400 BC and 0 AD. The relatively high temperatures reconstructed during Roman Period are consistent with a reduced glacier extent in the Alps (Giraudi, 2009; Holzhauser et al., 2005). Based on the pollen records in Georgia, a maximum phase of warming in the Holocene is reconstructed between 100 BC to 200 AD (Kvavadze and Connor, 2005). However, there are also several studies that reconstruct lower tempertures than today during the studied interval. For instance, Mangini et al. (2005) and Taricco et al. (2009) suggest a cold/dry Roman period based on $\delta^{18}O$ records in the Central Alps and the Gulf of Taranto respectively. Unfortunately, Taricco et al. (2009) did not correct the signal for potential influence of freshwater input in the Gulf. The fact that we find fossil remains of freshwater algae in the sediments indicates that varying amounts of freshwater must have been present in the upper waters which must have influenced the $\delta^{18}O$ signal. This suggests the $\delta^{18}O$ based temperature reconstruction might represent underestimated SST values. Based on Keigwin (1996), the reconstructed SST in Bermuda Rise region decreased between 200 BC and 200 AD. This suggests that temperatures might have varied largely between regions and that our result mainly reflect a local signal. Apart from this, part of the discrepancy might also be the result of different sensitivity of individual proxies to natural forcings. More detailed studies of this time interval from many different regions are therefore required to obtain an answer on the question "if and where temperatures were higher and lower than today". We observe a negative correlation between SST in Adriatic area and dust output from Northwestern Africa region where high temperature corresponds to low dust output (high moisture/precipitation) (Fig 7 A, D). This confirms the earlier suggestion that high temperature in Mediterranean area can cause wet conditions in Sahel region (e.g. Rowell, 2003). However, more studies are needed in future to testify this relationship.

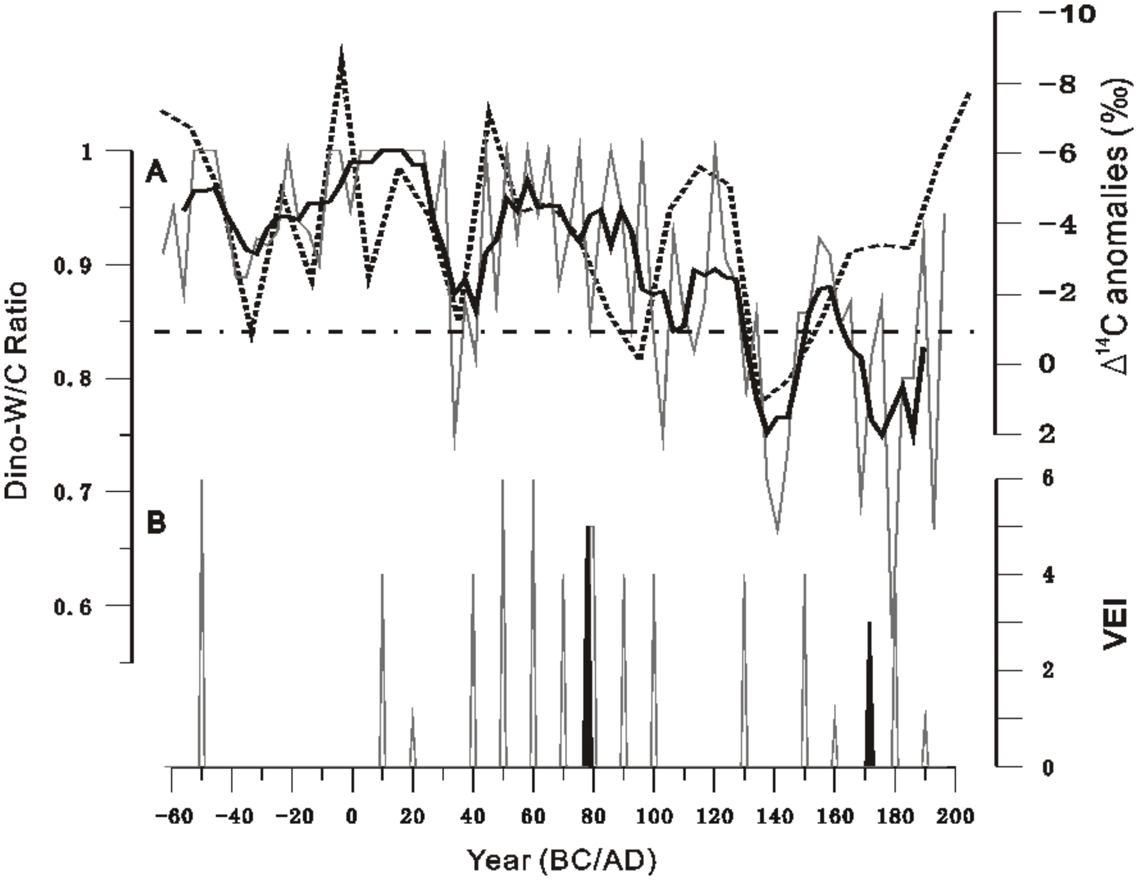


Fig 8. A. W/C ratio in the "Roman Classical Period", thick line represents 5 point running average, 20th century mean value is in horizontal dash dot line, and comparison with global $\Delta^{14}C$ anomalies (dotted line). B. Worldwide volcano eruptions with explosive intensity (VEI). Thick curve indicates Vesuvius eruption at 79 and 172 AD. Data are based on http://www.volcano.si.edu/world/largeeruptions.cfm (Siebert and Simkin, 2002).

5.4. Cyclic environmental changes in the Gulf of Taranto

The most prominent cyclic variations in our datasets have a frequency of 7-8 and 11 years in the ASW and SST records (Fig 6). Both curves show a synchronous pattern with relatively high temperatures when river output is enhanced (Fig 7 A, B). A climate mode that could influence both temperature and precipitation contemporaneously is the North Atlantic Oscillation (NAO). Our records do not give indications that other climatic modes that, for instance, strongly steer the Sirocco, have such a cyclic characters as well. We therefore assume that the NAO is the most prominent climate mode influencing the region. Our suggestion of NAO being a prominent climate mode influencing our cyclic variability is in agreement with findings from Northern Italy where variations in Po-river discharge and NAO could be linked for the last 200 years (Zanchettin et al., 2008a). During the last thousand years, a 7-8 years NAO cyclicity is often observed in the North Atlantic and Mediterranean regions and has been linked to SST anomalies between tropical Pacific and Atlantic (e.g.

Appenzeller et al., 1998; Berger, 2008; Hubeny et al., 2006; Rodwell et al., 1999).

The other significant periodicity of around 11 years can be linked to solar activity. The good matching between the W/C ratio and global ^{14}C anomalies (Stuiver et al., 1998) suggests that solar activity played an important role in Roman climate change in the Adriatic area as well (Fig 8). Similar conclusions have been provided by a number of studies which have been carried out in the same area (e.g. Brunetti et al., 2000; Castagnoli et al., 2002; Taricco et al., 2009; Versteegh et al., 2007). Although the exact mechanisms are largely unknown, it is clear that changes in solar activity can influence the earth’s climate (see e.g. de Jager et al., 2010; Erlykin et al., 2010 and references therein). In Gulf of Taranto area, the most prominent candidate for influencing local climate is the NAO rather than direct solar activity (Hurrell and VanLoon, 1997). However, several studies suggest that NAO might be strongly influenced by solar activity (Georgieva et al., 2007; Hu et al., 2003; Kodera 2003; Versteegh 2005). For the Mediterranean area, it is suggested that this relationship might be non-linear (Versteegh et al., 2007). As a result it is not easy to determine how much of the NAO variation is related to changes in solar activity. Our observations of the presence of a marked 11 years cyclicity in our signals suggest however that the effect is not neglectable.

5.5. Noncyclic forcing of local climate

Apart from cyclic variations in our data, we observe non-cyclic fluctuations in SST between 40 and 100 AD. The timing of these noncyclic variations correspond well to that of large volcano eruptions occurring worldwide. During intervals when SST is relatively stable, volcano eruptions appear to have occured unfrequently (Fig 8). It is well known that large volcanic eruptions can lower global temperature up to 0.5 ^{o}C during two to three years after the eruption (e.g. Crowley, 2000; Hegerl et al., 2003; Sear et al., 1987). Our record therefore provides strong indications that this has also been the case in the Roman Period. However, some caution is requested as the exact outbreak of the majority of the eruptions is rather unclear (Siebert and Simkin, 2002). One exception is formed by the volcano eruption of the Vesuvius (Italy) at 79 AD that destroyed the Roman city Pompeii (Cawthorne, 2003). This event corresponds to a temperature minimum in our dataset. We therefore assume that the Vesuvius eruption might be a candidate to have caused the observed cooling event at 79 AD.

5.6. Cultural changes in the Roman Empire and climate change

To date, there have been a lot of studies devoted to understand the relationship between climate change and ancient civilization. Most of these investigations suggest that cooling and drying climate might have played a significant role in the collapse of cultures as it might have caused crop failure and the enhancement of the occurrence of cultural conflicts caused by adverse environmental conditions (e.g. Binford et al., 1997; Haug et al., 2003; Hodell et al., 1995; Yancheva et al., 2007). Our study shows that the investigated part of the Roman Period might have been warmer than the 20th century, and it is interesting to note that our study interval is more or less the same as the “Pax Romana” (27 BC to 180 AD), which denotes a long period of relative peace (Gibbon and Saunders, 2001). We speculate that the booming period “Pax Romana” might be related to this relatively warm and stable situation. Interestingly, wars between Roman and neighboring cultures became more frequent along with the subsequent Roman decline after 200 AD, shortly after our records show a declining temperature trend. It would therefore be extremely interesting to dedicate more studies to this time interval to be able to pinpoint the relationship between climate and civilization.

6. Conclusion

To obtain insight into character and potential forcing of short term climatic and oceanographic variability in the southern Italian region during the “Roman Classical Period” (60 BC - 200 AD), detailed high temporal resolution climatic and environmental reconstructions based on a dinoflagelate cyst record from a well dated site in the Gulf of Taranto located at the distal end of the Po-river discharge plume have been established.

Changes in cyst accumulation rates are shown to reflect short term fluctuations in trophic state of the upper waters. Contemporaneous changes in cyst accumulation rates of the Adriatic Surface Water species *L. machaerophorum* and the fresh water algae *Concentricystes* with those of nutrient indicative species indicate that these changes can be related to river discharge of the Po-river and eastern Italian river systems which in turn reflects precipitation on the Italian continent.

SST reconstructions based on the dinoflagellate cysts composition suggest high stable temperatures between 60 BC and 90 AD followed by a decreasing trend between 90 AD and 200 AD. Consistent to earlier findings for the region, we reconstruct that local air temperature during Roman Period might have been warmer than that of the 20th century.

The contemporaneous cyclic character of the SST and river outflow records imply that the upper air circulation system of the so called North Atlantic Oscillation is the most prominent climate mode influencing the climate system in the research area during the “Roman Classical Period”. The observation of a strong 11 years cyclicity in our records together with a strong visual correlation of our temperature and river discharge records with global variation in $\Delta^{14}C$ anomalies suggest that solar activity might have been an important climate forcing factor during this time. Besides, we observe a strong visual correlation between non-cyclic variations in SST and volcanic activity suggesting that volcanisms might have been an important additional climate forcing as well.

Our reconstruction of relatively warm stable climatic conditions corresponds to the time of the “Pax Romana”. The interesting historical information that conflicts between Roman and neighboring cultures became more frequently along with the subsequent Roman decline about 100 years after we show the start of a cooling trend, suggesting that there might be a link between climate and the Roman history that is worth to be investigated in more details in future.

Acknowledgements

The study is funded by ESF (European Science Foundation) MOCCHA project (Multidisciplinary study of continental/ocean climate dynamics using high-resolution records from the eastern Mediterranean). We thank all the group members in Historical Geology and Palaeontology, Bremen University for the laboratory help and fruitful discussions. We thank Anna-Lena Grauel, Stefano M. Bernasconi and the AMS ^{14}C Dating Laboratory at ETH Zurich for preparing, measuring and calibrating the AMS ^{14}C-dates. We further would like to thank Arne Leider (MARUM Bremen), Marie-Louise Goudeau (Utrecht University) and Anna-Lena Grauel (ETH Zurich) for the core sub-sampling. Authors are grateful to Captains, Crew and Colleagues onboard RV Pelagia during the MOCCHA- Project Cruise (October-November 2008) under the coordination of Gert J. De Lange (Utrecht University). We wish to thank Prof. José Carrión (Editor), Prof. Rex Harland and an anonymous reviewer for their constructive comments on an earlier version of the manuscript.

References

Appenzeller, C., Stocker, T.F. and Anklin, M., 1998. North Atlantic oscillation dynamics recorded in Greenland ice cores. Science, 282(5388): 446-449.

Arno, V. et al., 1987. Eruptive history, in Somma-Vesuvius, edited by R. Santacroce, Progetto Finalizzato Geodin. 114, Monogr. Finali, 8, Cons. Naz. delle Ric., Rome.: pp. 53-104.

Asioli, A. et al., 2001. Sub-millennial scale climatic oscillations in the central Adriatic during the Lateglacial: palaeoceanographic implications. Quaternary Science Reviews, 20(11): 1201-1221.

Belmonte, G., Fanelli, G., Gravili, C. and Rubino, F., 2001. Composition, distribution and seasonality of zooplankton in Taranto Seas (Ionian Sea, Italy). Biologia Marina Mediterranea, 8(1): 352-362.

Berger, W.H., 2008. Solar modulation of the North Atlantic Oscillation: Assisted by the tides? Quaternary International, 188: 24-30.

Bianchi, G.G. and McCave, I.N., 1999. Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland. Nature, 397(6719): 515-517.

Binford, M.W. et al., 1997. Climate variation and the rise and fall of an Andean civilization. Quaternary Research, 47(2): 235-248.

Boldrin, A., Langone, L., Miserocchi, S., Turchetto, M. and Acri, F., 2005. Po River plume on the Adriatic continental shelf: Dispersion and sedimentation of dissolved and suspended matter during different river discharge rates. Marine Geology, 222: 135-158.

Bonino, G, Castagnoli, GC., Callegari, E. and Zhu, GM., 1993. Radiometric and Tephroanalysis Dating of

Recent Ionian Sea Cores. Nuovo Cimento Della Societa Italiana Di Fisica C-Geophysics and Space Physics, 16(2): 155-162.

Box, M.R. et al., 2008. Changes in the flux of Saharan dust to the East Mediterranean Sea since the last glacial maximum as observed through Sr-isotope geochemistry. Mineralogical Magazine, 72(1): 307-311.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbondates.

Brunetti, M., Maugeri, M. and Nanni, T., 2000. Variations of Temperature and Precipitation in Italy from 1866 to 1995. Theoretical and Applied Climatology, 65(3-4): 165-174.

Caroppo, C., Fiocca, A., Sammarco, P. and Magazzu, G., 1999. Seasonal variations of nutrients and phytoplankton in the coastal SW Adriatic Sea (1995-1997). Botanica Marina, 42(4): 389-400.

Caroppo, C., Turicchia, S. and Margheri, M.C., 2006. Phytoplankton assemblages in coastal waters of the northern Ionian Sea (eastern Mediterranean), with special reference to cyanobacteria. Journal of the Marine Biological Association of the United Kingdom, 86(5): 927-937.

Carslaw, K.S., Harrison, R.G. and Kirkby, J., 2002. Cosmic rays, clouds, and climate. Science, 298(5599): 1732-1737.

Cassou, C., Terray, L., Hurrell, J.W. and Deser, C., 2004. North Atlantic winter climate regimes: Spatial asymmetry, stationarity with time, and oceanic forcing. Journal of Climate, 17(5): 1055-1068.

Castagnoli, G.C. et al., 1990. The Carbonate Profile of 2 Recent Ionian Sea Cores - Evidence That the Sedimentation-Rate Is Constant over the Last Millennia. Geophysical Research Letters, 17(11): 1937-1940.

Castagnoli, G.C., Bonino, G., Provenzale, A., Serio, M. and Callegari, E., 1992. The Caco3 Profiles of Deep and Shallow Mediterranean-Sea Cores as Indicators of Past Solar-Terrestrial Relationships. Nuovo Cimento Della Societa Italiana Di Fisica C-Geophysics and Space Physics, 15(5): 547-563.

Castagnoli, G.C., Bonino, G., Taricco, C. and Bernasconi, S.M., 2002. Solar radiation variability in the last 1400 years recorded in the carbon isotope ratio of a Mediterranean sea core. In: C. Frohlich, J.M. Pap, L. Dame and E. Marsch (Editors), Solar Variability and Solar Physics Missions. Advances in Space Research. Pergamon-Elsevier Science Ltd, Oxford, pp. 1989-1994.

Cavaleri, L., Bertotti, L. and Tescaro, N., 1997. The modelled wind climatology of the Adriatic Sea. Theoretical and Applied Climatology, 56(3-4): 231-254.

Cawthorne, N., 2003. 100 Catastrophic Disasters. New York: Barnes & Noble Publishing, Inc.: 150.

Combourieu-Nebout, N., Paterne, M., Turon, J.L. and Siani, G., 1998. A high-resolution record of the last deglaciation in the Central Mediterranean Sea: Palaeovegetation and palaeohydrological evolution. Quaternary Science Reviews, 17(4-5): 303-317.

Crowley, T.J., 2000. Causes of climate change over the past 1000 years. Science, 289(5477): 270-277.

Dale, B., 1992. Dinoflagellate contribution to the open ocean sediment flux. In: Honjo, S., Ed., Dinoflagellate Contributions to the Deep Sea, Ocean Biocoenosis Series, 5. Woods Hole: Woods Hole Oceanographic Institution: 1-32.

Dale, B. and Fjellsa, A., 1994. Dinoflagellate cysts as paleoproductivity indicators: state of the art, potential, and limits. In: Zahn, R., Pedersen, T.F., Kaminski, M.A., Labeyrie, L. (Eds.), Carbon Cycling in the Glacial Ocean: Constraints on the Ocean's Role in Global Change. Springer, Berlin.: 521-537.

Dale, B., Dale, A.L. and Jansen, J.H.F., 2002. Dinoflagellate cysts as environmental indicators in surface sediments from the Congo deep-sea fan and adjacent regions. Palaeogeography Palaeoclimatology Palaeoecology, 185(3-4): 309-338.

De Vernal, A., Rochon, A., Turon, J.L. and Matthiessen, J., 1997. Organic-walled dinoflagellate cysts: Palynological tracers of sea-surface conditions in middle to high latitude marine environments. Geobios, 30(7): 905-920.

Degobbis, D., Gilmartin, M. and Revelante, N., 1986. An annotated nitrogen budget calculation for the Northern Adriatic Sea. Marine Chemistry, 20(2): 159-177.

de Jager, C., Duhau, S. and van Geel, B., 2010. Quantifying and specifying the solar influence on terrestrial surface temperature. Journal of Atmospheric and Solar-Terrestrial Physics, 72(13): 926-937.

deMenocal, P., Ortiz, J., Guilderson, T. and Sarnthein, M., 2000. Coherent high- and low-latitude climate variability during the Holocene warm period. Science, 288(5474): 2198-2202.

Di Rita, F. and Magri, D., 2009. Holocene drought, deforestation and evergreen vegetation development in the central Mediterranean: a 5500 year record from Lago Alimini Piccolo, Apulia, southeast Italy. Holocene, 19(2): 295-306.

Dulac, F. et al., 1996. Quantitative remote sensing of African dust transport to the Mediterranean. In: S. Guerzoni and R. Chester (Editors), Impact of Desert Dust across the Mediterranean. Environmental Science and Technology Library, pp. 25-49.

Eker-Develi, E., Kideys, A.E. and Tugrul, S., 2006. Role of Saharan dust on phytoplankton dynamics in the northeastern Mediterranean. Marine Ecology-Progress Series, 314: 61-75.

Elshanawany, R., Zonneveld, K., Ibrahim, M.I. and Kholeif, S.E.A., 2010. Distribution Patterns of Recent Organic-Walled Dinoflagellate Cysts in Relation to Environmental Parameters in the Mediterranean Sea. Palynology, 34(2): 233-260.

Erlykin, A.D., Sloan, T. and Wolfendale, A.W., 2010. Correlations of clouds, cosmic rays and solar irradiation over the Earth. Journal of Atmospheric and Solar-Terrestrial Physics, 72(2-3): 151-156.

Fensome, R.A. et al., 1993. Micropaleontology, Special Publication, 7: A Classification of Modern and Fossil Dinoflagellates. Sheridan Press, Hanover, NH: 351pp.

Ferrarese, S. et al., 2008. Response of temperature and sea surface circulation to a Sirocco wind event in the Adriatic basin: A model simulation. Journal of Marine Systems, 74(1-2): 659-671.

Fil, C. and Dubus, L., 2005. Winter climate regimes over the North Atlantic and European region in ERA40 reanalysis and DEMETER seasonal hindcasts. Tellus Series A-Dynamic Meteorology and Oceanography, 57(3): 290-307.

Frisia, S., Borsato, A., Spotl, C., Villa, I.M. and Cucchi, F., 2005. Climate variability in the SE Alps of Italy over the past 17 000 years reconstructed from a stalagmite record. Boreas, 34(4): 445-455.

Georgieva, K., Kirov, B., Tonev, P., Guineva, V. and Atanasov, D., 2007. Long-term variations in the correlation between NAO and solar activity: The importance of north-south solar activity asymmetry for atmospheric circulation. Advances in Space Research, 40(7): 1152-1166.

Ghil, M. et al., 2002. Advanced spectral methods for climatic time series. Reviews of Geophysics, 40(1): 41.

Giannakourou, A., Orlova, T.Y., Assimakopoulou, G. and Pagou, K., 2005. Dinoflagellate cysts in recent marine sediments from Thermaikos Gulf, Greece: Effects of resuspension events on vertical cyst distribution. Continental Shelf Research, 25(19-20): 2585-2596.

Gibbon, E. and Saunders, D., 2001. The History of the decline and fall of the Roman Empire. Penguin Classics; Abridged edition: 848p.

Giraudi, C., 2009. Late Holocene glacial and periglacial evolution in the upper Orco Valley, northwestern Italian Alps. Quaternary Research, 71(1): 1-8.

Grinsted, A., Moore, J.C. and Jevrejeva, S., 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlinear Processes in Geophysics, 11(5-6): 561-566.

Hainbucher, D., Rubino, A. and Klein, B., 2006. Water mass characteristics in the deep layers of the western Ionian Basin observed during May 2003. Geophysical Research Letters, 33(5).

Haug, G.H. et al., 2003. Climate and the collapse of Maya civilization. Science, 299(5613): 1731-1735.

Hegerl, G.C., Crowley, T.J., Baum, S.K., Kim, K.Y. and Hyde, W.T., 2003. Detection of volcanic, solar and greenhouse gas signals in paleo-reconstructions of Northern Hemispheric temperature. Geophysical Research Letters, 30(5): 4.

Hodell, D.A., Curtis, J.H. and Brenner, M., 1995. Possible role of climate in the collapse of classic Maya civilization. Nature, 375(6530): 391-394.

Holzhauser, H., Magny, M. and Zumbuhl, H.J., 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. Holocene, 15(6): 789-801.

Holzwarth, U., Esper, O. and Zonneveld, K., 2007. Distribution of organic-walled dinoflagellate cysts in shelf surface sediments of the Benguela upwelling system in relationship to environmental conditions. Marine Micropaleontology, 64(1-2): 91-119.

Horton, B.P. et al., 2005. Holocene sea levels and palaeoenvironments, Malay-Thai Peninsula, southeast Asia. Holocene, 15(8): 1199-1213.

Hu, F.S. et al., 2003. Cyclic variation and solar forcing of Holocene climate in the Alaskan subarctic. Science, 301(5641): 1890-1893.

Hubeny, J.B., King, J.W. and Santos, A., 2006. Subdecadal to multidecadal cycles of Late Holocene North Atlantic climate variability preserved by estuarine fossil pigments. Geology, 34(7): 569-572.

Hughen, K.A., et al., 2004. Marine04 marine radiocarbon age calibration, 0-26 cal kyr BP. Radiocarbon, 46(3): 1059-1086.

Hurrell, J.W., 1995. Decadal trends in the North-Atlantic Oscillation - Regional temperatures and precipitation. Science, 269(5224): 676-679.

Hurrell, J.W. and VanLoon, H., 1997. Decadal variations in climate associated with the north Atlantic oscillation. Climatic Change, 36(3-4): 301-326.

IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland: 104pp.

Jeromel, M., Malacic, V. and Rakovec, J., 2009. Weibull distribution of bora and sirocco winds in the northern Adriatic Sea. Geofizika, 26(1): 85-100.

Jickells, T.D. et al., 2005. Global iron connections between desert dust, ocean biogeochemistry, and climate. Science, 308(5718): 67-71.

Keigwin, L.D., 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. Science, 274(5292): 1504-1508.

Kodera, K., 2003. Solar influence on the spatial structure of the NAO during the winter 1900-1999. Geophysical Research Letters, 30(4): 4.

Kodrans-Nsiah, M., de Lange, G.J. and Zonneveld, K.A.F., 2008. A natural exposure experiment on short-term species-selective aerobic degradation of dinoflagellate cysts. Review of Palaeobotany and Palynology, 152(1-2): 32-39.

Kvavadze, E.V. and Connor, S.E., 2005. Zelkova carpinifolia (Pallas) K. Koch in Holocene sediments of Georgia - an indicator of climatic optima. Review of Palaeobotany and Palynology, 133(1-2): 69-89.

Lamb, H.H., 1977. Climate: Present, past and future. Volume 2. Climatic history and the future. Methuen, London: p 835.

Langmann, B., Zaksek, K., Hort, M. and Duggen, S., 2010. Volcanic ash as fertiliser for the surface ocean. Atmospheric Chemistry and Physics, 10(8): 3891-3899.

Lee, C.M., Orlic, M., Poulain, P.M. and Cushman-Roisin, B., 2007. Introduction to special section: Recent advances in oceanography and marine meteorology of the Adriatic Sea. Journal of Geophysical Research-Oceans, 112(C3): 3.

Lewis, J., 1988. Cysts and sediments: Gonyaulax polyedra (Lingulodinium machaerophorum) in Loch Ceran. Journal of the Marine Biology Association of the United Kingdom, 68: 701-714.

Lionello, P. and Sanna, A., 2005. Mediterranean wave climate variability and its links with NAO and Indian Monsoon. Climate Dynamics, 25(6): 611-623.

Mangini, A., Spotl, C. and Verdes, P., 2005. Reconstruction of temperature in the Central Alps during the past 2000 yr from a delta O-18 stalagmite record. Earth and Planetary Science Letters, 235(3-4): 741-751.

Marret, F., De Vernal, A., Benderra, F. and Harland, R., 2001. Late Quaternary sea-surface conditions at DSDP Hole 594 in the southwest Pacific Ocean based on dinoflagellate cyst assemblages. Journal of Quaternary Science, 16(7): 739-751.

Marret, F. and Zonneveld, K.A.F., 2003. Atlas of modern organic-walled dinoflagellate cyst distribution. Review of Palaeobotany and Palynology, 125(1-2): 1-200.

Matsuoka, K., Kawami, H., Nagai, S., Iwataki, M. and Takayama, H., 2009. Re-examination of cyst-motile relationships of Polykrikos kofoidii Chatton and Polykrikos schwartzii Butschli (Gymnodiniales, Dinophyceae). Review of Palaeobotany and Palynology, 154(1-4): 79-90.

Milligan, T.G. and Cattaneo, A., 2007. Sediment dynamics in the western Adriatic Sea: From transport to stratigraphy. Continental Shelf Research, 27(3-4): 287-295.

Montresor, M., Zingone, A. and Sarno, D., 1998. Dinoflagellate cyst production at a coastal Mediterranean site. Journal of Plankton Research, 20(12): 2291-2312.

Mudie, P.J., Rochon, A., Aksu, A.E. and Gillespie, H., 2002. Dinoflagellate cysts, freshwater algae and fungal spores as salinity indicators in Late Quaternary cores from Marmara and Black seas. Marine Geology, 190(1-2): 203-231.

Mulitza, S. et al., 2010. Increase in African dust flux at the onset of commercial agriculture in the Sahel region. Nature, 466(7303): 226-228.

Noti, R. et al., 2009. Mid- and late-Holocene vegetation and fire history at Biviere di Gela, a coastal lake in southern Sicily, Italy. Vegetation History and Archaeobotany, 18(5): 371-387.

Orlic, M., Kuzmic, M. and Pasaric, Z., 1994. Response of the Adriatic Sea to the Bora and Sirocco Forcing. Continental Shelf Research, 14(1): 91-116.

Pasaric, Z., Belusic, D. and Klaic, Z.B., 2007. Orographic influences on the Adriatic sirocco wind. Annales Geophysicae, 25(6): 1263-1267.

Pospelova, V., Chmura, G.L., Boothman, W.S. and Latimer, J.S., 2005. Spatial distribution of modern dinoflagellate cysts in polluted estuarine sediments from Buzzards Bay (Massachusetts, USA) embayments. Marine Ecology-Progress Series, 292: 23-40.

Pospelova, V., Pedersen, T.F. and de Vernal, A., 2006. Dinoflagellate cysts as indicators of climatic and oceanographic changes during the past 40 kyr in the Santa Barbara Basin, southern California. Paleoceanography, 21(2).

Rachev, N. and Purini, R., 2001. The Adriatic response to the bora forcing: A numerical study. Nuovo Cimento Della Societa Italiana Di Fisica C-Geophysics and Space Physics, 24(2): 303-311.

Radi, T. and de Vernal, A., 2008. Dinocysts as proxy of primary productivity in mid-high latitudes of the Northern Hemisphere. Marine Micropaleontology, 68(1-2): 84-114.

Reimer, P.J., et al., 2004. IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP. Radiocarbon, 46(3): 1029-1058.

Rodwell, M.J., Rowell, D.P. and Folland, C.K., 1999. Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. Nature, 398(6725): 320-323.

Rowell, D.P., 2003. The impact of Mediterranean SSTs on the Sahelian rainfall season. Journal of Climate, 16(5): 849-862.

Rubino, F., Belmonte, G., Miglietta, A.M., Geraci, S. and Boero, F., 2000. Resting stages of plankton in recent North Adriatic sediments. Marine Ecology-Pubblicazioni Della Stazione Zoologica Di Napoli I, 21(3-4): 263-284.

Sánchez-Goñi, M.F., Eynaud, F., Turon, J.L. and Shackleton, N.J., 1999. High resolution palynological record off the Iberian margin: direct land-sea correlation for the Last Interglacial complex. Earth and Planetary Science Letters, 171(1): 123-137.

Sangiorgi, F., Capotondi, L. and Brinkhuis, H., 2002. A centennial scale organic-walled dinoflagellate cyst record of the last deglaciation in the South Adriatic Sea (Central Mediterranean). Palaeogeography Palaeoclimatology Palaeoecology, 186(3-4): 199-216.

Sangiorgi, F., Fabbri, D., Comandini, M., Gabbianelli, G. and Tagliavini, E., 2005. The distribution of sterols and organic-walled dinoflagellate cysts in surface sediments of the North-western Adriatic Sea (Italy). Estuarine Coastal and Shelf Science, 64(2-3): 395-406.

Santese, M., Perrone, M.R., Zakey, A.S., De Tomasi, F. and Giorgi, F., 2010. Modeling of Saharan dust outbreaks over the Mediterranean by RegCM3: case studies. Atmospheric Chemistry and Physics, 10(1): 133-156.

Schulz, M. and Mudelsee, M., 2002. REDFIT: estimating red-noise spectra directly from unevenly spaced paleoclimatic time series. Computers & Geosciences, 28(3): 421-426.

Sear, C.B., Kelly, P.M., Jones, P.D. and Goodess, C.M., 1987. Global Surface-Temperature Responses to Major Volcanic-Eruptions. Nature, 330(6146): 365-367.

Sellschopp, J. and Alvarez, A., 2003. Dense low-salinity outflow from the Adriatic Sea under mild (2001) and strong (1999) winter conditions. Journal of Geophysical Research-Oceans, 108(C9).

Siebert, L. and Simkin, T., 2002. Volcanoes of the World: an Illustrated Catalog of Holocene Volcanoes and their Eruptions. Smithsonian Institution, Global Volcanism Program, Digital Information Series, GVP-3.

Sivall, T., 1957. Sirocco in the Levant. Geografiska Annaler, 39(2/3): 114-142.

Smayda, T.J. and Trainer, V.L., 2010. Dinoflagellate blooms in upwelling systems: Seeding, variability, and contrasts with diatom bloom behaviour. Progress in Oceanography, 85(1-2): 92-107.

Socal, G. et al., 1999. Nutrient, particulate matter and phytoplankton variability in the photic layer of the Otranto strait. Journal of Marine Systems, 20(1-4): 381-398.

Stott, P.A. et al., 2000. External control of 20th century temperature by natural and anthropogenic forcings. Science, 290(5499): 2133-2137.

Stuiver, M. et al., 1998. INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. Radiocarbon, 40(3): 1041-1083.

Susek, E., Zonneveld, K.A.F., Fischer, G., Versteegh, G.J.M. and Willems, H., 2005. Organic-walled dinoflagellate cyst production in relation to upwelling intensity and lithogenic influx in the Cape Blanc region (off north-west Africa). Phycological Research, 53(2): 97-112.

Tafuro, A.M., Barnaba, F., De Tomasi, F., Perrone, M.R. and Gobbi, G.P., 2006. Saharan dust particle properties over the central Mediterranean. Atmospheric Research, 81(1): 67-93.

Taricco, C., Ghil, M., Alessio, S. and Vivaldo, G., 2009. Two millennia of climate variability in the Central Mediterranean. Climate of the Past, 5(2): 171-181.

Tinner, W. et al., 2009. Holocene environmental and climatic changes at Gorgo Basso, a coastal lake in southern Sicily, Italy. Quaternary Science Reviews, 28(15-16): 1498-1510.

Versteegh, G.J.M., 2005. Solar forcing of climate. 2: Evidence from the past. Space Science Reviews, 120(3-4):

243-286.

Versteegh, G.J.M., de Leeuw, J.W., Taricco, C. and Romero, A., 2007. Temperature and productivity influences on U-37(K') and their possible relation to solar forcing of the Mediterranean winter. Geochemistry Geophysics Geosystems, 8.

Versteegh, G.J.M. and Zonneveld, K.A.F., 2002. Use of selective degradation to separate preservation from productivity. Geology, 30(7): 615-618.

Wang, Z.H., Matsuoka, K., Qi, Y.Z., Chen, J.F. and Lu, S.H., 2004. Dinoflagellate cyst records in recent sediments from Daya Bay, South China Sea. Phycological Research, 52(4): 396-407.

Yancheva, G. et al., 2007. Influence of the intertropical convergence zone on the East Asian monsoon. Nature, 445(7123): 74-77.

Zanchettin, D., Rubino, A., Traverso, P. and Tomasino, M., 2008a. Impact of variations in solar activity on hydrological decadal patterns in northern Italy. Journal of Geophysical Research-Atmospheres, 113(D12).

Zanchettin, D., Traverso, P. and Tomasino, M., 2008b. Po River discharges: a preliminary analysis of a 200-year time series. Climatic Change, 89(3-4): 411-433.

Zonneveld, K.A.F. and Brummer, G.J.A., 2000. (Palaeo-)ecological significance, transport and preservation of organic-walled dinoflagellate cysts in the Somali Basin, NW Arabian Sea. Deep-Sea Research Part Ii-Topical Studies in Oceanography, 47(9-11): 2229-2256.

Zonneveld, K.A.F., Bockelmann, F. and Holzwarth, U., 2007. Selective preservation of organic-walled dinoflagellate cysts as a tool to quantify past net primary production and bottom water oxygen concentrations. Marine Geology, 237(3-4): 109-126.

Zonneveld, K.A.F., Versteegh, G. and Kodrans-Nsiah, M., 2008. Preservation and organic chemistry of Late Cenozoic organic-walled dinoflagellate cysts: A review. Marine Micropaleontology, 68(1-2): 179-197.

Zonneveld, K. et al., 2008. Report and preliminary results of R/V POSEIDON Cruise P339, Piräus - Messina, 16 June - 2 July 2006. CAPPUCCINO - Calabrian and Adriatic palaeoproductivity and climatic variability in the last two millenia. Berichte, Fachbereich Geowissenschaften, Universität Bremen, No. 268: 61.

Zonneveld, K.A.F., Chen, L., Mobius, J. and Mahmoud, M.S., 2009. Environmental significance of dinoflagellate cysts from the proximal part of the Po-river discharge plume (off southern Italy, Eastern Mediterranean). Journal of Sea Research, 62(4): 189-213.

Zonneveld, K.A.F., Susek, E. and Fischer, G., 2010a. Seasonal Variability of the Organic-Walled Dinoflagellate Cyst Production in the Coastal Upwelling Region Off Cape Blanc (Mauritania): a Five-Year Survey. Journal of Phycology, 46(1): 202-215.

Zonneveld, K.A.F. et al., 2010b. Selective preservation of organic matter in marine environments; processes and impact on the sedimentary record. Biogeosciences, 7(2): 483-511.

Appendix. Original counts of organic walled dinoflagellate cysts.

Age (AD)	Start Dep(mm)	Rev.	Bri. spp	E. spp	S. ste	S. qua	S. nep	P. kof	A. cho	B. tep	T. pel	N. lab	I. acu	I. pat	I. para	I. sph	L. mac
196.3352	722.5	0	6	0	0	3	11	2	4	1	0	4	7	1	1	1	2
192.8797	725	3	8	1	0	2	3	6	2	2	0	1	0	0	0	3	4
189.4241	727.5	2	11	0	1	0	6	2	2	1	0	1	3	0	0	4	2
185.9685	730	2	13	1	0	4	8	8	1	3	1	1	3	1	1	2	9
182.5129	732.5	0	5	1	0	0	5	4	3	2	1	4	1	0	0	0	4
179.0573	735	1	5	2	0	2	1	3	0	6	0	2	2	0	0	5	2
175.6017	737.5	0	6	2	0	2	5	4	1	2	0	1	3	0	1	0	7
172.1461	740	0	14	4	0	1	5	9	4	2	3	0	1	1	1	2	13
168.6905	742.5	1	9	0	0	0	10	6	3	4	0	4	1	0	0	2	6
165.235	745	3	9	1	0	1	7	6	1	2	0	0	4	0	1	3	9
161.7794	747.5	0	7	5	0	0	6	3	2	2	2	0	3	0	0	2	8
158.3238	750	1	5	2	0	1	3	1	4	1	1	3	1	1	0	0	3
154.8682	752.5	2	5	0	0	1	4	5	2	1	2	0	1	0	0	2	3
151.4126	755	1	5	1	0	1	4	3	7	2	0	0	1	1	0	0	1
147.957	757.5	1	3	0	1	2	16	1	0	1	0	6	2	0	0	1	3
144.5014	760	1	2	1	3	3	9	0	0	6	0	0	1	1	1	2	4
141.0458	762.5	1	7	1	2	2	6	5	5	6	2	2	3	1	3	6	4
137.5903	765	5	6	4	1	4	10	3	3	7	1	0	2	3	2	0	3
134.1347	767.5	1	1	2	0	0	3	1	0	2	0	0	3	0	0	0	9
130.6791	770	2	0	0	0	0	7	0	1	4	1	0	1	1	0	1	6
127.2235	772.5	5	3	1	0	4	5	0	0	3	1	3	3	1	1	0	5
123.7679	775	4	1	2	0	2	7	0	1	2	0	3	5	0	2	5	5
120.3123	777.5	1	0	2	0	0	1	0	1	0	1	0	0	0	1	0	9
116.8567	780	2	9	1	0	1	8	3	2	2	0	3	6	1	0	3	3
113.4011	782.5	2	1	0	1	0	8	0	1	3	0	0	1	0	0	2	10
109.9456	785	3	5	2	1	0	9	3	1	2	0	2	1	0	2	1	5
106.49	787.5	3	5	1	0	9	17	7	1	1	0	1	2	3	0	3	4
103.0344	790	0	1	0	0	2	12	0	0	3	0	0	0	1	0	1	4
99.57879	792.5	1	11	3	0	0	6	4	1	2	0	1	3	1	0	1	2
96.1232	795	3	7	3	0	0	8	2	0	0	0	1	3	0	0	1	7
92.66762	797.5	4	2	0	0	2	6	0	0	2	0	1	1	0	0	0	4
89.21203	800	1	1	1	0	1	9	0	0	1	0	1	0	0	1	1	6
85.75644	802.5	3	0	2	0	0	6	2	4	0	0	0	1	1	1	2	7
82.30085	805	2	1	1	0	3	9	0	2	1	0	3	2	0	0	2	3
78.84527	807.5	3	0	0	0	0	3	4	3	2	1	0	2	1	0	1	4
75.38968	810	2	3	2	0	0	4	1	1	0	0	1	0	2	1	1	7
71.93409	812.5	0	0	1	1	0	8	0	1	1	0	0	3	0	0	3	7
68.4785	815	0	3	1	0	0	4	4	0	2	0	1	1	1	2	3	4
65.02292	817.5	1	1	1	0	2	7	0	1	0	0	0	0	1	1	0	3
61.56733	820	3	0	1	0	3	15	0	2	1	1	3	3	0	0	3	9
58.11174	822.5	0	4	0	2	1	10	0	2	0	0	1	0	0	1	0	5
54.65616	825	1	0	0	1	0	7	0	1	1	0	1	0	0	0	0	6
51.20057	827.5	1	1	1	0	4	15	0	0	0	0	2	2	1	0	1	4
47.74498	830	0	0	3	0	1	7	0	0	2	0	1	4	0	0	0	6
44.28939	832.5	2	3	2	1	4	8	6	1	0	0	1	3	0	1	3	4
40.83381	835	1	5	2	2	2	11	1	0	2	0	4	4	0	0	2	5
37.37822	837.5	0	6	1	0	2	8	6	1	2	1	1	2	2	0	1	5
33.92263	840	5	4	1	1	2	4	8	0	3	0	1	1	2	0	0	2
30.46704	842.5	0	6	0	0	2	8	6	0	0	0	1	1	0	1	0	1
27.01146	845	2	7	1	2	2	6	2	0	1	0	1	2	0	0	1	7
23.55587	847.5	1	7	1	0	3	7	1	0	0	0	2	6	0	1	1	7
20.10028	850	1	11	2	0	2	10	1	0	0	1	0	0	0	0	3	1
16.64469	852.5	2	4	3	0	2	8	2	0	0	0	1	2	0	0	2	3
13.18911	855	0	6	4	3	2	9	5	0	0	0	1	2	0	0	1	10
9.733519	857.5	0	5	2	1	2	9	6	1	0	0	1	1	0	0	2	8
6.277932	860	1	7	0	0	1	6	5	0	0	0	0	2	0	0	1	4
2.822344	862.5	2	4	0	0	3	6	4	2	0	0	1	1	1	1	0	9
-0.63324	865	1	11	1	0	0	5	5	0	1	1	3	6	0	0	1	3
-4.08883	867.5	2	4	2	0	0	5	10	1	0	0	0	0	0	0	1	9
-7.54442	870	1	13	3	0	0	9	3	0	0	0	2	2	1	0	0	5
-11	872.5	1	9	2	0	2	7	4	1	1	0	0	2	0	0	1	5
-14.4556	875	4	18	0	0	1	5	1	3	1	0	3	0	0	0	0	4
-17.9112	877.5	2	12	0	0	2	8	3	2	1	0	2	1	0	1	1	3
-21.3668	880	1	9	1	0	2	11	6	3	0	0	0	3	0	1	1	6
-24.8224	882.5	2	5	0	0	1	10	3	0	1	1	1	4	0	0	1	2
-28.2779	885	2	4	3	0	3	7	5	1	1	0	2	3	3	1	4	9
-31.7335	887.5	4	8	1	0	1	15	4	3	1	0	3	0	1	0	1	8
-35.1891	890	0	10	0	1	4	17	3	1	2	1	1	6	1	2	2	4
-38.6447	892.5	1	3	1	0	4	9	9	0	1	0	2	4	0	0	1	5
-42.1003	895	2	4	0	0	0	10	12	1	1	0	4	4	0	0	1	4
-45.5559	897.5	1	7	1	0	3	18	8	0	0	0	1	1	0	0	0	1
-49.0115	900	2	9	2	0	1	16	7	0	0	0	2	2	0	0	3	6
-52.4671	902.5	1	5	2	0	2	11	5	2	0	0	2	2	0	0	1	7
-55.9226	905	2	11	2	0	3	12	10	0	1	0	0	1	0	0	1	6
-59.3782	907.5	1	8	1	0	2	17	5	0	1	1	2	4	0	1	1	5
-62.8338	910	0	6	0	0	4	15	3	0	2	1	1	6	1	0	0	10

Continued

Age (AD)	O.cen	O.isr	S.spp	S.mir	S.ram	T.app	L.inv	Q.con	X.xan	P.zoh	others	Total	Gram/Processed(g)	Gram/Count(g)	Den.(g/cm3)	dinocyst/g	kt
196.34	63	3	31	6	4	8	1	1	1	0	0	161	1.07	0.21	0.73	751.83	3.65
192.88	81	2	34	2	1	4	1	0	0	0	0	160	1.03	0.41	0.73	388.59	3.12
189.42	67	3	33	6	4	4	2	0	0	0	1	155	0.96	0.29	0.73	538.95	3.53
185.97	81	1	41	7	2	9	1	1	0	1	0	202	1.01	0.41	0.73	497.83	2.94
182.51	57	2	48	5	2	5	2	0	0	0	0	151	1.29	0.26	0.73	585.45	3.39
179.06	76	1	41	5	6	10	0	0	0	0	0	170	0.98	0.39	0.73	434.57	3.53
175.60	73	1	30	8	2	2	1	0	0	0	0	151	0.96	0.48	0.73	315.13	3.18
172.15	42	1	36	6	3	4	0	0	0	0	0	152	1.73	1.04	0.73	146.58	2.68
168.69	60	4	34	4	4	7	3	2	0	0	0	164	1.20	0.36	0.73	454.05	3.29
165.23	52	1	32	7	3	6	1	0	0	0	1	150	0.96	0.29	0.73	518.69	3.24
161.78	73	0	31	8	3	4	0	0	0	0	0	159	0.93	0.28	0.73	568.70	2.74
158.32	62	1	46	8	4	4	1	0	0	0	0	153	1.10	0.44	0.73	349.09	3.30
154.87	69	4	40	7	2	0	1	0	0	0	1	152	0.94	0.37	0.73	406.06	3.86
151.41	67	4	44	7	5	0	0	0	0	0	1	155	1.14	0.34	0.73	454.34	3.61
147.96	84	0	21	4	6	5	3	0	0	0	0	160	0.83	0.58	0.73	276.04	3.12
144.50	90	4	37	11	3	8	2	0	2	0	0	191	1.55	0.46	0.73	411.50	3.08
141.05	92	3	45	3	3	5	5	0	0	0	0	212	0.95	0.48	0.73	445.84	3.97
137.59	105	2	42	11	5	4	2	0	0	0	1	226	0.92	0.28	0.73	817.05	3.05
134.13	107	1	40	8	3	7	0	0	0	0	0	188	1.14	0.34	0.73	551.68	3.04
130.68	90	4	45	10	10	7	1	0	0	1	0	192	0.99	0.40	0.73	485.04	3.66
127.22	87	6	29	13	10	5	1	0	0	0	0	186	1.20	0.36	0.73	516.29	3.97
123.77	72	1	46	11	10	3	1	0	0	0	0	183	0.85	0.26	0.73	713.61	4.28
120.31	91	1	29	9	6	2	0	0	0	0	0	154	1.12	0.33	0.73	459.71	3.30
116.86	70	2	46	5	2	4	0	0	0	0	0	173	1.05	0.42	0.73	410.22	3.79
113.40	67	4	32	9	9	2	1	0	0	0	0	153	0.89	0.27	0.73	570.33	3.68
109.95	65	1	36	8	4	7	2	0	0	0	0	160	1.23	0.37	0.73	433.82	2.99
106.49	61	2	33	9	3	1	0	0	1	0	0	167	0.97	0.58	0.73	287.20	3.09
103.03	88	1	28	8	7	2	0	0	0	1	0	159	1.59	0.63	0.73	250.64	2.77
99.58	89	1	41	7	2	9	2	0	0	1	0	188	1.18	0.35	0.73	532.02	2.93
96.12	83	0	32	5	3	6	1	0	0	1	0	166	0.90	0.36	0.73	461.82	2.83
92.67	94	4	39	6	5	4	2	0	0	0	0	176	1.22	0.24	0.73	722.97	3.37
89.21	91	8	21	10	2	2	0	0	0	1	0	158	1.41	0.28	0.73	561.69	4.07
85.76	85	0	40	7	7	0	0	1	0	1	0	170	0.87	0.26	0.73	650.64	3.81
82.30	78	3	29	11	2	5	0	0	0	0	0	157	1.01	0.20	0.73	776.38	3.58
78.85	78	1	27	8	7	4	1	0	0	0	0	150	0.91	0.27	0.73	551.87	3.88
75.39	69	2	35	7	5	7	0	1	0	0	1	152	0.64	0.25	0.73	598.30	3.33
71.93	74	1	43	9	5	2	1	0	0	0	0	160	0.98	0.30	0.73	541.70	3.68
68.48	81	4	41	8	3	2	1	0	1	1	0	168	1.28	0.51	0.73	327.52	4.39
65.02	101	4	28	10	5	3	2	0	1	0	0	172	1.11	0.22	0.73	777.45	3.30
61.57	121	2	58	12	13	6	0	0	1	2	0	259	1.05	0.32	0.73	821.16	3.53
58.11	70	0	38	14	3	6	0	0	1	0	0	158	1.03	0.31	0.73	512.15	1.73
54.66	90	2	51	10	4	5	1	0	0	0	0	181	1.43	0.29	0.73	631.61	2.75
51.20	65	2	32	6	7	5	3	0	0	0	0	152	0.94	0.28	0.73	540.04	3.04
47.74	89	0	40	9	3	5	0	0	0	0	0	170	1.02	0.30	0.73	557.44	3.06
44.29	61	1	36	6	6	1	4	0	0	1	4	159	1.22	0.24	0.73	651.94	3.58
40.83	61	0	36	5	3	5	2	0	0	0	0	153	1.26	0.50	0.73	304.46	3.23
37.38	91	3	43	8	4	5	1	0	0	1	0	194	1.51	0.45	0.73	429.34	3.43
33.92	79	2	23	6	3	3	1	0	1	0	0	152	0.83	0.33	0.73	459.21	3.24
30.47	73	0	37	6	7	2	1	0	0	0	0	152	1.05	0.31	0.73	483.31	2.43
27.01	78	2	43	11	10	2	3	0	1	0	0	184	1.50	0.30	0.73	613.41	2.97
23.56	69	4	32	7	4	0	0	0	0	0	0	153	1.05	0.32	0.73	484.65	3.97
20.10	104	3	30	8	2	3	0	0	0	0	0	182	1.18	0.35	0.73	515.24	2.68
16.64	78	4	35	6	6	2	3	1	0	0	0	164	1.17	0.23	0.73	700.32	3.42
13.19	75	1	43	11	4	2	3	0	0	0	0	182	0.89	0.35	0.73	512.79	2.57
9.73	78	3	38	5	8	2	1	0	0	0	0	173	1.12	0.34	0.73	514.62	3.12
6.28	74	2	36	3	6	1	2	1	0	0	0	152	0.88	0.35	0.73	430.03	3.06
2.82	71	1	38	5	1	3	1	0	0	0	1	155	1.34	0.27	0.73	579.34	3.06
-0.63	75	2	40	10	9	0	1	0	0	1	0	176	1.30	0.65	0.73	271.68	3.95
-4.09	58	4	39	4	8	1	1	0	1	0	0	150	1.71	0.86	0.73	175.43	3.26
-7.54	58	2	30	14	11	0	0	0	0	0	0	154	1.66	0.33	0.73	463.70	2.95
-11.00	75	2	35	5	4	2	0	0	0	0	0	158	1.02	0.31	0.73	514.09	2.74
-14.46	83	4	42	9	9	2	0	0	1	0	1	191	1.48	0.30	0.73	647.32	2.87
-17.91	87	2	44	11	5	3	3	0	1	0	0	194	1.26	0.38	0.73	513.12	2.91
-21.37	63	1	33	9	4	0	2	0	0	0	0	156	1.01	0.61	0.73	257.29	2.88
-24.82	69	2	30	7	13	3	0	0	0	0	0	155	1.70	0.34	0.73	454.81	3.35
-28.28	67	1	42	6	6	3	0	1	0	0	0	174	1.09	0.44	0.73	399.46	3.81
-31.73	93	4	51	8	4	8	0	0	0	2	0	220	1.28	0.39	0.73	571.38	3.12
-35.19	69	2	26	6	2	1	0	0	0	0	0	161	1.24	0.37	0.73	434.10	3.36
-38.64	82	1	40	3	14	0	1	0	0	2	0	183	1.14	0.34	0.73	537.36	3.69
-42.10	63	5	36	9	4	0	3	0	0	0	1	164	1.03	0.41	0.73	397.33	4.22
-45.56	62	3	24	12	5	0	4	0	0	0	0	151	1.06	0.32	0.73	473.99	2.46
-49.01	50	7	33	12	3	3	0	0	1	0	0	159	1.14	0.34	0.73	465.26	3.39
-52.47	66	2	37	6	7	0	0	0	0	0	0	158	1.31	0.26	0.73	602.53	3.17
-55.92	91	0	33	6	5	3	2	2	0	0	0	191	1.27	0.38	0.73	500.84	1.42
-59.38	98	5	34	9	8	3	0	0	0	2	0	208	1.62	0.32	0.73	642.58	3.49
-62.83	98	3	29	11	8	3	1	0	0	3	0	205	1.54	0.31	0.73	664.43	3.53

8. Conclusions and perspectives

8. 1 Main conclusions

The detailed high temporal resolution climatic and environmental reconstructions from Gulf of Taranto area have been established based on dinoflagelate cyst records. The past sea surface temperature, river discharge and precipitation as well as marine nutrient availbility in the Southern Adriatic area show highly sensitivity to variations of dinocyst assemblages and abundance during three special time period: (1) last 400 years, (2) Medieval Classical Period (MCP 1000-1200 AD) and (3) Roman Classical Period (RCP 60 BC-200 AD).

Dinoflagellate cyst association reflects both upper and bottom water circulation. Based on the relative abundance data from 48 surface samples in the middle and distal part of the Po river discharge plume area, four associations can be distinguished that are characteristic for the major oceanographic settings in the region. (1) River discharge association. This group species have high relative abundances in sites where bottom waters are low in oxygen and upper waters are influenced by river discharge waters that are characterized by high productivity and relative low salinity. (2) Warm water association. Species in this group have their highest relative abundances in the sites that are characterized by relative warm upper waters with intermediate chlorophyll-a concentrations. (3) Oxygenated bottom water group. Species of this group have their highest relative abundance at sites where bottom waters are well oxygenated and formed by ADW or EMDW. (4) Golfo di Taranto group consisting of *Protoperidinium* species have their highest relative abundances in the Golfo di Taranto that is characterized by enhanced primary production in winter. The variation in accumulation rates can be related to gradient changes in the trophic state of the surface waters linked to river outflow. Most species show a positive relationship between cyst production and nutrient/trace element availability in upper waters.

Accumulation rates of autotrophic dinoflagellate species *L. machaerophorum* shows the evolution of eutrophication status in the Gulf of Taranto area, results reveal that the eutrophication in the Gulf of Taranto area started at 1880 AD that are highly associated with the industrial, agricultural development and population growth in Italy. The trophic state of the upper waters are suggested to be closely linked to the variations of river discharge which in turn is strongly related to precipitation in Italy. Besides, dust from African regions might form another sources of nutrients in the study area. Reconstructed precipitation and sea surface temperature variability during these time intervals are consistent with instrumental, documentary and proxy records in the Southern Adriatic region. We speculate that anthropogenic activity might have disturbed the naturally cyclic occurred temperature and to a less extent precipitation perturbations during the last 400 years. The reconstructed sea surface temperature (SST) appears to be lower in the Medieval Period compared to those of today.

Besides, low river discharge/precipitation was registered in Adriatic area during this period that is synchronous to widespread drought events in other subtropical regions. It is suggested that the climate is influenced by NAO and ENSO related large scale ocean-atmosphere circulation shifts during the Medieval Period. However, the dinoflagellate cyst association indicates that local sea surface temperatures which are strongly linked to local air temperatures were slightly higher during the Roman Classical Period than it is today. This relatively warm stable climatic condition corresponds well to the "Pax Romana" of a long and relative peace period during the Roman Empire.

Predominant cycles of around 7-8 and 11 years are observed in all three periods that can be related to the North Atlantic Oscillation climate mode and solar activity. Apart from the cyclic climate variability, good correlation between non-cyclic temperature drops and global volcanic activity are observed, indicating that the latter forms an additional major forcing factor of the southern Italian climate. It is suggested that the highly fluctuated climate in the Gulf of Taranto region might be largely influenced by NAO and solar activity during the last 2000 years. However, the variation of NAO can also be modulated by solar activity. Therefore more studies are required to obtain more insights on how these factors might be teleconnected to have influenced the climate change in Southern Adriatic area.

8. 2 Future perspectives

The current work focuses on high resolution climatic and oceanographic reconstructions during several interesting time intervals in Southern Adriatic area, the potential natural/anthropogenic forcing factors are also discussed for our better understanding of the climate mechanisms. However, there are some aspects need to be considered and addressed adequately in future to improve this work.

(1) The age models of the thesis are based on radiocarbon ^{14}C, ^{210}Pb and ^{137}Cs measurements. It is interesting to notice that our core locations are situated downwind from South Italian volcanoes, respective volcanic ash layers are documented in both marine and lacustrine deposits. Previous studies have found numerous ash layers (clinopyroxene peaks) in the marine sediments that can corresponding to the historical volcanic eruptions for example Pompei (79 AD), Ischia (1301 AD) and Monte Nuovo (1538 AD) (e.g. Bonino et al., 1993; Castagnoli et al., 1992). Therefore it is allowed to establish a detailed tephra-based chronology in future work that can constrain the age better.

(2) The high resolution environmental and climatic changes in our study area have been carried out by several different methods for instance planktic foraminifera isotopes (Grauel and Bernasconi, 2010), alkenone thermometers (Leider et al., 2010) and inorganic geochemical analysis at more or less the same time, therefore it is of great significance to compare the results based on different approaches in the next step to have a complete view of

the paleoclimate variations in the study area.

(3) Marine (dinoflagellate cysts) and terrestrial palynomorphs (pollen/spores) have been combined together as an effective tool to establish direct land-sea correlations in different locations during past decades (e.g. Bouimetarhan et al., 2009; Turon et al., 2003; Zonneveld, 1996), investigating of pollen assemblages can establish a detailed reconstruction of vegetation in the catchment area, it therefore offers an opportunity to obtain information on human induced environmental change and terrestrial input in the marine realm, and enhance the insight in natural and anthropogenic induced climate change.

(4) Quantitative reconstructions on climatic and oceanographic parameters for instance sea surface temperature, sea surface salinity based on dinocyst assemblages have been established in different locations especially in high latitude regions (e.g. de Vernal et al., 2001; Devernal et al., 1994; Esper and Zonneveld, 2007; Marret et al., 2001). However, most of the studies on climate change by dinocyst records in the Mediterranean area are currently qualitative and empirical, there is no interpretations carried out by quantitative ways such as modern analogue technique in our study area probably due to limited and relatively small spaced sample locations, therefore the dinocyst based quantitative analysis forms an important supplement for the high quality reconstructions on paleoclimatology and paleoceanography.

References

Bonino, G., Castagnoli, G.C., Callegari, E. and Zhu, G.M., 1993. Radiometric and Tephroanalysis Dating of Recent Ionian Sea Cores. Nuovo Cimento Della Societa Italiana Di Fisica C-Geophysics and Space Physics, 16(2): 155-162.

Bouimetarhan, I. et al., 2009. Palynological evidence for climatic and oceanic variability off NW Africa during the late Holocene. Quaternary Research, 72(2): 188-197.

Castagnoli, G.C., Bonino, G., Provenzale, A., Serio, M. and Callegari, E., 1992. The Caco3 Profiles of Deep and Shallow Mediterranean-Sea Cores as Indicators of Past Solar-Terrestrial Relationships. Nuovo Cimento Della Societa Italiana Di Fisica C-Geophysics and Space Physics, 15(5): 547-563.

de Vernal, A. et al., 2001. Dinoflagellate cyst assemblages as tracers of sea-surface conditions in the northern North Atlantic, Arctic and sub-Arctic seas: the new 'n=677' data base and its application for quantitative palaeoceanographic reconstruction. Journal of Quaternary Science, 16(7): 681-698.

Devernal, A., Turon, J.L. and Guiot, J., 1994. Dinoflagellate Cyst Distribution in High-Latitude Marine Environments and Quantitative Reconstruction of Sea-Surface Salinity, Temperature, and Seasonality. Canadian Journal of Earth Sciences, 31(1): 48-62.

Esper, O. and Zonneveld, K.A.F., 2007. The potential of organic-walled dinoflagellate cysts for the reconstruction of past sea-surface conditions in the Southern Ocean. Marine Micropaleontology, 65(3-4):

185-212.

Grauel, A.L. and Bernasconi, S.M., 2010. Core-top calibration of delta(18)O and delta(13)C of G. ruber (white) and U. mediterranea along the southern Adriatic coast of Italy. Marine Micropaleontology, 77(3-4): 175-186.

Leider, A., Hinrichs, K.-U., Mollenhauer, G. and Versteegh, G.J.M., 2010. Core-top calibration of the lipid-based U(37)(K)' and TEX(86) temperature proxies on the southern Italian shelf (SW Adriatic Sea, Gulf of Taranto). Earth and Planetary Science Letters, 300(1-2): 112-124.

Marret, F., De Vernal, A., Benderra, F. and Harland, R., 2001. Late Quaternary sea-surface conditions at DSDP Hole 594 in the southwest Pacific Ocean based on dinoflagellate cyst assemblages. Journal of Quaternary Science, 16(7): 739-751.

Turon, J.L., Lezine, A.M. and Denefle, M., 2003. Land-sea correlations for the last glaciation inferred from a pollen and dinocyst record from the Portuguese margin. Quaternary Research, 59(1): 88-96.

Zonneveld, K.A.F., 1996. Palaeoclimatic reconstruction of the last deglaciation (18-8 ka BP) in the Adriatic Sea region; A land-sea correlation based on palynological evidence. Palaeogeography Palaeoclimatology Palaeoecology, 122(1-4): 89-106.

Appendix 1. The use of dinoflagellate cysts to separate human and natural variability in the trophic state of the Po River discharge plume during the last two centuries

Karin A.F. Zonneveld[1], Liang Chen[1], Rehab Elshanawany[1,3], Helmut W. Fischer[2], Mirja Hoins[1], Mohammed I. Ibrahim[3], Daniela Pittauerova[2], Gerard J.M. Versteegh[1]

1. MARUM/Fachbereich 5-Geowissenschaften, University of Bremen, Leobener Straße, D-28334 Bremen, Germany
2. Institute of Environmental Physics, University of Bremen, Otto-Hahn-Allee 1, D-28359 Bremen, Germany
3. Faculty of Science, Alexandria University, Baghdad St. Moharam Bay 21511, Alexandria, Egypt

***Marine Pollution Bulletin*, 2011, in press**

Abstract

To obtain insight in natural and/or human induced changes in the trophic state of the distal part of the Po River discharge plume during the last two centuries, high temporal resolution dinoflagellate cyst records have been established at three sites. Cyst production rates appear to reflect natural variability in river discharge whereas the cyst associations reflect the trophic state of the upper waters, which can be related to agricultural developments. Increased abundances of *Lingulodinium machaerophorum* and *Stelladinium stellatum* as early as 1890 and 1920, correspond to the start of the industrial revolution in Italy and the first chemical production and dispersion of ammonia throughout Europe. After 1955 increased abundances of these species as well as of *Polykrikos schwartzii, Brigantedinium* spp. and *Pentapharsodinium dalei* correspond to an agriculturally induced change to hypertrophic conditions. A slight improvement of the water quality can be observed from 1987 onward.

Keywords**:** dinoflagellate cyst; eutrophication; high temporal resolution; Po River; Mediterranean Sea.

1. Introduction

Today eutrophication is an increasing environmental and economic problem in numerous coastal areas. During the last century human activity has accelerated nutrient and trace element enrichment of coastal areas through increasing inputs of mostly nitrogen and phosphorus, stimulating production of phytoplankton (e.g. Rabalais et al., 2009). Although at an early stage, eutrophication can have a positive impact on the planktic and benthic communities, successive increases in nutrients and/or trace-element loads can lead to undesirable changes in the ecosystem such as a decrease in species diversity, over-production and algal blooms that, in turn, can result in oxygen depletion (e.g. Maskell et al., 2010; Zhang et al., 2010). Over the last decades the awareness increased of the problems caused by eutrophication and its social-economic effects and many national and local governments started waste-management programmes to improve the coastal water quality (see references in e.g. IPCC, 2007). One of the main questions of these governments is the extent to which their activities have had effect on the coastal ecosystems. Before this question can be answered detailed information must be available about how the ecosystem reacted on natural and anthropogenic changes prior to the governmental measurements. A proven method is to monitor the biological, chemical and physical characteristics of an ecosystem. However, with some valuable exceptions, monitoring programs start after the 1980s whereas anthropogenic changes often affected the ecosystems long before this date. It is therefore required to study the ecosystem variability prior to the strong anthropogenic influence on the system (e.g. pre-industrial times) and compare this to the later developments (post industrial times). In this paper we use a micropalaeontological approach to obtain insight in the state of the southern Italian coastal ecosystem over the last 2 centuries with emphasis on the last 60-80 years. This area is one of the coastal regions in Europe that suffers most from eutrophication. This region is influenced by northern and eastern Italian river-discharge waters, notably of the Po River. The Po River is the largest Italian river which receives input from the Alps and the Apennines. Due to the anti-clockwise surface water circulation in the Adriatic Sea, Po discharge water is pressed along the Italian coast and moves southward where it is spiced by discharge waters of local eastern Italian rivers that drain the Apennines. The river-waters are used as a source of water as well as being receiver of waste when passing through areas that are intensively industrialised or used by agriculture. Increasing anthropogenic activity in the drainage areas since the beginning of the last century, is assumed to have resulted in a steadily increasing nutrient and trace element load of the river waters that, in turn, could be related to e.g. the more frequent (toxic) plankton blooms and anoxia in the North Adriatic Sea (e.g. Degobbis et al., 2000; Giordani and Angiolini, 1983; Justič et al., 1987; Justič, 1987; Marchetti et al., 1989). The Italian government reacted on this trend by regulating the use of phosphates in the late seventies of the last century and since about this time a the surface water chlorophyll-*a* concentrations are reducing in the northern Adriatic Sea (de Wit; Bendoricchio, 2001; Mozetic et al., 2010; Solidoro et al., 2009). However, to date it is not clear if these changes are the result of the cultural oligotrophication as an effect of governmental coastal-water protection measurements and population dynamics or the result of climate factors such as climatically induced changes in river outflow (see discussion in Mozetic et al., 2010).

To obtain insight into the trophic state of the ecosystem previous and during industrial time we studied the sedimentary record of dinoflagellate cysts. Marine cyst forming dinoflagellates react very sensitively to changes in the trophic state of the upper waters and their fossilised sedimentary cyst associations are useful eutrophication indicators in marine settings, especially in estuarine and fjord systems (e.g. Dale and Fjellså, 1994; Dale, 2009; Krepakevich and Pospelova, 2010; Pospelova et al., 2002; Pospelova and Kim, 2010; Radi et al., 2007; Saetre et al., 1997; Shin et al., 2010). By correlating cyst accumulation rates and cyst associations with river discharge rates, changes in the nutrient load of the river outflow waters, the demographic history in the catchment areas and the use of artificial fertilisers, we obtain insight into the natural and anthropogenic impacts on the system. We show that cyst accumulation rates of species that resist aerobic degradation as well as species that are characteristically present in the modern river plume can be related to the quantity of the Po river discharge. Changes in the cyst association and the accumulation rates of individual species can be related to demographic changes and human activity in the river catchment. We suggest that accumulation rates of these species can be used to reconstruct the quality of discharge-water rather than the quantity. We discuss the value of these findings for future eutrophication studies.

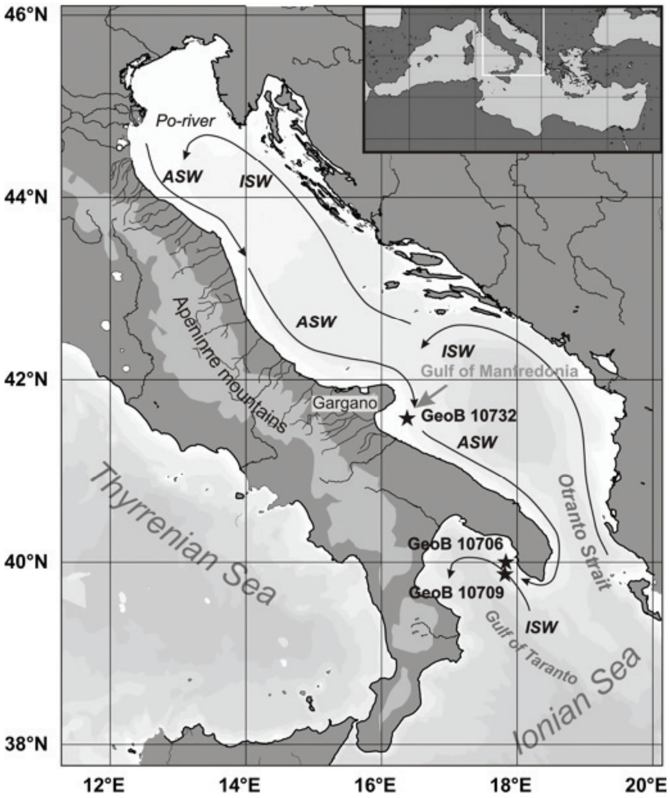


Fig 1. Map of Italy the Adriatic Sea showing major river systems, marine surface water currents and core positions. ISW = Ionian surface Water, ASW = Adriatic Surface Water.

2. Oceanographic setting

The Adriatic Sea and the Golfo di Taranto are two side-basins of the Eastern Mediterranean Sea (Fig. 1). The Adriatic Sea is land-locked by Italy in the west and Balkan countries in the east whereas the Golfo di Taranto is land-locked at three sides by the southern part of Italy. The current systems of both basins are strongly related to each other and to that of the eastern Mediterranean Sea. Surface waters at the eastern side of the Golfo di Taranto and the western part of the Adriatic Sea are formed by the same water mass that finds its origin in the north-western North Adriatic Sea. Here large amounts of water from the Po River and northern Italian rivers enter the marine system (e.g. Boldrin et al., 2005; Syvitski and Kettner, 2007). The Po River is the largest Italian river draining the southern part of the Alps and northern part of the Apennines. It enters the north-western North Adriatic Sea through a deltaic system. The major part of its catchment area, the so-called Po-valley, is intensely used for agriculture and industry and its large cities of Milano, Venezia and Torino inhabit the majority of the Italian population.

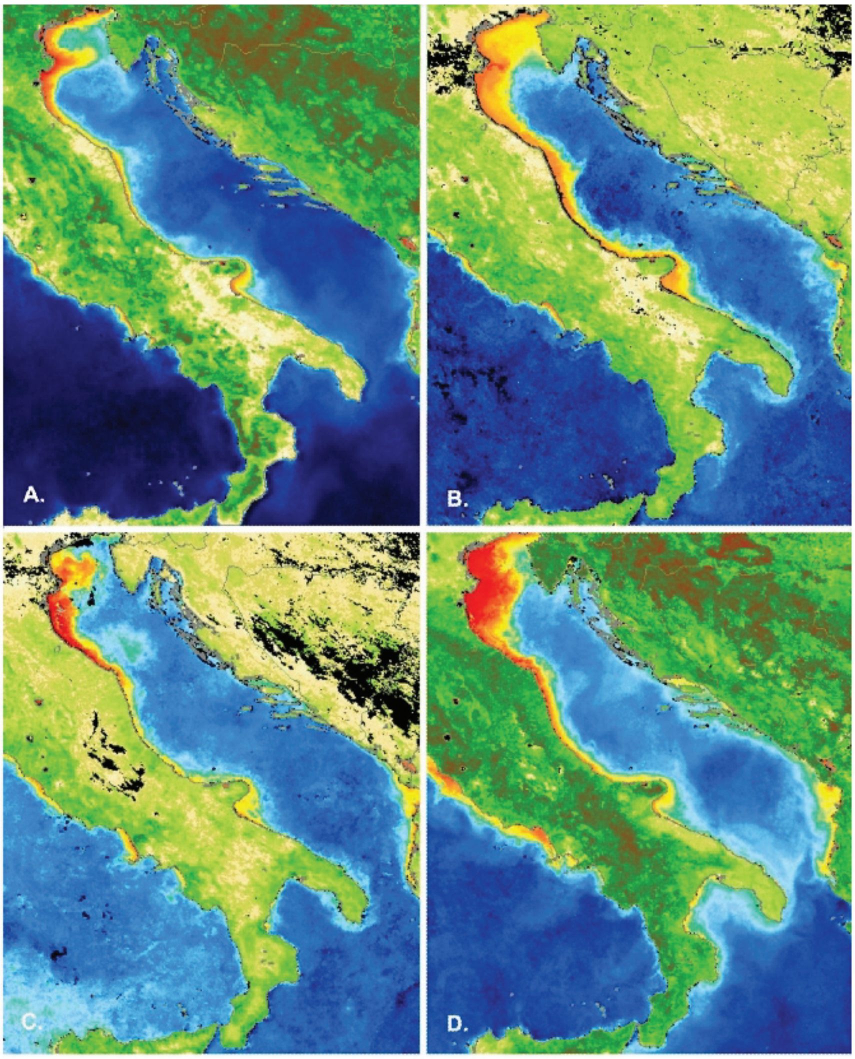


Fig 2. Compiled satellite image of upper ocean chlorophyll-a concentrations in (a) summer, (b) autumn, (c) winter, (d) spring (gcmd.nasa.gov).

As a result of the anti-clockwise surface water circulation induced by Coriolis forcing, the fresh, nutrient and sediment rich discharge waters are pressed against the western coastal margin of the Adriatic Sea (e.g. Lee et al., 2007; Orlic, 2009 and references therein). The discharge waters that enter the marine realm have a clear sedimentological, physical and biological character such as high chlorophyll-*a* concentrations (Fig. 2). A band of these waters can be traced along the whole western margin of the Adriatic Sea, the Strait of Otranto and around the Calabrian Peninsula into the Golfo di Taranto. Classically these waters are classified as Adriatic Surface Water (ASW). Along their way southward, the plume waters are additionally spiced by sediment loaded, fresh, nutrient and element rich waters from local eastern Italian rivers draining the eastern side of the Apennines. Although the loads of nutrients and sediments of these local rivers are considerably lower with respect to the Po River discharge, their sedimentary signal can be traced clearly in the most coast-near waters whereas the Po discharge signal can be traced in the more offshore parts of the coastal discharge plume (e.g. Milligan and Cattaneo, 2007; Tomadin, 2000). These differential sedimentary signals can be traced as far as the Gargano Peninsula whereas further south the plume-waters are characterised by a mixed signal. South of the Gargano peninsula the Golfo di Manfredonia is located. This small basin is relatively shallow but its depth increases significantly in seaward direction beyond the 30m isobath. Surface waters are formed by the AWS that show a cyclonic circulation inside the Gulf and a southwestward direction at its outer rim. The surface waters of the central and eastern side of the Adriatic Sea are formed by the oligotrophic Ionian Sea surface waters (ISW) that enter the basin through the Strait of Otranto (Fig. 1). They are pressed against the most offshore side of the river plume waters slowly mixing with the ASW on their ways southwestward.

Within the Golfo di Taranto, the circulation is cyclonic with both ASW and ISW entering along the eastern part the basin. Within this gulf both water masses mix with ASW being characteristically traceable as far north as the city of Taranto (Boldrin et al., 2005; Lee et al., 2007). The surface circulation and the extension of the ASW plume are strongly dependent on the seasonal cycles, with ISW invading the basin in late winter and early spring. In late spring, summer and autumn, ASW enters the basin from the south-east along the Calabrian margin. Maximal influx of ASW can be observed in late spring and autumn related to enhanced Po River discharge due to the melting of snow and ice in the Alps and Apennines in spring and enhanced precipitation in autumn. During winter enhanced mixing between the oligotrophic ISW and more nutrient enriched Levantine Intermediate Waters (LIW) results in locally enhanced phytoplankton production in the upper waters. Nutrients and trace elements in the research area not only introduced by the ASW and by winter mixing, but also by the deposition of volcanic ash and dust from the Sahara-Sahel (Eker-Develi et al., 2006; Langmann et al., 2010; Stuut et al., 2009). Aeolian dust is brought into the system by a northward wind called the Sirocco. The Sirocco tends to occur year round without a favoured season although strong gale-forced Siroccos are most common during spring (Pasaric et al., 2007).

Intermediate waters of both the Adriatic Sea and the Golf of Taranto that reside between 150 and 600 m water depth, are formed by the LIW originating from the Levantine basin (Greece). In winter these waters mix with the ISW in the Adriatic Sea to form Adriatic Deep Water that in turn forms a considerable part of the dense Eastern Mediterranean Deep Water (EMDW) that is represented by the deep water masses of the Golf of Taranto below about 600m water depth (e.g. Hainbucher et al., 2006; Sellschopp and Alvarez, 2003).

3. Material and methods

3.1. Core Material

The cores GeoB 10709-5 (39° 45.39‘N - 17°53.57‘E water depth 172.3 m), GeoB 10706-3 (39° 49.50`N - 17° 50.00`E water depth 218m) and GeoB 10732-3 (41°30.00‘N - 16°24.46‘E water depth 50.7 m) have been collected by a multicoring device during the research cruise CAPPUCCINO with the R.V. POSEIDON in June 2006 at 218.3 m water depth (Zonneveld et al., 2008; Fig. 1). Immediately after recovery, the cores have been frozen and stored at -20°C until further treatment. Previous to sampling the still frozen cores were stored at -4°C for one day enabling high precision cutting of the core in slices of 2.5 mm

(Cores GeoB 10709, 10732) and 3 mm (Core 10706). The cutting was carried out in a cold storage room at 4°C. Care was taken that the core temperature remained under -2°C to avoid damage of the core structure. Sediments of all cores consist of homogenous greenish/grey soft mud. Oxygen penetration depth is registered to be 5 cm, 7 cm and 2.5 cm for cores GeoB 10732, GeoB 10709 and GeoB 10706 respectively. Slight bioturbation is registered in all cores (Zonneveld et al., 2008).

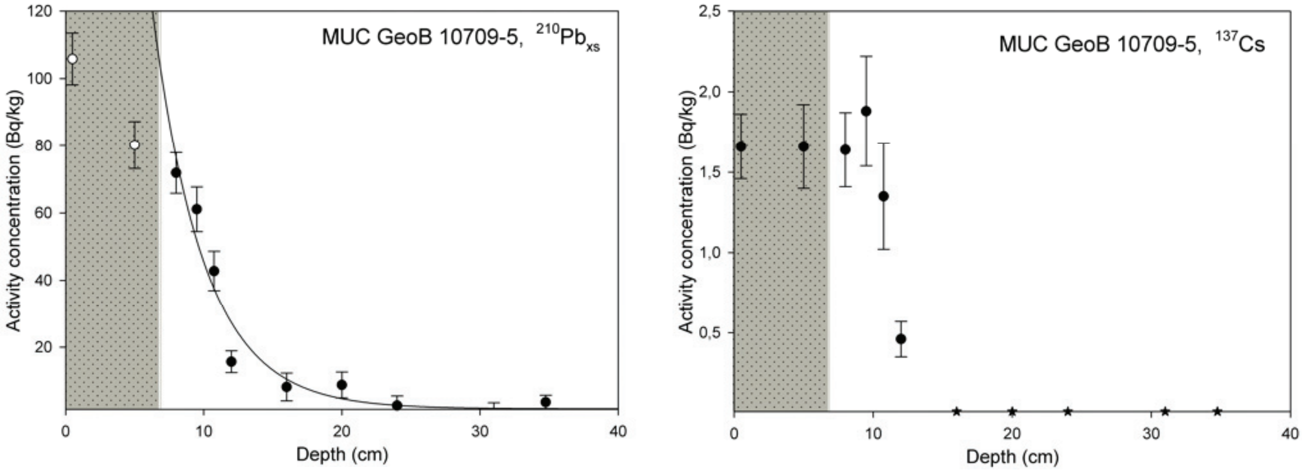


Fig 3. Depth profiles of total excess ^{210}Pb (^{210}Pb$_{xs}$) and ^{137}Cs for multicore GeoB 10709-5. The assumed mixed layer at the top 7 cm of the record is shaded. Error bars mark 1 standard deviation of the activity including counting statistics and detector calibration uncertainty. Analyses marked with stars are assigned to measurements with values below decision threshold.

3.2. Core chronology

The age model of core GeoB 10709-5 is based on ^{210}Pb/^{137}Cs-dating by gamma spectroscopy at the Institute of Environmental Physics, University of Bremen (Fig. 3). Wet samples were sealed into plastic cylindrical dishes with a diameter of 7 cm using Rn tight foil. Before measurement they were left sealed for a minimum of 3 weeks so that the radioactive equilibrium between ^{226}Ra and ^{222}Rn (and its daughters) had been established. A coaxial HPGe detector Canberra Industries (50% rel. efficiency) housed in a 10 cm Pb shielding with Cu and plastic lining operated under Genie 2000 software was used for gamma spectroscopy. Measurement live-times were 2 days or more. The full energy peak efficiencies have been calculated using LabSOCS© (Laboratory SOurceless Calibration System), Genie 2000 software calibration tool, based on defined sample to detector geometry and density. For determination of excess-^{210}Pb activity (^{210}Pb$_{xs}$) ^{210}Pb-supported activity was subtracted from the ^{210}Pb-total signal, measured via 46.5 keV line. Supported ^{210}Pb was determined via the 351.9 keV line of ^{214}Pb. Additionally, the artificial isotope ^{137}Cs was analysed. ^{137}Cs values above the limit of detection were found in the uppermost 4 slices (down to depth of 12 cm). ^{210}Pb$_{xs}$ decreases monotonously in the profile with maximum value of 106 Bq/kg in the depth of 0.5cm. A sedimentation rate of 1.17 ± 0.266 mm/y was estimated using CIC model

(Appleby and Oldfield, 1978) on the $^{210}Pb_{xs}$ data excluding the uppermost 2 points (assuming a bioturbation depth of 7 cm).

The age model of core GeoB 10932-3 is obtained by calculating the mean sedimentation rates of four ^{210}Pb-dated sites close to the sampling position (Table 1). Since the sedimentation rate variations at these sites are relatively small, a constant flux-constant sedimentation model (CF-CS) according to Robbins et al. (1978) was applied. Sedimentation rate is calculated to be 4.48 mm/y with a standard deviation of 0.0475 mm/y from the mean. The base of the core is estimated to represent the year 1928 AD.

The age model of Core GeoB 10706-3 is based on a tuning of the dinoflagellate cyst record to core GeoB 10709-5. It is assumed that sedimentation rates were constant throughout the sampled interval and that the variation in accumulation rates of the degradation resistant species. *Pentapharsodinium dalei* occurs synchronous in both cores. Based on these assumptions a sedimentation rate of 2.81 mm/y is assumed. The base of the core is estimated to represent the year 1921 AD.

3.3. Palynological processing and geochemical sediment analysis

Palynological preparation has been carried out according to the method described by Zonneveld et al. (2009). Sediment samples were dried at 60°C, weighed and treated with 10% HCl and 40% HF in subsequent steps. Decantation was carried out after each step. Samples were sieved over a 20 µm sieve and the residue was centrifuged (8 min; 3000 rpm) and concentrated to 0.5 ml with a micropipette, subsamples of a known volume (50-100 µl) of homogenised residue were placed on a microscope slide, embedded in glycerine jelly and sealed with paraffin wax. Whole slides were counted for dinoflagellate cysts using a light microscope with 400x magnification. When slides contained less than 150 specimens additional slides were counted. Dinoflagellate cyst accumulation rates were calculated by multiplication of the amount of cysts per cm^3 by the sedimentation rate (cm/y).

The concentration of total organic carbon (TOC, dry weight%) has been determined by a Leco CS-200 elemental analyser (error 1%). Prior to measurement 0.5 ml wet sample was dried for 24 hours. Successively the material was treated with 12.5% HCL to remove carbonates. The standard used for calibration contains 0.176% Carbon.

The taxonomical concept is consistent to that cited in Rochon et al. (2009) and Radi and de Vernal (2008). When possible, cyst names are used rather than motile names. Distinction between cysts of *Gymnodinium catenatum* and those of other *Gymnodinium* species is based on their size and of the morphological characteristics of the sulcal area (Bolch et al., 1999). Only brown, microreticulate cysts with a size > 38 mm containing more than 4 rows of reticulae in the sulcal area have been categorised as *Gymnodinium catenatum* cysts. The taxonomy of *Polykrikos schwartzii* and *Polykrikos kofoidii* is based on Matsuoka et al. (2009). Since both species show comparable distribution patterns in our record their occurrences have been grouped in the graphs but not in the count data (see appendix).

3.4. Paleoenvironmental indicators

Information about potential post-depositional aerobic degradation of palynomorphs is estimated using the degradation index "kt" (Versteegh and Zonneveld, 2002) according to the formula: $kt = \ln (X_i/X_f)$, with $X_i = 68 \times R_f$

with k= component specific degradation rate, t= time, X_f = observed cyst concentration of degradation sensitive species (cysts/cm^2/y), X_i = initial cyst concentration of sensitive cyst species (cysts/cm^2/y), R_f = observed cyst concentration of degradation resistant species (cysts/cm^2/y). Resistant and sensitive species are determined according to the division given in (Zonneveld et al., 2008). R_f = *Ataxodinium choanum, Bitectatodinium tepikiense, Impagidinium aculeatum, Impagidinium paradoxum, Impagidinium patulum, Impagidinium plicatum, Impagidinium sphaericum, Impagidinium* spp., *Impagidinium strialatum, Nematosphaeropsis labyrinthus, Operculodinium israelianum,* cysts of *Pentapharsodinium dalei* and *Polysphaeridium zoharyi.*

X_i and X_f = *Brigantedinium* spp., *Echinidinium granulatum, Echinidinium transparantum, Echinidinium* spp., *Echinidinium zonneveldii,* cysts of *Gymnodinium catenatum, Islandinium minutum, Leipokatium invisitatum Lejeunecysta oliva, Lejeunecysta sabrina,* cysts of *Polykrikos kofoidii,* cysts of *Polykrikos schwartzii,* cyst of *Protoperidinium americanum*, *Quincuecuspis concreta*, *Selenopemphix nephroides, Selenopemphix quanta*, *Stelladinium stellatum, Votadinium calvum* and *Xandarodinium xanthum.*

Qualitative information about variations in sea surface temperature is obtained using the following ratio:

$W/C = W_n / (W_n + C_n)$

where n = number of specimens counted, W = warm water species, C = cold water species. W = *Impagidinium aculeatum, Impagidinium paradoxum, Impagidinium patulum, Operculodinium israelianum, Polysphaeridium zoharyi, Spiniferites mirabilis*. C = *Bitectatodinium tepikiense* and *Spiniferites elongatus.*

Species selection is based on the global geographic distribution of organic walled dinoflagellate cyst (e.g. Marret and Zonneveld, 2003)

Information about the trophic state of the upper waters is obtained by:

a. Cyst accumulation rates of degradation resistant species:

R_f ar (cysts/cm^2/y) = SR x DBD x R_f/g SR= sedimentation rate (cm/y), DBD=dry bulk density (g/cm^3), R_f/g = cysts of degradation resistant species as given above/gram dry weight.

b. Accumulation rates and relative abundances of species that currently are characteristically present in areas influenced by ASW (Sangiorgi et al., 2005; Zonneveld et al., 2009): *Lejeunecysta sabrina, Lingulodinium machaerophorum, Polykrikos schwartzii, Polykrikos kofoidii, Selenopemphix quanta* and *Stelladinium stellatum.*

c. Accumulation rates and relative abundances of heterotrophic cyst species.

d. The total amount of carbon in the sediments from cores GeoB 10706 and GeoB 10732.

Information about the total Po River discharge in the months August, September and October has been obtained from daily measurements from 1918 – 1979 at a station near Pontelagoscuro, which is situated just in front of the apex of the Po River delta about 90 km from the shore (http://daac.ornl.gov/RIVDIS/rivdis.shtml). For the time interval prior to 1918 only information about the maximum monthly outflow (and not total outflow) of the Po River of the months August, September and October is available for the last 200 years (Zanchettin et al. 2008). Information about the local air-temperature in the region is obtained by calculating the mean monthly temperatures of the cities Foggia, Taranto, Crotone, Lecce,

Brindisi and Leuca using the „climate explorer“ service of the Royal Dutch Meteorological Survey (Koninklijk Nederlands Meteorologisch Instituut (KNMI) http://climexp.knmi.nl/getstations.cgi).
Data of fertiliser use of Italy between 1961 and 2006 has been obtained from the online dataset “NationMaster” of agriculture statistics (http://www.nationmaster.com/graph/agr_fer_use-agriculture-fertiliser-use). Information about the demographic history of northern and eastern Italy since1800 has been obtained from the ”Istituto Nazionale di Statistica and from the ”Populstat“ project (http://www.istat.it/, http://www.populstat.info/Europe/italyc.htm).

4. Results

In the core sediments 45 differential dinoflagellate cyst species have been observed (see additional information). Species diversity is similar and constant through time in al cores. The degradation index kt is rather constant through time for all cores as well. Lowest kt values of around 1.8 are observed in the Gulf of Manfredonia (GeoB 10732) whereas kt values in the Gulf of Taranto are somewhat higher and vary around 3.1 (Fig. 4). In core GeoB 10709 (Gulf of Taranto) an exponential increase in accumulation rates of heterotrophic cyst species can be observed towards the core top. Such an increase cannot be observed at the other sites (Figs. 8, 10, 12).

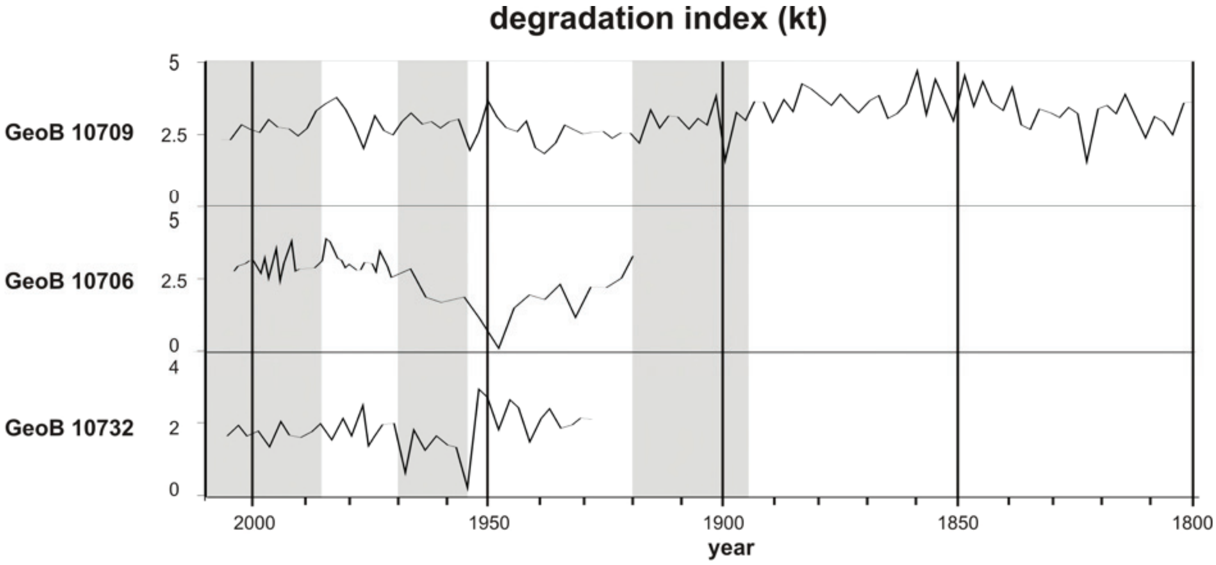


Fig 4. Degradation index kt through time of the investigated cores. Grey bars indicate phases 1-7 with characteristic dinoflagellate associations.

The W/C ratio is rather constant through time in all cores for the last 150, 80 and 60 years (Fig. 5). In the Gulf of Taranto the W/C values decrease between 1800 and about 1830 and are followed by an increase to about 1860. After 1860 values remain rather constant although a slight increase is visible. The total organic carbon (TOC weight%) content in cores GeoB 10706 and GeoB 10732 increases slowly between 1920 and about 1950 (Fig. 6). After about 1950/1960 the increase accelerates and highest TOC values are observed in the top of the cores.

Based on the variations in the dinoflagellate cyst association, several intervals with characteristic signals can be identified:

Phase 1. 1800 - ~1895

During this phase accumulation rates of all species are relatively low. We observed a coherence between fluctuations in total accumulation rates of R_f species and the ASW species *Lingulodinium machaerophorum* (Fig. 7). These fluctuations correspond well to maximum Po River outflow for the months August, September and October. *Operculodinium centrocarpum* is the most dominant species forming about 48% of the association. Cysts of all heterotrophic species form only up to 15% of the association with *Brigantedinium* forming only about 0.5%. *Lingulodinium machaerophorum* forms about 4% of the association (Fig. 9).

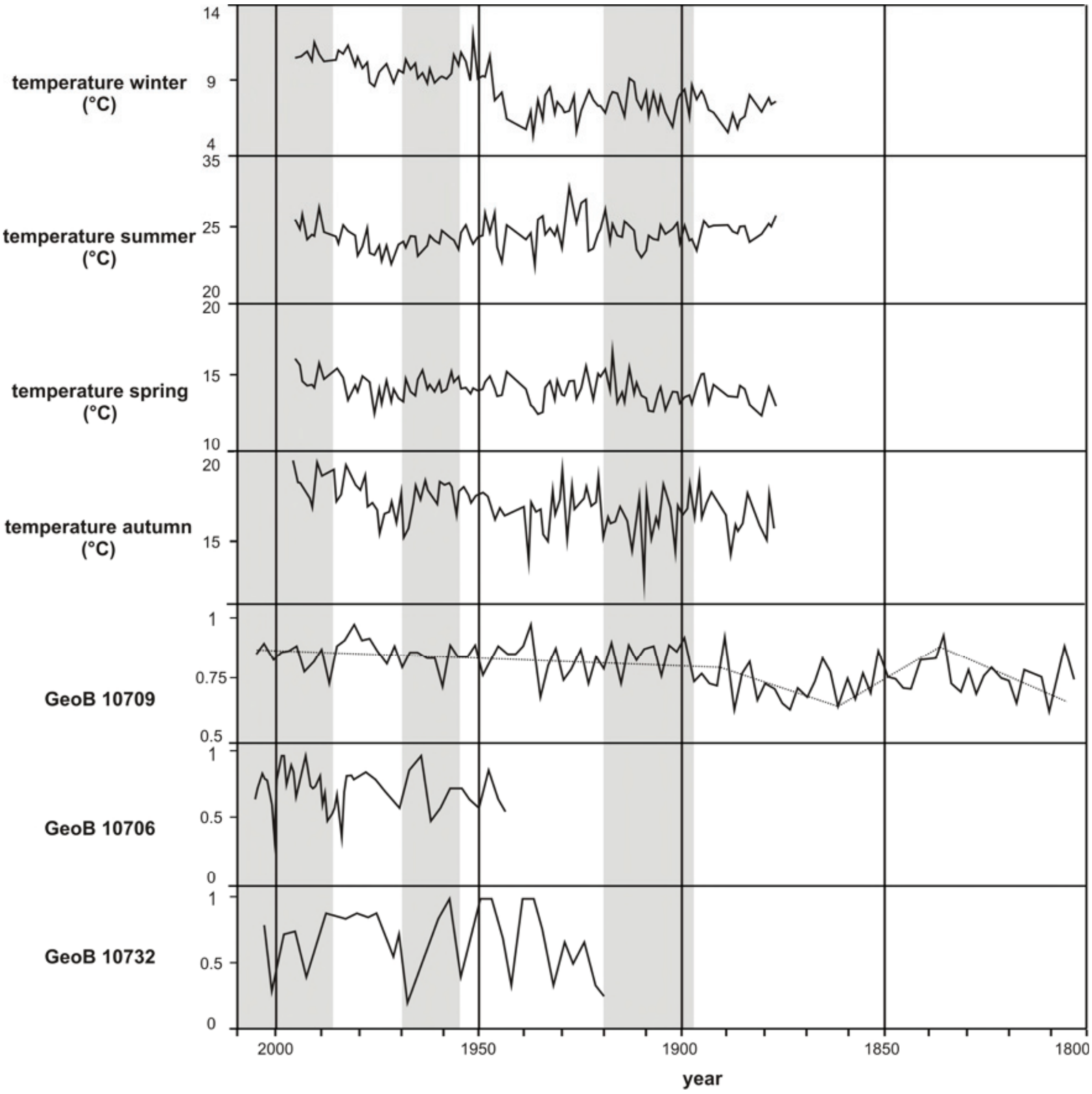


Fig 5. Relationship between abundances of “warm” and “cold” dinoflagellate cyst species. W = ∑ *Impagidinium aculeatum, Impagidinium paradoxum, Impagidinium patulum, Operculodinium israelianum, Polysphaeridium zoharyi, Spiniferites mirabilis*. C = ∑ *Bitectatodinium tepikiense* and *Spiniferites elongatus.* Grey bars indicate phases 1-7 with characteristic dinoflagellate associations.

Phase 2. 1895 - 1920

From about 1895 a the accumulation rates diverge of the R_f species the ASW species *L. machaerophorum* and *Stelladinium stellatum* with the latter ones showing an increase whereas R_f species remain at a relatively constant basis-level (Figs. 7, 8). Furthermore a slight increase in total accumulation rates of heterotrophic species can be observed (Figs. 7, 8, 9). *Operculodinium centrocarpum* remains the most dominant species forming about 39% of the association. *L. machaerophorum* forms now the second most abundant species accounting for about 9% of the association (Fig. 9). The heterotrophic species increase including *Brigantedinium* spp. to form about 21% and 4% of the association respectively.

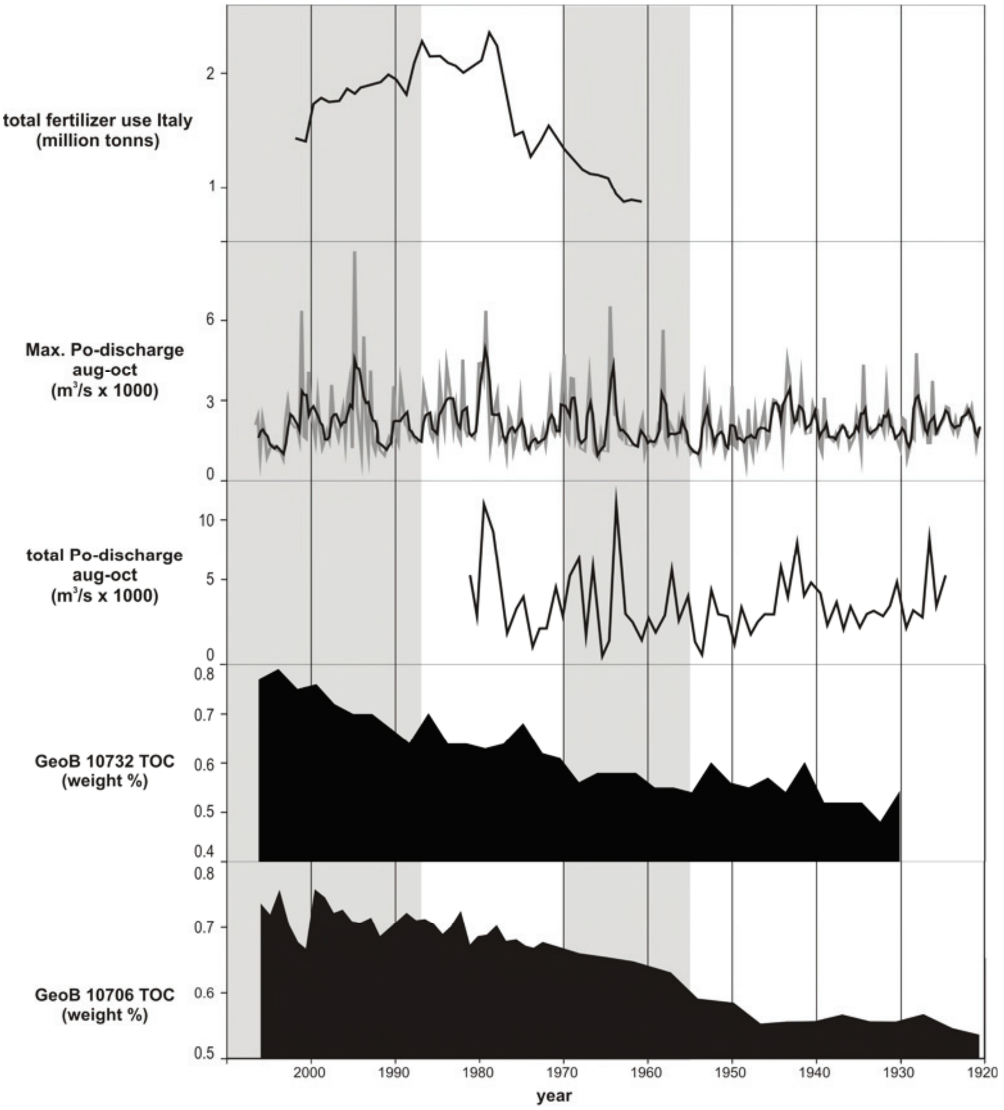


Fig 6. Total organic carbon content of sediments of cores GeoB 10706 and GeoB 10732, total Po River discharge rates (Aug - Oct), maximal Po River discharge rates (Aug-Oct: black line, 3 points mean, grey line monthly data) and total use of fertiliser in Italy.

Phase 3. 1920 - 1955

This phase is characterised by increasing accumulation rates and relative abundances *L. machaerophorum* and heterotrophic species but relative low values of R_f species (Figs. 8, 10). *O. centrocarpum* forms still the most abundant species (37%) in core GeoB 10709 and 31%

in core GeoB 10706 (Figs. 9, 11). In the Gulf of Manfredonia it forms 20% of the association. The contribution of heterotrophic species is somewhat lower compared to the previous phase whereas *Brigantedinium* spp increase somewhat forming about 18% and 6% of the association respectively at site GeoB 10709. At site 10706 these values are 32% and 9% whereas in the Gulf of Manfredonia they are 33% and 8%. The relative abundance of *L. machaerophorum* increases to about 16% of the association in core 10709. In cores GeoB 10706 and GeoB 10732 these values are 6% and 8% respectively.

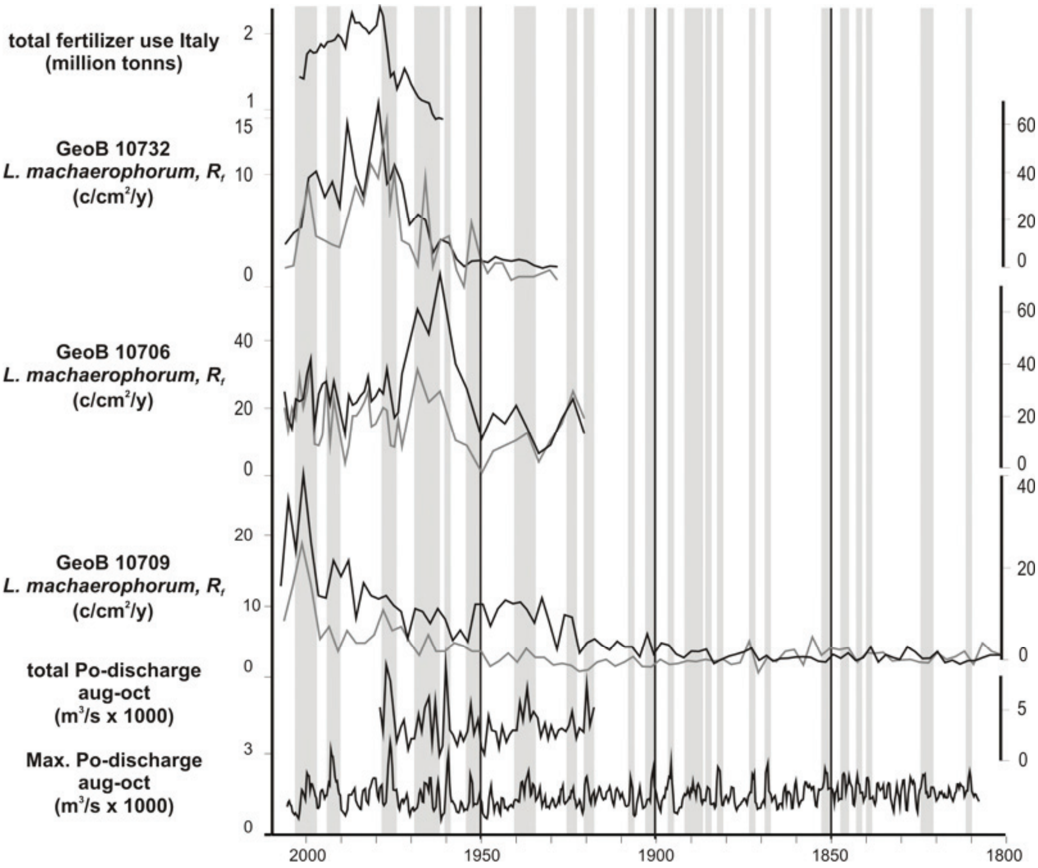


Fig 7. Accumulation rates of R_f species (gray lines) and *Lingulodinium machaerophorum,* maximal Po River discharge rates and total Po River discharge rates of the months August, September and October during the last 200 years. Grey bars indicate phases with maximal discharge. Accumulation rates of dinoflagellate cyst species in core GeoB 10709 (Gulf of Taranto), maximal Po River discharge of August, September, October, total fertiliser use in Italy and Italian population history of the last 200 years. Grey triangles mark major volcanic eruptions.

Phase 4. 1955 - 1970

From 1955 accumulation rates increase of generally all species (Figs. 8, 10, 12). Accumulation rates and relative abundances increase strongest for *Stelladinium stellatum, Polykrikos* spp., *Pentapharsodinium dalei* and other heterotrophic species (Figs. 8-13). With exception of *P. dalei* this increase is more pronounced in cores GeoB 10706 and 10732 than in 10709. In the Gulf of Manfredonia *S. stellatum* even replaces *O. centrocarpum* as the most dominant species forming 25% of the association. Heterotrophic species form 51% of the association in the Gulf of Manfredonia and 25-37% of the association in the Gulf of Taranto. *O. centrocarpum* now forms 13% and 19-21% of the association in the Gulf of Manfredonia and Gulf of Taranto respectively with *L. machaerophorum* forming 10% and 15-13% in both regions. In both cores 10732 and 10706 an upwards increase in TOC can be observed.

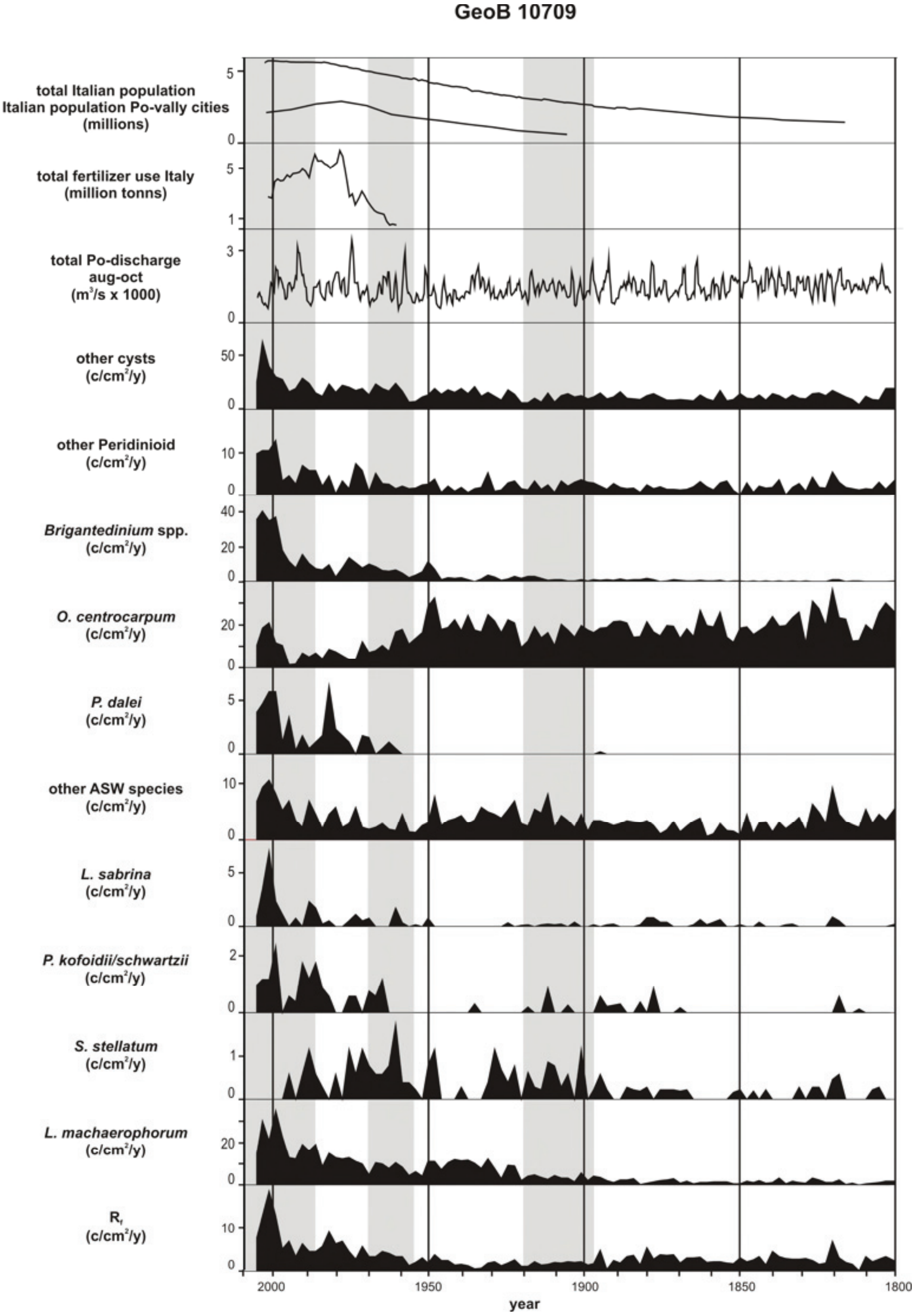


Fig 8. Accumulation rates of dinoflagellate cyst species in core GeoB 10709 (Gulf of Taranto), maximal Po River discharge of August, September, October, total fertiliser use in Italy and Italian population history of the last 60 years.

Phase 5. 1970 - 1987

This phase is characterised by high accumulation rates of generally all species, especially those that nowadays are typically present in the ASW (Figs. 7, 8, 10, 12). The exception is *S. stellatum* which accumulation rates and relative abundances reduce markedly. In this time interval *O. centrocarpum* is replaced as most dominant species by *L. machaerophorum* that now forms about 22% and 18-21% of the association in the Gulf of Manfredonia and the Gulf of Taranto respectively (Figs. 9, 11, 13). High accumulation rates of *P. dalei* can be observed in all cores between about 1975 - 1982 forming 3-7% of the association in the Gulf of Taranto and 1% in the Gulf of Manfredonia. Heterotrophic species form 42% of the association in the Gulf of Manfredonia and 27-29% of the association in the Gulf of Taranto. Of these, *Brigantedinium* spp. is the most abundant species group forming about 14% of the total association at all sites. In both the Gulf of Manfredonia and the Gulf of Taranto TOC values increase over time.

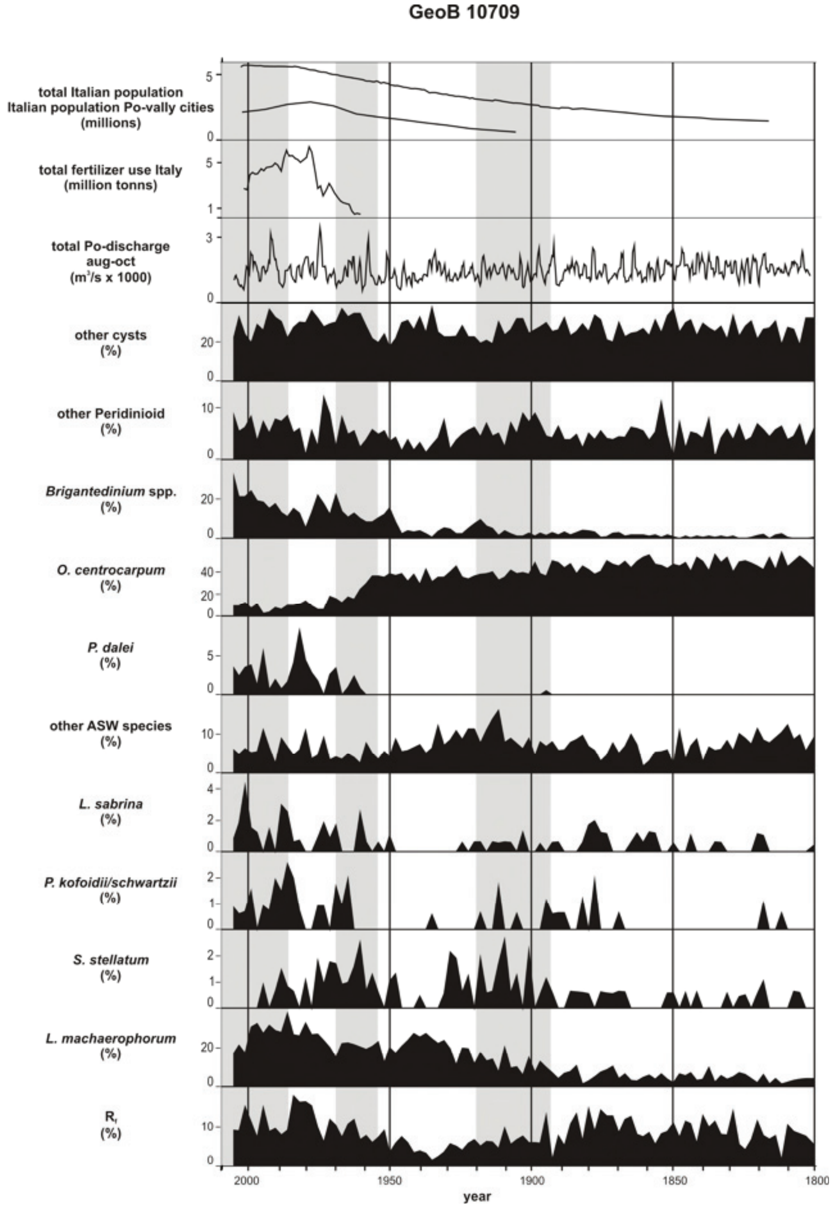


Fig 9. Relative abundances of dinoflagellate cyst species in core GeoB 10709 (Gulf of Taranto), maximal Po River discharge of August, September, October, total fertiliser use in Italy and Italian population history of the last 200 years.

Phase 6. 1987 - 2006

In this phase accumulation rates decrease of *L. machaerophorum, S. stellatum* and *Brigantedinium* spp. in the Gulf of Manfredonia (Fig. 12). In the Gulf of Taranto a decrease in relative abundance of the first two species can be observed with *L. machaerophorum* forming 15-19% of the association (Figs. 9, 11). The relative abundances of *Brigantedinium* spp. increase to 18-20% in the Gulf of Taranto whereas they reduce in the Gulf of Manfredonia to only 5% of the association. A short peak in accumulation rates of generally all species can be observed in all cores around the year 2000. Generally all species show an increase in accumulation rates towards the top at site GeoB 10709 (Fig. 8). In both the Gulf of Manfredonia and the Gulf of Taranto TOC values increase over time.

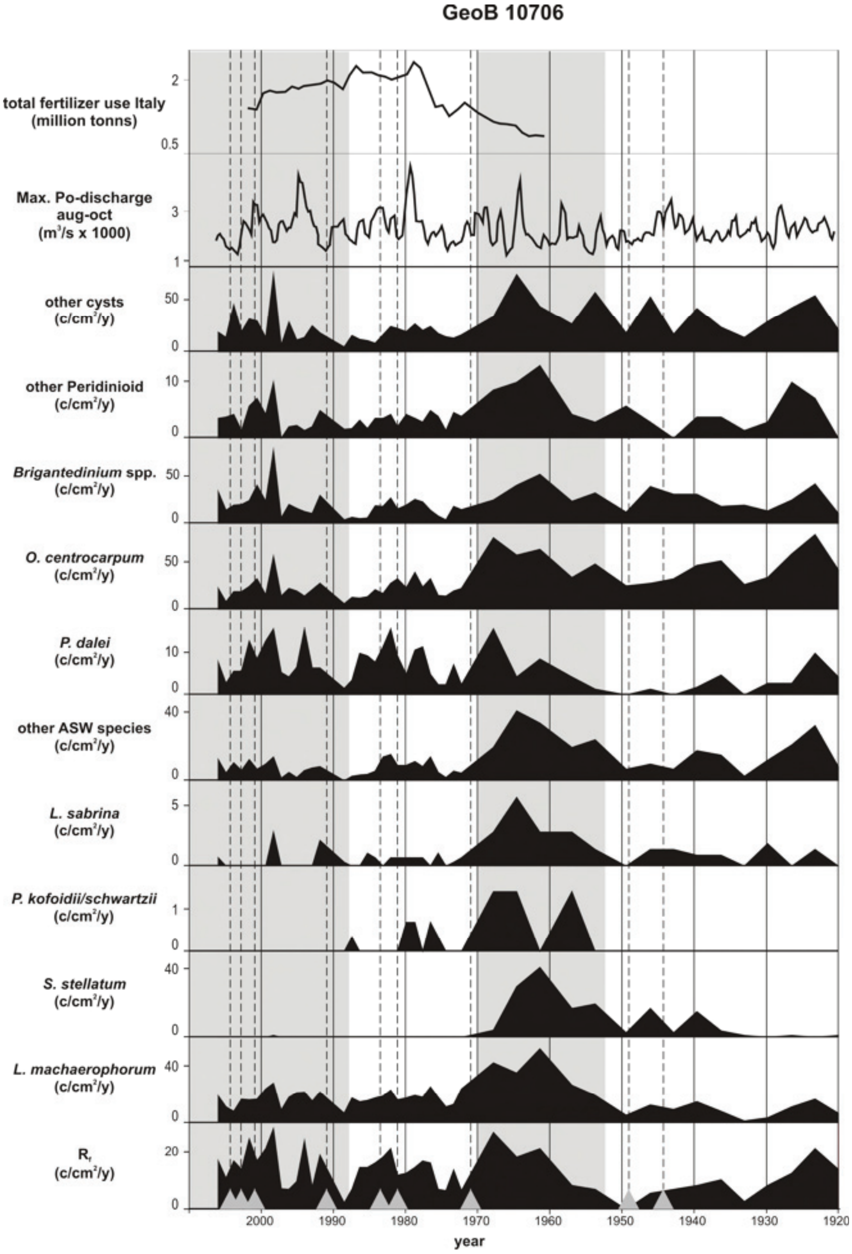


Fig 10. Accumulation rates of dinoflagellate cyst species in core GeoB 10706 (Gulf of Taranto), maximal Po River discharge of August, September, October, total fertiliser use in Italy and Italian population history of the last 60 years. Grey triangles mark major volcanic eruptions.

5. Discussion

5.1. Selective degradation and transport

Within the last years it has become evident that early diagenetic aerobic degradation can affect the dinoflagellate cyst association post-depositionally (Persson, 2000; Zonneveld et al., 1997, 2001, 2010b). Whereas the accumulation rates of all cysts species in sediments are likely to reflect cyst production at conditions of optimal preservation, these rates may underestimate the production of cysts of species that are sensitive to aerobic degradation when the preservation state is not optimal. Studies on surface sediment samples world-wide revealed that degradation rates of cyst species that are sensitive to aerobic degradation increase rapidly when bottom water oxygen concentrations increase from 2.5 to 5 ml/l (see references in Zonneveld et al., 2008). This corresponds to a kt between 2.5 - 4.5. Within this study we observe a higher kt in the Gulf of Taranto of about 3.1 compared to the Gulf of Manfredonia where kt remains close to 1.8 suggesting that sediments of the Gulf of Taranto might have been affected by species selective degradation (Fig. 4). Shipboard observations registered a visible oxygen penetration depth of 2.5 cm in core GeoB 10706, 7 cm in core 10709 (Gulf of Taranto) and 5 cm in core GeoB 10732. This indicates that cysts in bottom sediments could have been exposed to oxygen for up to about 11 years in the Gulf of Manfredonia and up to about 9 years and 60 years at sites GeoB 10706 and GeoB 10709 in the Gulf of Taranto respectively. Recently, degradation experiments carried out in the central Eastern Mediterranean Sea documented that, the dinoflagellate cyst concentrations of the most sensitive dinoflagellate cyst species decrease 24% to 57% when sediments are being exposed for 15 months to waters with oxygen concentrations of 200 µM (Kodrans-Nsiah et al., 2008). This indicates that aerobic degradation might have modified the initial signal in the Gulf of Taranto; most strongly at site GeoB 10709. Indeed the accumulation rates of all species that are known to be extremely sensitive or moderately sensitive to aerobic degradation increase towards the top of this core. As a result, we concentrate for site GeoB 10709 on cyst species that resist aerobic degradation and take into account that values of species sensitive to aerobic degradation, notably cysts formed by heterotrophic species might underestimate their initial abundance. Also the total amount of organic carbon arriving on the sea floor is reduced by degradation. However, in case of excellent preservation variation in TOC weight % is known to reflect upper water export production. Since at site GeoB 10709 preservation is not excellent we have not determined its TOC concentration.

Some traces of bioturbation have been documented for all cores. This suggest that apart from the risk of degradative overprint also a, so called, „smoothing“ of the original ecological signal might have taken place (Ruddiman et al., 1972; Trauth et al., 1997; Turekian et al., 1978). The sedimentation rates at sites GeoB 10732 and GeoB 10706 are, however, extremely high which makes it unlikely that the original signal has been smoothed much. We therefore assume that species peak occurrences have become replaced by maximally a few millimetres only.

Another factor that can alter the fossil dinoflagellate cyst association is relocation of cysts. According to their size, dinoflagellate cysts belong to the silt fraction and traditionally it was assumed that they might be transported over long distances before they sink to the sea floor (e.g. Anderson et al., 1985; Dale and Dale, 1992). However, recent sediment trap studies show that the cysts sink like phytoplankton and fecal pellet aggregates with sinking rates of about 274 m/day, much faster than marine snow (Zonneveld and Brummer, 2000; Zonneveld et al., 2010a). Given the water depth of maximal 270m at the core positions, strong lateral translocation is unlikely. The sedimentary dinoflagellate cyst association reflects therefore local environmental conditions. Apart from the factors described above also the processes of winnowing and focussing can change the dinoflagellate cyst concentration post-depositionally. However, this would have resulted in differences in grain size or sediment type of the core sediments and since these are uniform throughout the cores we assume that winnowing and focussing did not affect the sediment composition.

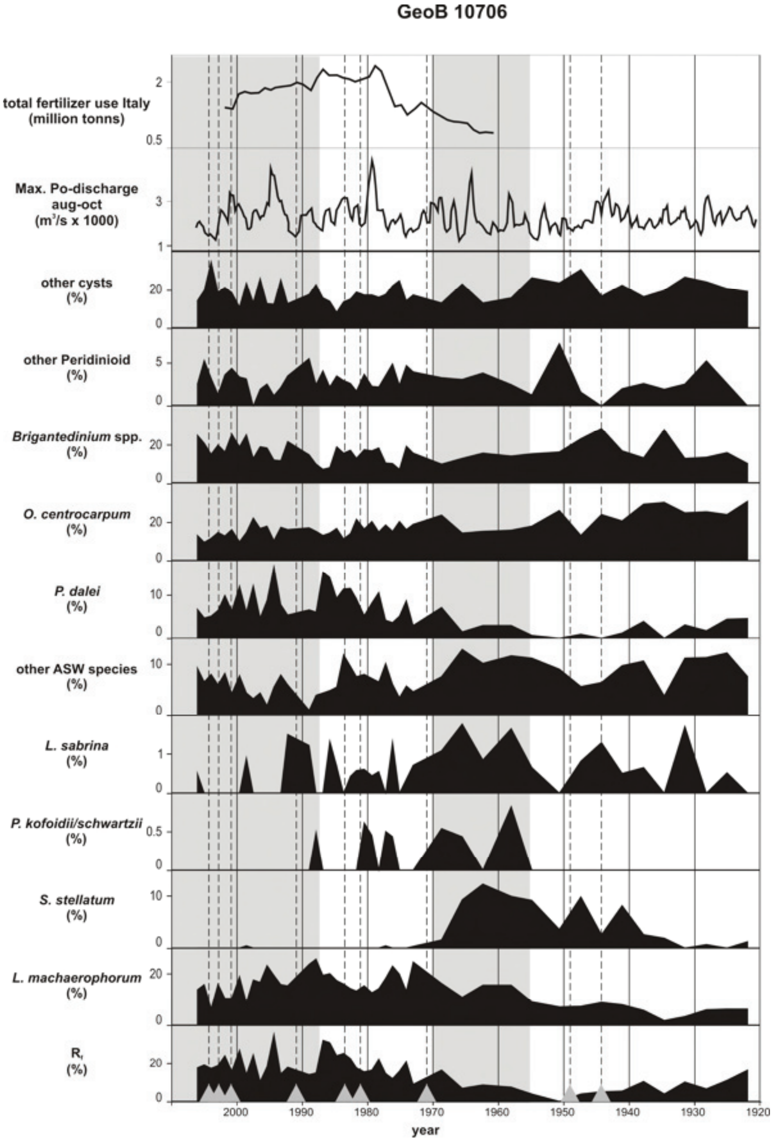

GeoB 10706

Fig 11. Relative abundance of dinoflagellate cyst species in core GeoB 10706 (Gulf of Manfredonia), maximal Po River discharge of August, September, October, total fertiliser use in Italy and Italian population history of the last 80 years. Grey triangles mark major volcanic eruptions.

5.2. Upper water temperatures

Our dataset shows that in the Gulf of Taranto the warm water versus cold water species (W/C ratio) increase between 1800 - 1830 and decrease between about 1830 - 1860 (Fig. 5). From 1860 to 1890 warm water species become again increasingly dominant. The "warm/cold" ratio slightly increases again during the last 110 years. This suggests that upper water temperatures might have increased from 1800-1830 and decreased between 1830-1860. A relatively strong temperature increase can successively be observed until 1890 followed by slightly increasing temperatures in the following 110 years. This corresponds most closely to instrument-based local records of upper air temperatures for autumn and to a lesser extent spring, but not to the summer and winter temperature records (Fig. 5). This suggests that our dinoflagellate signal reflects either autumn or spring conditions. Plankton surveys of the southwesten Adriatic Sea and the Gulf of Taranto reveal that major dinoflagellate cyst production occurs during late summer/autumn whereas production is minimal in winter (Belmonte et al., 2001; Caroppo et al., 1999; 2006; Rubino et al., 1998). We therefore assume that our cyst association is mainly influenced by the late summer/autumn conditions.

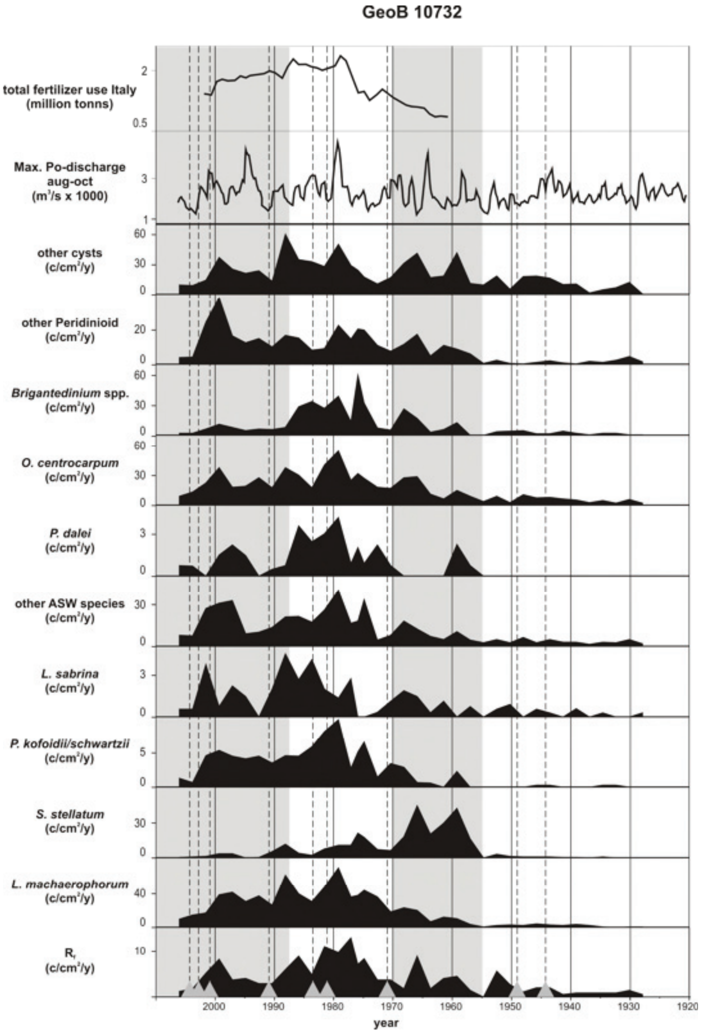


Fig 12. Accumulation rates of dinoflagellate cyst species in core GeoB 10732 (Gulf of Manfredonia), maximal Po River discharge of August, September, October, total fertiliser use in Italy and Italian population history of the last 80 years. Grey triangles mark major volcanic eruptions.

Our results are also partly consistant to temperature reconstruction based on the $U^{K'}_{37}$ record of the same core location (Versteegh et al. 2007) which shows a temperature decrease of about 3°C between 1800 and 1850 followed by an increase of 1.5°C between 1850 and 1900. Versteegh et al. (2007) also report a strong increase in temperature between 1950 and 1960 that is neither registered in our record, nor in the regional instrumental temperature records. Part of this discrepancy might be the fact that the $U^{K'}_{37}$ records reflect the winter situation (see also Leider et al., 2010) whereas the dinoflagellate cysts are likely to reflect summer/autumn conditions.

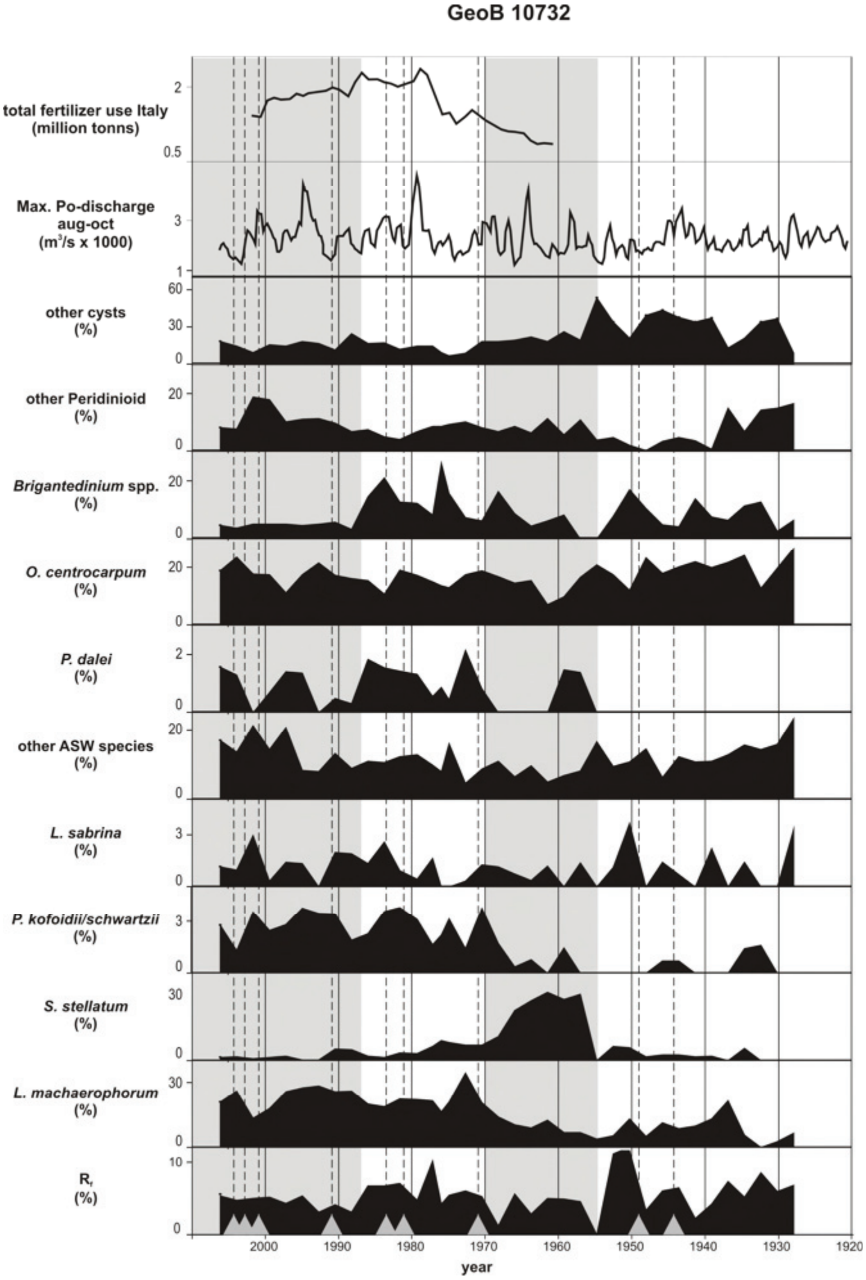


Fig 13. Relative abundances of dinoflagellate cyst species in core GeoB 10732 Gulf of Manfredonia), maximal Po River discharge of August, September, October, total fertiliser use in Italy and Italian population history of the last 80 years. Grey triangles mark major volcanic eruptions.

Our results do not correspond to the temperature reconstruction on $\delta^{18}O$ values of planktic foraminifera by Taricco et al. (2009). They observed a strong increasing trend during the last 120 years which is not registered in any of the seasonal instrumental records of local air temperature. Unfortunately Taricco et al. (2009) did not take into account the effect of changing upper water salinities, which are likely to have occurred in the region and which have been demonstrated to influence the foraminifera stable isotopic composition in the region (Grauel et al., 2010). We therefore assume that salinity changes are the reason for the discrepancy between the isotope-based record and the instrumental record of South Italian air temperatures as well as with our observations.

Changes in W/C ratio or in the instrumental air temperature records do not correspond to changes in accumulation rates and relative abundances of R_f species, heterotrophic species and ASW species. This implies that these latter changes are not a result of temperature fluctuations.

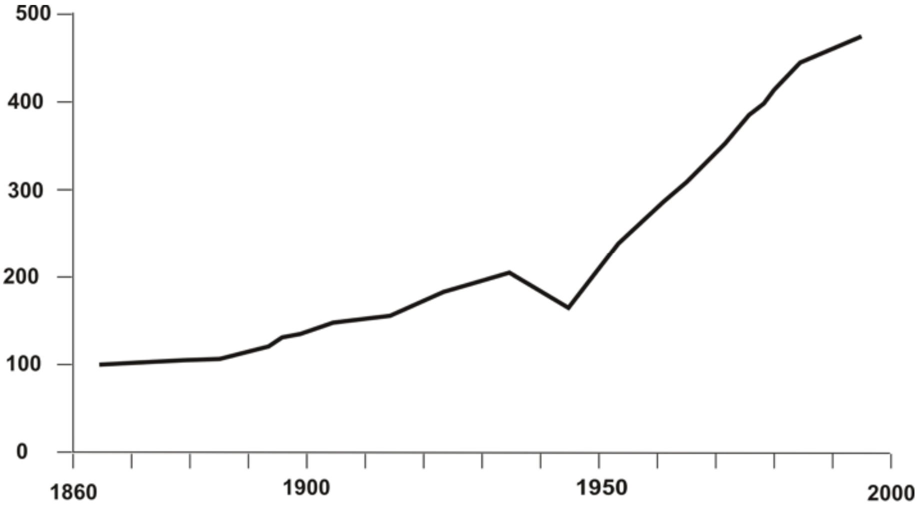


Fig 14. Gross agricultural production in central and north Italy between 1860 - 2000 (redrawn from Frederico and Malanima, 2004).

5.3. *Trophic state of the upper waters*

In the research area nutrients and trace elements can be brought into the system by air, through river discharge or as a result of enhanced winter mixing of surface waters. As mentioned above, in the research area dinoflagellates are not abundant in winter, which indicates that winter mixing is probably not an important steering factor. The research area is located downwind of the Italian volcanoes. Volcanic ash can release large amounts of phosphate, iron, and other trace metals, which can support microscopic biological life in the marine ecosystem (Jickells et al., 2005; Langmann et al., 2010). For the research area, eruptions of the Vesuvio, Ishia, Etna, and Vulcano might be of importance. Eruptions occurred at 1822, 1834, 1839, 1850, 1855, 1861, 1868, 1872, 1988, 1906, 1926, 1929, 1944, 1949, 1971, 1981, 1983 and 1991–1993, 2001, 2003-2003, 2004-2005. We see no changes in cyst accumulation rates in relation to these eruptions. We therefore assume that volcanic ash input is not influencing our signal significantly.

Other aeolian particles transported into the system can be Saharan dust, anthropogenic aerosols and aerosol products of fires (e.g. Bonilla-Findji et al., 2010; Hamann et al., 2008).

Unfortunately we do not have detailed information about variation in dust input into the research area for the last 200 years so we can not verify to what extent dust input modified the dinoflagellate cyst production or association. Further studies are required to investigate this aspect.

The majority of the nutrients and trace elements are brought into the Gulf of Manfredonia and the Gulf of Taranto by the ASW. Although we do not have detailed information about the exact amount of ASW input into the research area, we do have a record of maximum monthly Po River discharge rates for the last 200 years as well as the total Po River discharge rates between 1918 and 1979 (Fig. 7). Studies on the sediment composition of the ASW waters reveal that a characteristic signal of Po-discharge can be traced as far as the Gargano peninsula, the northern boundary of the Gulf of Manfredonia (Tomadin, 2000). This indicates that Po River discharge waters will probably only reach our sampling site in the Gulf of Manfredonia (core GeoB 10732) but not the Gulf of Taranto (Cores GeoB 10709, GeoB 10706). Nevertheless, increased Po-discharge will „push" the plume waters further south resulting in an extension of the "plume". This in turn will result in more ASW waters entering the southern Adriatic Sea and the Gulf of Taranto. In nature cyst production is highest during or just after dinoflagellate cyst blooms and notably in oligotrophic/mesotrophic coastal environments, dinoflagellate production, and related to that, the cyst flux, increases when more nutrients/trace elements become available in the upper water column (e.g. Dale, 2009; Domingues et al., 2011; Godhe et al., 2001; Ishikawa and Taniguchi, 1996; Kremp and Heiskanen, 1999; Montresor et al., 1998; Shin et al., 2010; Susek et al., 2005; Zonneveld et al., 2010a). As mentioned above, cyst production is highest in our research area during late summer/autumn (Belmonte et al., 2001; Rubino et al., 1998). Therefore, we expect a relationship between the cyst record and Po River discharge values of summer/autumn. Indeed we see a good correlation between the total accumulation rates of R_f and ASW species and changes in Po-discharge rates (Fig. 7). This suggests that accumulation rates of resistant cysts and ASW species might be largely influenced by the quantity of river discharge waters.

Phase 2. 1895 - 1920

From about 1895 onward we see on top of the above described signal an association change with the ASW signal diverging from the R_f signal. From this time on, the species *L. machaerophorum* and *S. stellatum* become increasingly prominent in the association (Figs 7, 8, 9). We do not find indications that this association change is a result of changed preservation state as non of the other degradation sensitive species shows a change in accumulation rates at this point. Today, cyst concentrations of both *L. machaerophorum* and *S. stellatum* are highest in the vicinity of the Po River mouth in regions where highest nutrient concentrations occur (Rubino et al., 2000; Sangiorgi et al., 2005). The sediment survey in the more distal part of the Po River discharge plume revealed that cyst accumulation rates of both species are positively related to the upper water trophic conditions (Zonneveld et al., 2009). Together with *Polykrikos* an increase in their concentrations can often be related to (anthropogenic) eutrophication, mainly as a result of enhanced input of nitrate and phosphate (e.g. Dale, 2009; Matsuoka et al., 2003; Pospelova et al., 2002; 2005; Shin et al., 2010). Our results suggest therefore that on top of variations in the quantity of ASW water influx, there is a change in ASW water quality starting already at about 1890. Historical records support these findings as this date corresponds to the start of the industrial development after the unification of Italy in 1870 (Collantes, 2006; Federico and Malanima, 2004; Pescosolido, 2010). After the unification, agriculture and industry in the Po River valley was intensified (Fig. 14). Our results correspond as well with the long-term dinoflagellate cyst record available from core 108 taken in the North Adriatic Sea in the vicinity of the Po River mouth (Sangiorgi and Donders, 2004). In this record a change in the cyst association started also around 1880 with an increase of relative abundances of the heterotrophic species *Selenopemphix quanta* followed by an increase of *Brigantedinium* spp. between about 1900 and 1910. Since core 108 is located very close to the Po River mouth where high sedimentation rates occur, the preservation may be considered as excellent which suggests that the increase of heterotrophic species reliably reflects enhanced nutrient/trace element availability in surface waters.

Phase 3. 1920 - 1955

In this interval we observe a transition in the composition of the cyst association. From 1920 on, accumulation rates and relative abundances of *L. machaerophorum* increase more rapidly than during the previous time interval. *L. machaerophorum* is moderately sensitive to aerobic degradation. If selective preservation would have been the cause of this association change, species that are more sensitive than *L. machaerophorum* would show an equal or even more pronounced increase in accumulation rates. Since this is not the case, we assume that preservation changes are not the cause. Historical information learns that from 1913 ammonia could be produced chemically and its distribution as artificial fertiliser became quickly wide-spread throughout Europe. Furthermore, increasing amounts of guano were exported to Europe. As a result the output per agricultural worker in Italy started to increase (Fig. 14). Today, the use of fertiliser is the major source for nitrate and phosphate in discharge waters of the Italian rivers (e.g. de Wit; Bendoricchio, 2001). We therefore assume that the eutrophication accelerated from this time on due to agricultural developments. Our results are more or less conform the only long-term dinoflagellate cyst study of the region that is currently present which reports an increase in abundance values of *L. machaerophorum* somewhat later at about 1930 (Sangiorgi and Donders 2004).

Phase 4. 1955 - 1970

This phase is characterised by a marked increase in the cyst accumulation rates and relative abundances of *Echinidinium* spp. *L. machaerophorum, Lejeunecysta sabrina*, *Stelladinium stellatum, Pentapharsodinium dalei* and *Polykrikos* species in all cores. With exception of *P. dalei* these species are characteristic for the ASW and are most abundant in the surface sediments below the most eutrophic parts of the Po-plume today (Sangiorgi et al., 2005; Zonneveld et al., 2009). We do not see a marked increase in Po River discharge in this time interval and therefore assume that this change reflects a change in ASW quality rather than quantity. This is in agreement with historical data and the limited amount of instrumental data on the physical conditions available for the region. The longest eutrophication records that are currently available focus on the oxygen conditions in the Northern Adriatic Sea (Justič et al., 1987). First indications for reducing oxygen concentrations near the sea bottom are found between 1955 and 1965. Justič et al. (1987) conclude this to be strongly related to the increase of phosphate concentrations in the surface waters. Historical data show an accelerated increase in agricultural production from 1950 whereas the population density in Italy and the Po River valley continued to increase steadily (Fig. 7). We therefore assume that our change in association is the result of enhanced pollution due to increased agricultural activity rather than changes in population.

The increase in accumulation rates of the heterotrophic species is less pronounced in core GeoB 10709 than in the other cores. As discussed before, the signal of core GeoB 10709 might be overprinted by selective degradation. Our observations show, however, that selective preservation did not erase the initial signal but might have had a damping effect.

The increase of ASW species is accompanied by a decrease in accumulation rates and relative abundances of *Operculodinium centrocarpum. O. centrocarpum* is a cosmopolitan species thriving in oligotrophic to mesotrophic environments. It has been suggested to be especially present in areas with unstable surface waters (e.g. Marret and Zonneveld, 2003; Verleye and Louwye, 2010). It is not characteristically abundant in polluted regions (e.g. Dale, 2009; Limoges et al., 2010; Krepakevich; and Pospelova, 2010; Matsuoka, 1999; 2001; Pospelova et al., 2002; 2004; Pospelova and Kim, 2010; Shin et al., 2010). Our results suggest that the changing environmental conditions related to the increasing pollution such as the enhanced eutrophication in upper waters and decreasing oxygen concentrations in bottom waters, are unfavourable for this species.

We observe also a marked increase in accumulation rates and relative abundances of *P. dalei*. *P. dalei* is extremely resistant to aerobic degradation. It is however not known to be an indicator for enhanced nutrient/trace element concentrations in upper waters although it is often found in more eutrophic environments such as upwelling areas and fjords characterised by high upper water bio-productivity (e.g. Marret and Zonneveld, 2003; Howe et al., 2010). Pospelova et al. (2005) document high relative abundances of this species close to the New Bedford Sewer overflow, a point-source pollution site in Buzards Bay (Massachusetts, USA). So far *P. dalei* has not received much attention in pollution studies and is often only marginally reported. Our results suggest, however, that also this species might react sensitively on enhanced (anthropogenic induced) nutrient influx in coastal environments and we hope that this aspect becomes more attention in future pollution studies.

Phase 5. 1970 - 1987

The interval from 1970 to 1987 is characterised by high accumulation rates of generally all ASW species with exception of *S. stellatum*. From about 1965 onwards, the total use of fertiliser increases strongly in Italy and it is estimated that this resulted in a doubling of the nutrient load carried by the Po River. (Degobbis and Gilmartin, 1990; Degobbis et al., 1979; Degobbis, 1989; de Wit and Bendoricchio, 2001; Justič et al., 1987; Marchetti et al., 1989). In the North Adriatic, episodes of severe anoxia have been registered and the trophic state of the upper waters changed from eutrophic to hypertrophic. Our observation of a marked increase in production of generally all ASW species suggests that the trophic state of the upper waters at the distal part of the plume increased as well.

The exception is formed by *S. stellatum* for which accumulation rates and relative abundances reduce remarkably. To date there is not much known about the ecology of *S. stellatum*. The species is often observed in subtropical to tropical areas where upwelling or high nutrient concentrations prevail (e.g. Holzwarth et al., 2010; Marret and Zonneveld, 2003; Shin et al., 2010; Vilanova et al., 2008). Shin et al. (2010) could link an increase in abundance of this species to the change from eutrophic to hypertrophic conditions in the highly polluted Gamak Bay (Korea). It is therefore unlikely that an overload of nutrients and trace elements reduced the cyst production of this species in our research area. Another possibility might be that anoxic bottom waters in late summer/autumn are unfavourable for *S. stellatum.* This would form a contrast to other species such as *L. machaerophorum* that require anoxic pre-conditioning for excystment, (Lewis and Hallett, 1997; Smayda and Trainer, 2010). To date it is unknown if *S. stellatum* tolerates bottom water anoxia. Remarkable is that cyst concentrations of this species reduce strongly in the upper part of the core from Gamak Bay (Shin et al., 2010). Shin et al. (2010) note that anoxic bottom waters became more frequent in this bay in the last couple of years. Unfortunately, their data don't reveal if this increase is time equivalent to the decrease in cyst production of *S. stellatum.*

In a five year sediment trap record from the upwelling region off NW Africa, Zonneveld et al. (2010) document that *S. stellatum* and *L. machaerophorum* have similar seasonal distributions with maximal cyst production during upwelling relaxation. Recently, Smayda and Trainer (2010) suggested that the multiple seeding behaviour of *L. machaerophorum* in the highly variable upwelling environment might be cause of this. Namely, Figueroa and Bravo (2005) had shown earlier that apart from sexual resting cysts, *L. machaerophorum* is able to make asexual ecdysal cysts of which the production can be induced by turbulence. These asexual cysts protect the specimens to turbulence during upwelling and allow a fast re-colonisation of the water column upon upwelling relaxation. Comparable changes in upper water conditions can be observed in the Po River environment; not as result of upwelling but as result of varying river outflow. When river discharge increases in late summer a wedge of nutrient-rich fresh water is moving southwards along the coast over the oligotrophic highly saline ISW. Where both water masses contact, mixing occurs. The asexual ecdysal cyst production might be of benefit for *L. machaerophorum* to quickly recolonize the photic zone when upper waters become stratified again as result of the presence of overlying river-outflow water. To date we have no information if *S. stellatum* is able to produce asexual ecdysal cysts but it might be interesting to investigate this aspect further.

Within our study we have no information about changes in industrial pollution over time, neither have we about the concentrations of toxins, elements or heavy metals in the plume waters, which might be disadvantageous for cyst production. Consequently we have no insight in how far these kinds of pollution influenced the cyst assemblages. However, we do not see a relationship between the cyst composition of our samples and population growth of Italy (that stagnates from about 1980) or the population size of the major Italian cities in the Po-valley (that decreases after 1970). The industrial development of Italy is strongly linked to the population dynamics of the major cities and it might be expected that industrial pollution decreased simultaneous to the population decrease.

At site 10732 in the Gulf of Manfredonia we see a strong correlation between the accumulation rates of *Brigantedinium* spp.*, P. dalei, L. machaerophorum* and *Polykrikos* species with the amount of used fertiliser. In Italy the majority of fertiliser is used in the Po-valley. It forms the major source for the phosphate, ammonium and nitrate load of the discharge waters. The Gulf of Manfredonia is located at the southern edge of the region where the characteristic water properties of the Po River discharge waters can be distinguished from those of the eastern Italian rivers that drain the Apennines (Tomadin, 2000). Our results suggest therefore that the cyst production of these species is reflecting the water quality of the Po- and other Italian rivers and that changes in the water quality are strongly influenced by agricultural developments.

Phase 6. 1987-2006

In all cores a short peak in accumulation rates of generally all species can be observed around the year 2000. Records of the Po River discharge rates document a top-discharge for the year 2000 which might be the cause of our observation.

At sites 10706 and 10732 a reduction of cyst accumulation rates of the majority of species occurs in this time interval. Apart from changes in the cyst accumulation rates we observe decreasing relative abundances of *L. machaerophorum* and a disappearance of *Polykrikos* from the association in all cores. This may suggest an improvement of the water quality after about 1992. This is in agreement with decreasing upper water chlorophyll-*a* concentrations and phytoplankton production in the North Adriatic Sea (e.g. Degobbis et al., 2005; Mozetic et al., 2010). This reduction might be due to a ban of phosphorus in artificial fertiliser and washing products by the Italian government since 1979. This has led to decreasing concentrations of phosphorus and ammonia in the Po River outflow waters since the mid 1980s (de Wit and Bendoricchio, 2001; Marchetti et al., 1989; Solidoro et al., 2009). In contrast to phosphate and ammonia, the nitrate concentrations continue to increase steadily in the Po River system. The decrease in accumulation rates of *L. machaerophorum* thus suggests that in this eco-system *L. machaerophorum* might be phosphate- rather than nitrate-limited. This seems logical as it is known that especially phosphorus is an important nutrient for *L. machaerophorum* in triggering cyst formation in cultures (Smayda and Trainer, 2010 an references therein). It is also in accordance to recent observations in Todos Santos Bay (Baja California, Mexico)where dissolved inorganic phosphate concentrations were the most important environmental factor influencing the cyst production of *L. machaerophorum* (Pena-Manjarrez et al. 2009). The comparable trend in *Polykrikos* accumulations might reflect a predator-prey relationship as *L. machaerophorum* forms one of its potential preys (Jeong et al., 2001). In contrast, *P. dalei* does not show a reduction in cyst production. We therefore assume that *P. dalei* is not so sensitive to changes in phosphate or ammonia and that the high amounts of nitrate in the water favour cyst production of this species.

Although our results suggest a recent improvement of the water quality the high TOC concentrations and still high accumulation rates of cyst species characteristic for eutrophic conditions indicates that ASW waters are still eutrophic. More (governmental steered) waste management might therefore be needed to further improve the water quality.

5.4. Anthropogenic eutrophication

Within this study we observe a strong relationship between agricultural eutrophication and the cyst production of the species *L. machaerophorum*, *S. stellatum, Polykrikos schwartzii/kofoidii, P. dalei* and to a lesser extent *Brigantedinium* spp. Similar changes in cyst associations have been observed in several other studies. For instance *L. machaerophorum* has been shown to react sensitively to cultural eutrophication in estuarine environments such as Fjords, river systems and bays (e.g. Dale et al., 1999; Dale, 2009; Harland et al., 2010; Shin et al., 2010). In other regions it has been found that heterotrophic cysts, notably *Polykrikos* and *Brigantedinium* species increase their cyst production or relative abundance in response to anthropogenic eutrophication (Dale, 2009; Pospelova and Kim, 2010; Kim et al., 2009; Saetre et al., 1997; Shin et al., 2010). Also *Diplopsalidaceae* such as *Dubridinium* spp. are in some coastal areas typical indicators for anthropogenic eutrophication (e.g. Pospelova et al., 2002; 2005; Pospelova and Kim, 2010). These studies show that there is a set of species that has the potential to reflect anthropogenic eutrophication in sedimentary datasets but that it is region dependent which species shows the most prominent signal. This is logical as the local environmental conditions such as the occurrence of turbulence/stratification, inflow of open ocean waters, the presence of river plumes, seasonal stability, the presence of winter sea ice etc. are different for all regions and even can vary remarkably within a small geographic area (Radi et al., 2007). Furthermore, as a result of their different ecology, species might react differently on different forms of eutrophication or pollution. Nevertheless, this study as well as those cited above, demonstrates that dinoflagellate cyst associations react extremely sensitive to changes in trophic state of the surface waters and are excellent tools to separate natural from anthropogenic signals. They appear to be an ultimate tool to investigate in how far coastal management activities affect ecosystems and in how far these systems are influenced by natural and human induced environmental change.

6. Conclusions

To obtain insight in the character of natural and/or human induced changes in the trophic state of the distal part of the Po River discharge plume in the course of the last two centuries, high temporal resolution dinoflagellate cyst records have been established for two sites in the Gulf of Taranto and one site in the Gulf of Manfredonia (southern Italy). Changes in dinoflagellate cyst production rates of species that resist aerobic post-depositional degradation and ASW species are positively related to changes in plume extension related to natural variations in Po River discharge in late summer/autumn. On top of changes that can be related to natural variability in river outflow we observe changes in the dinoflagellate cyst association that can be linked to changes in the quality rather than the quantity of the plume waters.

An increase in absolute and relative abundances of the species *Lingulodinium machaerophorum* and *Stelladinium stellatum* can be observed as early as 1895. This corresponds to the start of the industrial revolution in Italy that is marked by enhanced industrial and agricultural activity in northern Italy, notably the Po-valley. A second marked increase in accumulation rate and relative abundance of *L. machaerophorum* is observed at about 1920, which corresponds to the start of chemical ammonia production as agricultural fertiliser and its use throughout Europe.

From 1955 onward, accumulation rates and relative abundances of species that characterise the river plume such as *L. machaerophorum, Polykrikos* spp., *S. stellatum, Brigantedinium* spp. and *Pentapharsodinium dalei* increase strongly. This increase corresponds to an enhanced use of artificial fertilisers in Italy and a marked increase in agricultural production. Furthermore, it corresponds to the first occurrence of eutrophication-related anoxic events in the North Adriatic Sea.

Between 1970 and 1987 hypertrophic river discharge waters in the North Adriatic Sea and severe anoxic events of bottom waters in late summer and autumn correspond to cyst production maxima of *L. machaerophorum, Polykrikos* spp., *Brigantedinium* spp. and *P. dalei.* The now prevailing environmental conditions might be unfavourable for *S. stellatum* as its cyst flux reduces markedly.

From 1987 cyst production of *L. machaerophorum* and *Polykrikos* spp. reduce equivalent to a reduction in phosphate concentrations of river outflow waters and a slight improvement of the water quality. Cyst production of *P. dalei* remains high, suggesting that phosphate does not form a limiting nutrient for this species. We suggest that the still increasing production of this species might be linked to the still increasing nitrate concentrations in the discharge waters.

Acknowledgements

We thank the Deutscher Akademischer Austausch Dienst (DAAD) and the DFG funded International Graduate College „EUROPROX“ and the research Centrum MARUM for providing the scholarships, that allowed Rehab Elshanawany to carry out part of this research at Bremen University, Germany. The DFG is also acknowledged for funding the position of Liang Chen as part of the NSF/EuroMarc project „MOCCHA“.

References

Anderson, D.M., Lively, J. J., Reardon, E. M., Price, C. A., 1985. Sinking characteristics of dinoflagellate cysts. Limnol. and Oceanogr. 30, 1000-9.

Appleby, P.G., Oldfield, F., 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported 210Pb to the sediment. Catena 5, 1-8.

Belmonte, G., Fanelli, G., Gravili, C., Rubino, F., 2001. Composition, distribution and seasonality of zooplankton in Taranto Seas (Ionian Sea, Italy). Biol. Mar. Med. 8, 352-62.

Bolch, C.J.S., Negri, A. P., Hallegraeff, G. M., 1999. *Gymnodinium microreticulatum* sp.nov. (Dinophyceae): a naked, microreticulate cyst-producing dinoflagellate, distinct from *Gymnodinium catenatum* and *Gymnodinium nolleri*. Phycol. 38, 301-13.

Boldrin, A., Langone, L., Miserocchi, S., Turchetto, M., Acri, F., 2005. Po River plume on the Adriatic continental shelf: Dispersion and sedimentation of dissolved and suspended matter during different river discharge rates. Mar. Geol. 222, 135-58.

Bonilla-Findji, O., Gattuso, J., Pizay, M., Weinbauer, M. G., 2010. Autotrophic and heterotrophic metabolism of microbial planktonic communities in an oligotrophic coastal marine ecosystem: seasonal dynamics and episodic events. Biogeosc. 7, 3491-503.

Caroppo, C., Fiocca, A., Sammarco, P., Magazzu, G., 1999. Seasonal variations of nutrients and phytoplankton in the coastal SW Adriatic Sea (1995-1997). Bot. Mar. 42, 389-400.

Caroppo, C., Turicchia, S., Margheri, M. C., 2006. Phytoplankton assemblages in coastal waters of the northern Ionian Sea (eastern Mediterranean), with special reference to cyanobacteria. J. Mar. Biol. Ass. UK. 86, 927-37.

Collantes, F., 2006. Farewell to the peasant republic: marginal rural communities and European industrialisation, 1815-1990. Agr. Hist. Rev. 54, 257-73.

Dale, A.L., Dale, B., 1992. Dinoflagellate contributions to the open ocean sediment flux. in: Dale A.L., Dale B. (Eds.), Dinoflagellate Contributions to the Deep Sea, Woods Hole Oceanographic Institution, Woods Hole, pp. 45-73.

Dale, B., 2009. Eutrophication signals in the sedimentary record of dinoflagellate cysts in coastal waters. J. Sea Res. 61, 103-13.

Dale, B., Fjellså, A., 1994. Dinoflagellate cysts as paleoproductivity indicators: state of the art, potential, and limits. in: Zahn R., Pedersen T.F., Kaminski M.A., Labeyrie L. (Eds.), Carbon Cycling in the Glacial Ocean: Constraints on the Ocean's Role in Global Change, Springer, Berlin, pp. 521-37.

Dale, B., Thorsen, T. A., Fjellså, A., 1999. Dinoflagellate cysts as indicators of cultural eutrophication in the Oslofjord, Norway. Est. Coast. Shelf. Sci. 48 , 371-82.

Degobbis, D., 1989. Increased eutrophication of the Northern Adriatic Sea - 2nd act. Mar. Poll. Bull. 20, 452-7.

Degobbis, D., Gilmartin, M., 1990. Nitrogen, phosphorus and biogenic silicon budgets for the North Adriatic Sea. Oceanol. Acta. 13, 31-45.

Degobbis, D., Precali, R., Ferrari, C. R., Djakovac, T., Rinaldi, A., Ivancic, I., Gismondi, M., Smodlaka, N., 2005. Changes in nutrient concentrations and ratios during mucilage events in the period 1999-2002. Sci. Tot. Env. 353, 103-14.

Degobbis, D., Precali, R., Ivancic, I., Smodlaka, N., Fuks, D., Kveder, S., 2000. Long-term changes in the northern Adriatic ecosystem related to anthropogenic eutrophication. Int. J. Env. Poll. 13, 495-533.

Degobbis, D., Smodlaka, N., Pojed, I., Skrivanic, A., Precali, R., 1979. Increased eutrophication of the Northern Adriatic Sea. Mar. Poll. Bull. 10, 298-301.

Domingues, R.B., Anselmo, T. P., Barbosa, A. B., Sommer, U., Galvao, H. M., 2011. Nutrient limitation of phytoplankton growth in the freshwater tidal zone of a turbid, Mediterranean estuary. Est. Coast. Shelf. Sci. 91, 282-97.

Eker-Develi, E., Kideys, A. E., Tugrul, S., 2006. Role of Saharan dust on phytoplankton dynamics in the northeastern Mediterranean. Mar. Ecol. Progr. Ser. 314, 61-75.

Federico, G., Malanima, P., 2004. Progress, decline, growth: product and productivity in Italian agriculture, 1000-2000. Econ. Hist. Rev. 57, 1-437.

Figueroa, R.I., Bravo, I., 2005. Sexual reproduction and two different encystment strategies of Lingulodinium polyedrum (Dinophyceae) in culture. J. Phycol. 41, 370-9.

Giordani, P., Angiolini, L., 1983. Chemical parameters characterizing the sedimentary environment in a NW Adriatic coastal area (Italy). Est. Coast. Shelf. Sci. 17, 159-167.

Godhe, A., Norén, F., Kulenstierna, M., Ekberg, C., Karlson, B., 2001. Relationship between planktonic dinoflagellate abundance, cysts recovered in sediment traps and environmental factors in the Gullmar Fjord, Sweden. J. Plank. Res. 23, 923-38.

Grauel, A.L., Bernasconi, S. M., 2010. Core-top calibration of $\delta^{18}O$ and $\delta^{13}C$ of *G. ruber* (white) and *U. mediterranea* along the southern Adriatic coast of Italy. Mar. Micropal. 77, 175-186.

Hainbucher, D., Rubino, A., Klein, B., 2006. Water mass characteristics in the deep layers of the western Ionian Basin observed during May 2003. Geophys. Res. Lett. 33, 1-4.

Hamann, Y., Ehrmann, W., Schmiedl, G., Kruger, S., Stuut, J. B., Kuhnt, T., 2008. Sedimentation processes in the Eastern Mediterranean Sea during the Late Glacial and Holocene revealed by end-member modelling of the terrigenous fraction in marine sediments. Mar. Geol. 248, 97-114.

Harland, R., Nordberg, K., Fillipson, H.L., 2010. A major change in the dinoflagellate cyst flora of Gullmar Fjord, Sweden, at around 1969/1970 and its possible explanation, in: Howe, J.A., Austin, W.E.N., Forwick, M, Paetzel, M. (Eds.) Fjord systems and archives. Geol. Soc. London, Spec. Publ. 344, 75-82.

Holzwarth, U., Esper, O., Zonneveld, K. A. F., 2010. Organic-walled dinoflagellate cysts as indicators of oceanographic conditions and terrigenous input in the NW African upwelling region. Rev. Palaeobot. Palynol. 159, 35-55.

Howe, J.A., Harland, R., Cottier, F.R., Brand, T., Willis, K.J., Berge, J.R., Grøsfjeld, K., Eriksson, A., 2010. Dinoflagellate cysts as proxies for palaeoceanographic conditions in Arctic fjords, in: Howe, J.A., Austin, W.E.N., Forwick, M, Paetzel, M. (Eds.) Fjord systems and archives. Geol. Soc. London, Spec. Publ. 344, 61-74.

Ishikawa, A., Taniguchi, A., 1996. Contribution of benthic cysts to the population dynamics of Scrippsiella spp. (Dinophyceae) in Onagawa Bay, northeast Japan. Mar. Ecol. Progr. Ser. 140, 169-78

IPCC; Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., 2007. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change; impacts, adaptation and vulnerability. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 976 pp.

Jeong, H.J., Kim, S. K., Kim, J. S., Kim, J. T., Yoo, Y. D., Yoon, J. H., 2001. Growth and grazing rates of heterotrophic dinoflagellate *Polykrikos kofoidii* on Red-Tide and toxic dinoflagellates. J. Eukar. Microbiol. 48, 298-308.

Jickells, T.D., An, Z. S., Andersen, K. K., Baker, A. R., Bergametti, G., Brooks, N., Cao, J. J., Boyd, P. W., Duce, R. A., Hunter, K. A., Kawahata, H., Kubilay, N., laRoche, J., Liss, P. S., Mahowald, N., Prospero, J. M., Ridgwell, A. J., Tegen, I., Torres, R., 2005. Global iron connections between desert dust, ocean biogeochemistry, and climate. Science. 308, 67-71.

Justič, D., 1987. Long-term eutrophication of the Northern Adriatic Sea. Mar. Poll. Bull. 18, 281-4.

Justič, D., Legovic, T., Rottinsandrini, L., 1987. Trends in oxygen-content 1911-1984 and occurrence of benthic mortality in the Northern Adriatic Sea. Est. Coast. Shelf. Sci. 25, 435-45.

Kim, S.-Y., Moon, C. -H., Cho, H. -J., Lim, D. -I., 2009. Dinoflagellate cysts in coastal sediments as indicators of eutrophication: A case of Gwangyang Bay, South Sea of Korea. Est. Coasts. 32, 1225-33.

Kodrans-Nsiah, M., de Lange, G. J., Zonneveld, K. A. F., 2008. A natural exposure experiment on short-term species-selective aerobic degradation of dinoflagellate cysts. Rev. Palaeobot. Palynol. 152, 32-9.

Kremp, A., Heiskanen, A. S., 1999. Sexuality and cyst formation of the spring-bloom dinoflagellate *Scrippsiella hangoei* in the coastal northern Baltic Sea. Mar. Biol. 134, 771-7.

Krepakevich, A., Pospelova, V., 2010. Tracing the influence of sewage discharge on coastal bays of Southern Vancouver Island (BC, Canada) using sedimentary records of phytoplankton. Cont. Shelf Res. 30, 1924-40.

Langmann, B., Zaksek, K., Hort, M., Duggen, S., 2010. Volcanic ash as fertiliser for the surface ocean. Atmosph. Chem. Phys. 10, 3891-9.

Lee, C.M., Orlic, M., Poulain, P. M., Cushman-Roisin, B., 2007. Introduction to special section: Recent advances in oceanography and marine meteorology of the Adriatic Sea. J. Geophys. Res. Oceans. 112.

Leider, A. Hinrichs, K.-U. Mollenhauer, G., Versteegh, G. J. M., 2010. Core top calibration of the lipid-based $U^{K'}_{37}$ and TEX_{86} temperature proxies on the southern Italian shelf (SW Adriatic Sea, Gulf of Taranto). Earth Plan. Sci. Lett. 300, 112-124.

Lewis, J., Hallett, R., 1997. *Lingulodinium polyedrum* (*Gonyaulax polyedra*) a blooming dinoflagellate. Oceanogr. Mar. Biol. Ann. Rev. 35, 97-161.

Limoges, A., Kielt, J. F., Radi, T., Ruiz-Fernandez, A. C., de Vernal, A., 2010. Dinoflagellate cyst distribution in surface sediments along the south-western Mexican coast (14.76 degrees N to 24.75 degrees N). Mar. Micropal. 76, 104-23.

Marchetti, R., Provini, A., Crosa, G., 1989. Nutrient load carried by the river Po into the Adriatic Sea, 1968-87. Mar. Poll. Bull. 20, 168-72.

Marret, F., Zonneveld, K. A. F., 2003. Atlas of modern organic-walled dinoflagellate cyst distribution. Rev. Palaeobot. Palynol. 125, 1-200.

Maskell, L.C., Smart, S. M., Bullock, J. M., Thompson, K., Stevens, C. J., 2010. Nitrogen deposition causes widespread loss of species richness in British habitats. Glob. Change Biol. 16, 671-9.

Matsuoka, K., 1999. Eutrophication process recorded in dinoflagellate cyst assemblages - a case of Yokohama Port, Tokyo Bay, Japan. Sci. Tot. Env. 231, 17-35.

Matsuoka, K., 2001. Further evidence for a marine dinoflagellate cyst as an indicator of eutrophication in Yokohama Port, Tokyo Bay, Japan. Comments on a discussion by B. Dale. Sci. Tot. Env. 264, 221-33.

Matsuoka, K., Joyce, L. B., Kotani, Y., Matsuyama, Y., 2003. Modern dinoflagellate cysts in hypertrophic coastal waters of Tokyo Bay, Japan. J. Plankt. Res. 25, 1461-70.

Matsuoka, K., Kawami, H., Nagai, S., Iwataki, M., Takayama, H., 2009. Re-examination of cyst-motile relationships of *Polykrikos kofoidii* Chatton and *Polykrikos schwartzii* Bütschli (Gymnodiniales, Dinophyceae). Rev. Palaeobot. Palynol. 154, 79-90.

Milligan, T.G., Cattaneo, A., 2007. Sediment dynamics in the western Adriatic Sea: from transport to stratigraphy. Cont. Shelf Res. 27, 287-95.

Montresor, M., Zingone, A., Sarno, D., 1998. Dinoflagellate cyst production at a coastal Mediterranean site. J. Plankt. Res. 20, 2291-312.

Mozetic, P., Solidoro, C., Cossarini, G., Socal, G., Precali, R., France, J., Bianchi, F., De Vittor, C., Smodlaka, N., Umani, S., 2010. Recent Trends Towards Oligotrophication of the Northern Adriatic: Evidence from Chlorophyll a Time Series. Est. Coasts. 33, 362-75.

Orlic, M., 2009. "Recent Advances in Adriatic Oceanography and Marine Meteorology" Preface. Geofizika 26, 113-4.

Pasaric, Z., Belusic, D., Klaic, Z. B., 2007. Orographic influences on the Adriatic sirocco wind. Ann. Geoph. 25, 1263-7.

Pena-Manjarrez, J.L., Gaxiola-Castro, G., Helenes-Escamilla, J., 2009. Environmental factors influencing the variability of *Lingulodinium polyedrum*? and *Scrippsiella trochoidea* (Dinophyceae) cyst production. Cienc. Mar. 35, 1-14.

Persson, A., 2000. Possible predation of cysts - a gap in the knowledge of dinoflagellate ecology? J. Plankt. Res. 22, 803-9.

Pescosolido, G., 2010. The Sicilian economy in the Unification of Italy. Med- Rich. Stor., 217.

Pospelova, V., Chmura, G. L., Boothman, W. S., Latimer, J. S., 2002. Dinoflagellate cyst records human disturbance in two neighboring estuaries, New Bedford Harbor and Apponagansett Bay, Massachusetts (USA). Sci. Tot. Env. 298, 81-102.

Pospelova, V., Chmura, G. L., Boothman, W. S., Latimer, J. S., 2005. Spatial distribution of modern dinoflagellate cysts in polluted estuarine sediments from Buzzards Bay (Massachusetts, USA) embayments. Marine. Ecology. Progress. Series. 292, 23-40.

Pospelova, V., Chmura, G. L., Walker, H. A., 2004. Environmental factors influencing the spatial distribution of dinoflagellate cyst assemblages in shallow lagoons of southern New England (USA). Rev. Palaeobot. Palynol. 128, 7-34.

Pospelova, V., Kim, S. J., 2010. Dinoflagellate cysts in recent estuarine sediments from aquaculture sites of southern South Korea. Mar. Micropal. 76, 37-51.

Rabalais, N.N., Turner, R. E., Diaz, R. J., Justic, D., 2009. Global change and eutrophication of coastal waters. Ices J. Mar. Sci. 66, 1528-37.

Radi, T., de Vernal, A., 2008. Dinocysts as proxy of primary productivity in mid-high latitudes of the Northern Hemisphere. Mar. Micropal. 68, 84-114.

Radi, T., Pospelova, V., de Vernal, A., Barrie, J. V., 2007. Dinoflagellate cysts as indicators of water quality and productivity in British Columbia estuarine environments. Mar. Micropal. 62, 269-97.

Robbins, J.A., Edginton, D. N., Kemp, A. L. W., 1978. Comparative ^{210}Pb, ^{13}7Cs and pollen geochonologies of sediments from lakes Ontario and Erie. Quat. Res. 10, 256-78.

Rochon, A., Lewis, J., Ellegaard, M., Harding, I. C., 2009. The *Gonyaulax spinifera* (Dinophyceae) "complex": perpetuating the paradox? Rev. Palaeobot. Palynol. 155, 52-60.

Rubino, F., Belmonte, G., Miglietta, A. M., Geraci, S., Boero, F., 2000. Resting stages of plankton in recent North Adriatic sediments. Mar. Ecol. 21, 263-86.

Rubino, F., Saracino, O. D., Fanelli, G., Belmonte, G., Miglietta, A., Boero, F., 1998. Life cycles and pelagos-benthos interactions. Biol. Mar. Med. 5, 253-7.

Ruddiman, W.F. and Glover, L.K., 1972. Vertical mixing of ice-rafted volcanic ash in North Atlantic sediments. Geol. Soc. Am. Bull. 83, 2817-2836.

Saetre, M.M.L., Dale, B., Abdullah, M. I., Saetre, G. P., 1997. Dinoflagellate cysts as potential indicators of industrial pollution in a Norwegian Fjord. Mar. Env. Res. 44, 167-89.

Sangiorgi, F., Donders, T. H., 2004. Reconstructing 150 years of eutrophication in the north-western Adriatic Sea (Italy) using dinoflagellate cysts, pollen and spores. Est. Coast. Shelf Sci. 60, 69-79.

Sangiorgi, F., Fabbri, D., Comandini, M., Gabbianelli, G., Tagliavini, E., 2005. The distribution of sterols and organic-walled dinoflagellate cysts in surface sediments of the North-western Adriatic Sea (Italy). Est. Coast. Shelf Sci. 64, 395-406.

Sellschopp, J., Alvarez, A., 2003. Dense low-salinity outflow from the Adriatic Sea under mild (2001) and strong (1999) winter conditions. J. Geophys. Res. Oceans. 108.

Shin, H.H., Mizushima, K., Oh, S. J., Park, J. S., Noh, I. H., Iwataki, M., Matsuoka, K., Yoon, Y. H., 2010. Reconstruction of historical nutrient levels in Korean and Japanese coastal areas based on dinoflagellate cyst assemblages. Mar. Poll. Bull. 60, 1243 - 1258.

Smayda, T.J., Trainer, V. L., 2010. Dinoflagellate blooms in upwelling systems: Seeding, variability, and contrasts with diatom bloom behaviour. Prog. Oceanogr. 85, 92-107.

Solidoro, C., Bastianini, M., Bandelj, V., Codermatz, R., Cossarini, G., Canu, D. M., Ravagnan, E., Salon, S., Trevisani, S., 2009. Current state, scales of variability, and trends of biogeochemical properties in the northern Adriatic Sea. J. Geophys. Res. Oceans. 114, pp. 21

Stuut, J.B., Smalley, I., O'Hara-Dhand, K., 2009. Aeolian dust in Europe: African sources and European deposits. Quat. Int. 198, 234-45.

Susek, E., Zonneveld, K. A. F., Fischer, G., Versteegh, G. J. M., Willems, H., 2005. Organic-walled dinoflagellate cyst production in relation to upwelling intensity and lithogenic influx in the Cape Blanc region (off north-west Africa). Phycol. Res. 53, 97-112.

Syvitski, J.P.M., Kettner, A. J., 2007. On the flux of water and sediment into the Northern Adriatic Sea. Cont. Shelf. Res. 27, 296-308.

Taricco, C., Ghil, M., Alessio, S., Vivaldo, G., 2009. Two millennia of climate variability in the Central Mediterranean. Clim. Past. 5, 171-81.

Trauth, M.H., Sarnthein, M., Arnold, M., 1997. Bioturbational mixing depth and carbon flux to the seafloor. Paleoceanogr. 12, 517-26.

Tomadin, L. (2000) Sedimentary fluxes and different dispersion mechanisms of the clay sediments in the Adriatic Basin. Rendiconti Lincei. 11, 161-174.

Turekian, K.K., Cochran, J. K., DeMaster, D. J., 1978. Bioturbation in deep-sea deposits: rates and consequences. Oceanus. 21, 34-41.

Verleye, T.J., Louwye, S., 2010. Late Quaternary environmental changes and latitudinal shifts of the Antarctic Circumpolar Current as recorded by dinoflagellate cysts from offshore Chile (41°S). Quat. Sci. Rev. 29, 1025 - 1039.

Versteegh, G.J.M., de Leeuw, J. W., Taricco, C., Romero, A., 2007. Temperature and productivity influences on $U^{K'}_{37}$ and their possible relation to solar forcing of the Mediterranean winter. Geochem. Geophys. Geosys. 8, Q09005.

Vilanova, I., Guerstein, G. R., Akselman, R., Prieto, A. R., 2008. Mid- to Late Holocene organic-walled dinoflagellate cysts from the northern Argentine shelf. Rev. Palaeobot. Palynol. 152, 11-20.

de Wit, M., Bendoricchio, G., 2001. Nutrient fluxes in the Po basin. Sci. Tot. Env. 273, 147-61.

Zanchettin, D., Traverso, P., Tomasino, M., 2008. Po River discharges: a preliminary analysis of a 200-year time series. Clim. Change. 98, 411-33.

Zhang, J., Gilbert, D., Gooday, A. J., Levin, L., Naqvi, S. W. A., Middelburg, J. J., Scranton, M., Ekau, W., Pena, A., Dewitte, B., Oguz, T., Monteiro, P. M. S., Urban, E., Rabalais, N. N., Ittekkot, V., Kemp, W. M., Ulloa, O., Elmgren, R., Escobar-Briones, E., AK, V. D. P., 2010. Natural and human-induced hypoxia and consequences for coastal areas: synthesis and future development. Biogeosci. 7, 1443-67.

Zonneveld, K.A.F., Brummer, G. J. A., 2000. Ecological significance, transport and preservation of organic-walled dinoflagellate cysts in the Somali Basin, NW Arabian Sea. Deep-Sea. Res. II. 47, 2229-56.

Zonneveld, K.A.F., Chen, L., Möbius, J., Mahmoud, M. S., 2009. Environmental significance of dinoflagellate cysts from the proximal part of the Po River discharge plume (off southern Italy, Eastern Mediterranean). J. Sea. Res. 62, 189-213.

Zonneveld, K.A.F., Emeis, K. C., Holzwarth, U., Kniebel, N., Kuhnt, T., Möbius, J., Ní Fhlaithearta, S., Schmiedl, G., Versteegh, G., Welti, R., 2008. Report and preliminary results of R/V POSEIDON Cruise P339, Piräus - Messina, 16 June - 2 July 2006. CAPPUCCINO - Calabrian and Adriatic palaeoproductivity and climatic variability in the last two millennia. Ber. Fachber. Geowiss. Univ. Bremen. 268, 1-61.

Zonneveld, K.A.F., Susek, E., Fischer, G., 2010a. Seasonal variability of the organic-walled dinoflagellate cyst production in the coastal upwelling region off Cape Blanc (Mauritania): a five-year survey. J. Phycol. 46, 202-15.

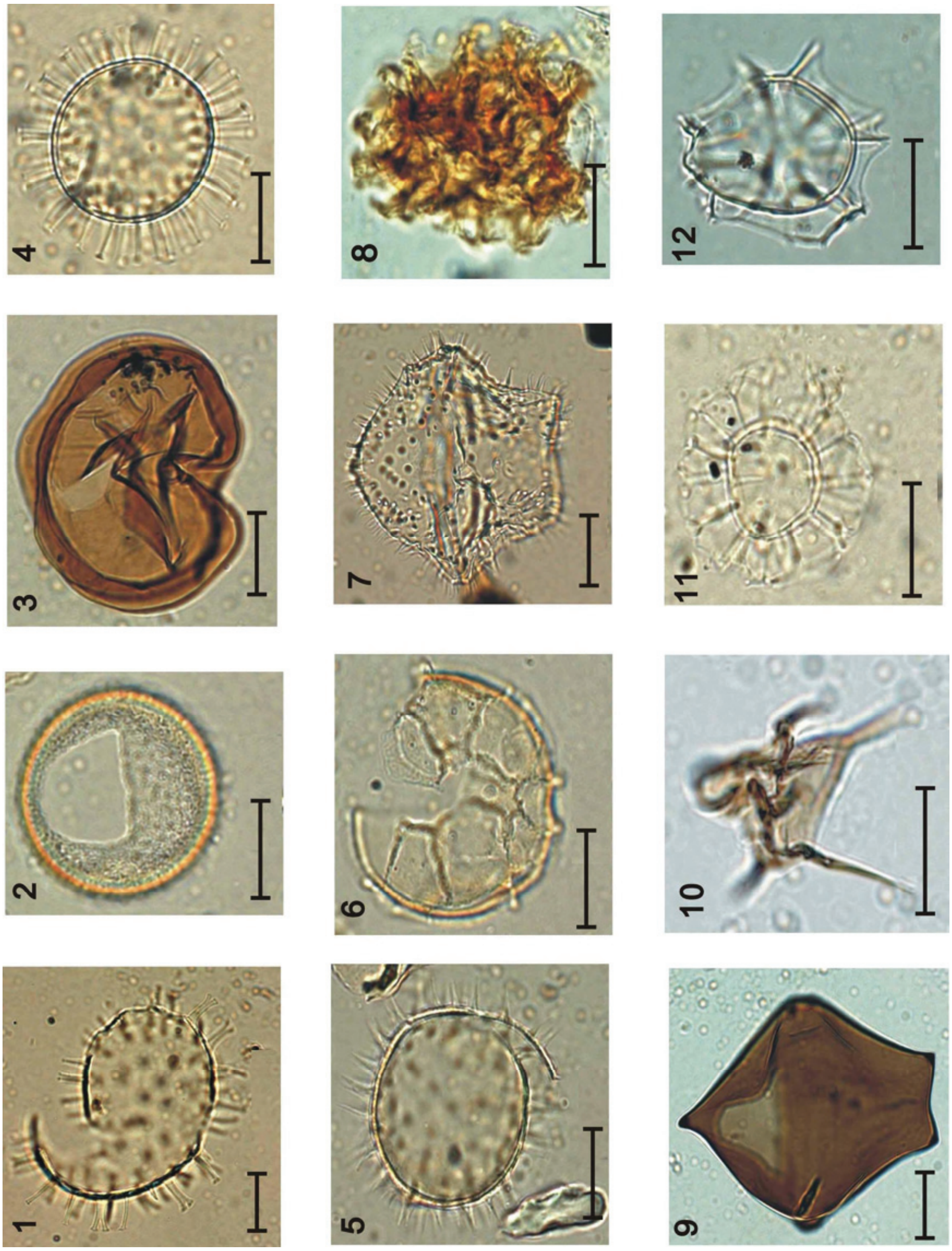
Zonneveld, K.A.F., Versteegh, G. J. M., de Lange, G. J., 1997. Preservation of organic walled dinoflagellate cysts in different oxygen regimes: a 10,000 years natural experiment. Mar. Micropal. 29, 393-405.

Zonneveld, K.A.F., Versteegh, G. J. M., de Lange, G. J., 2001. Palaeoproductivity and post-depositional aerobic organic matter decay reflected by dinoflagellate cyst assemblages of the Eastern Mediterranean S1 sapropel. Mar. Geol.. 172, 181-95.

Zonneveld, K.A.F., Versteegh, G. J. M., Kasten, S., Eglinton, T. I., Emeis, K. C., Huguet, C., Koch, B. P., de Lange, G. J., de Leeuw, J. W., Middelburg, J. J., Mollenhauer, G., Prahl, F. G., Rethemeyer, J., Wakeham, S. G., 2010b. Selective preservation of organic matter in marine sediments - processes and impact on the fossil record. Biogeosci. 7, 483-511.

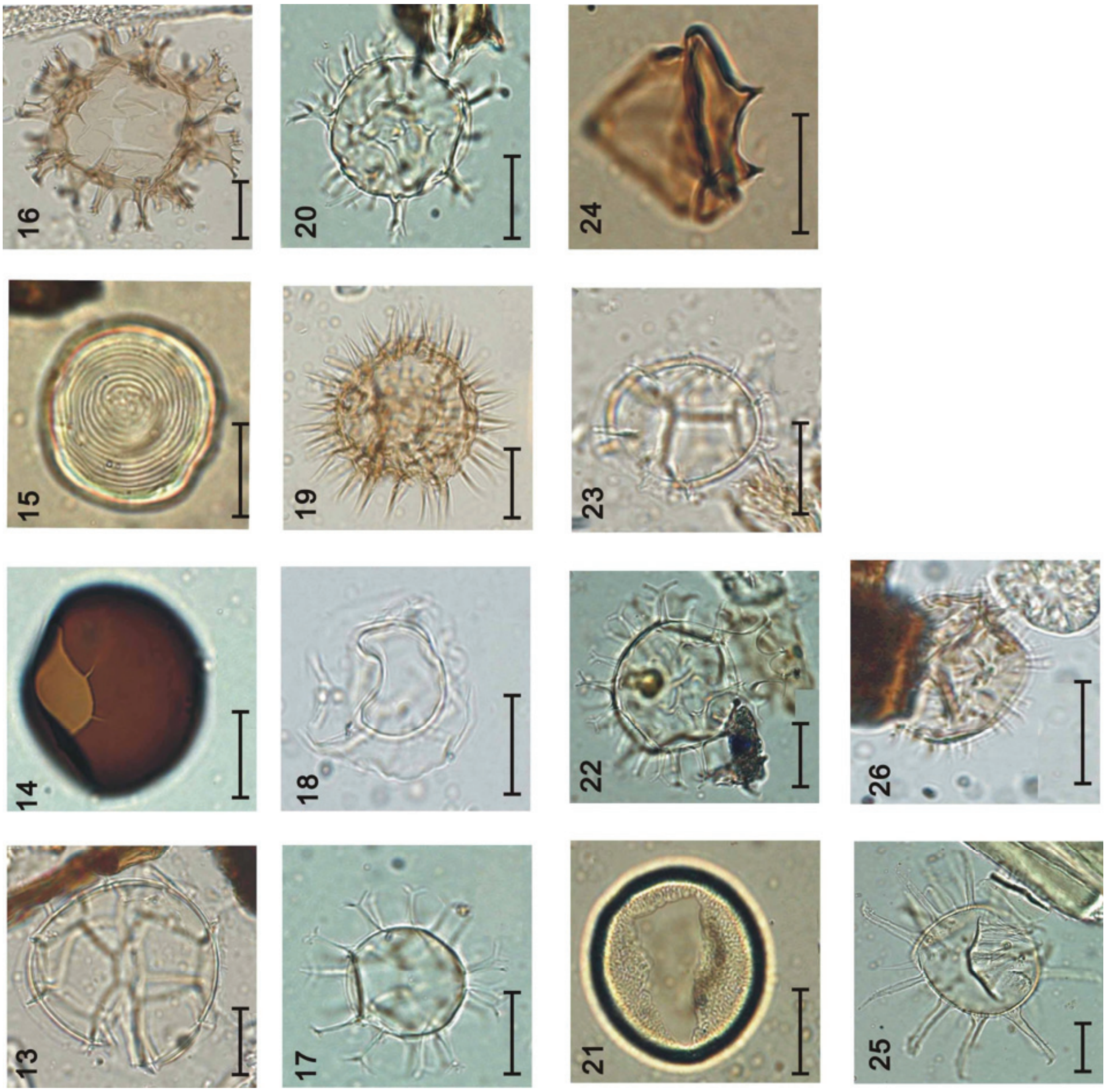
Zonneveld, K.A.F., Versteegh, G. J. M., Kodrans-Nsiah, M., 2008. Preservation and organic chemistry of Late Cenozoic organic-walled dinoflagellate cysts: A review. Mar. Micropal. 86, 179-97.

Appendix 2. Photo plate of main dinoflagellate species, scale bar represents 20 μm.



1. Polysphaeridium zoharyi 2. Tectatodinium pellitum 3. Selenopemphix nephroides 4. Operculodinium centrocarpum 5. Operculodinium israelianum 6. Impagidinium sphaericum 7. Trinovantedinium applanatum 8. Polykrikos kofoidii 9. QuinCuecuspis concreta 10. Stelladinium Stelladinium 11. Nematosphaeropsis labyrinthus 12. Impagidinium aculeatum

Continued



13. Impagidinium patulum 14. Brigantedinium spp 15. Fresh water species Concentricystes spp 16. Xandarodinium xanthum 17. Spiniferites ramosus 18. Ataxodinium choane 19. Selenopemphix quanta 20. Spiniferites spp 21. Bitectatodinium tepikiense 22. Spiniferites mirabilis 23. Impagidinium paradoxum 24. Leipokatium invisitatum 25. Lingulodinium machaerophorum 26. Echinidinium spp