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Multiproxy approach for the reconstruction of the glacial ocean surface (MARGO)

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The oceans and the atmosphere are the two main reservoirs of greenhouse gases and latent heat on Earth. These reservoirs interact through the ocean surface, and the dynamics of this interaction is a major determinant of global climate. Accurate reconstructions of the physical state of the global ocean are therefore critical to the understanding of past climate changes. This is in turn required to assess the significance of instrumentally observed climate variability, and for the forcing and validation of global circulation models, which are used to predict future climate change.

Systematic instrumental measurements of sea surface properties exist for only a few decades, with the longest regional records rarely extending beyond the 19th century. Yet, it is only with the aid of climate records spanning thousands of years and encompassing dramatically different climatic states of the planet that one can truly understand the dynamics of the ocean–atmosphere interface and perform meaningful and useful tests of global climate models. Information on the state of the planet in the past, and the amplitude, frequency and mechanisms of its changes is of paramount importance to our society, as it is used to inform and guide long-term environmental policies and planning and to predict impact of climate change on land, our habitat.

Any effort to provide past climate records of sufficient extent and time range will have to resort to the use of indirect information: proxies based on biological, chemical and physical signals preserved in ancient geological materials. In open-ocean settings, the organic

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and mineral remains of marine microplankton in deep-sea sediments provide the most comprehensive source of such proxies (Mix et al., 2001; Henderson, 2002). Unfortunately, it is scientifically and technically not possible at present to aim to reconstruct a continuous record in space and time of past climate variation. Instead, a discrete and distinct time interval is needed to focus research efforts of the scientific community. To be useful for validation of climate models, this time interval ought to represent a period of climate markedly different from that of today, yet not too distant from the present so that the basic assumptions and parameters of the climate models need not be modified.

With respect to past ocean surface conditions, particularly since the pioneering effort of the CLIMAP group (climate long-range investigation, mapping, and prediction; CLIMAP, 1976, 1981) which started 30 years ago, the time of the last glacial maximum (LGM) has served as common target for climate modelling experiments and palaeoenvironmental proxy reconstructions. The LGM interval, around 21,000 years ago, represents the nearest of a series of past climatic extremes characterising the waxing and waning of Quaternary ice ages and as such serves as an excellent testing ground for assessment of sensitivity of the Earth's climatic system. Since the CLIMAP project conclusions were published, a large amount of new sediment material has been recovered, its age determined using ever-improving dating techniques, and its palaeoclimatic significance assessed with an ever-expanding battery of proxies. Yet, a global synthesis of this material is still lacking. In 1999, an international initiative was launched by the scientific community, with the aim to facilitate a new synthesis of the last ice age Earth's surface. The environmental processes of the ice age: land, ocean, glaciers (EPILOG) initiative commenced by the IMAGES-PAGES program (the international marine past global changes study-past global changes; core project of the international geosphere-biosphere programme) provided an updated review of the progress in palaeoclimatic reconstructions since CLIMAP. It summarised the salient points and obstacles in the way of a new synthesis, and set a series of benchmarks to allow a precise definition of the LGM chronozone (Mix et al., 2001).

Following EPILOG, and with the above advancements in mind, the MARGO working group was launched in September 2002, when 33 scientists from 13 countries met at the Hanse Institute for Advanced Studies in Delmenhorst, Germany, to initiate the "multiproxy approach for the reconstruction of the glacial ocean surface" (MARGO). MARGO acts as an open international project involving data gathering, sharing and harmonisation, with the aim of producing a new synthesis of sea-surface temperature (SST) and sea-ice extent of the glacial ocean. The overall MARGO objective is to collate and harmonise all the available proxy data and transfer function techniques, and place them into a common framework for a multi-proxy global glacial ocean reconstruction. However, prior to this global synthesis, huge efforts have been put by the MARGO working group members into the assembly of new regional or proxy-specific SST reconstructions which are reported in this volume or in recently published studies, like the GLAMAP reconstruction (Sarnthein et al., 2003; and references therein) and the TEMPUS compilation (Rosell-Melé et al., 1998, 2004). The contributions presented in this issue form the first phase of MARGO: (i) compilation of quality-assessed and harmonised proxy-specific calibration datasets and LGM reconstructions, (ii) documentation of individual proxies and techniques and (iii) an outline of possible methods of the presentation of the final synthesis.

A selection of 8 papers out of 13 herein provides a series of compilations for different SST proxies (Fig. 1), including Mg/Ca ratios of planktonic foraminifera (Barker et al., 2005; Meland et al., 2005) and various transfer function approaches based on census counts of assemblages of planktonic foraminifera (Barrows and Juggins, 2005; Chen et al., 2005; Hayes et al., 2005; Kucera et al., 2005), diatoms and radiolaria (Gersonde et al., 2005) as well as dinoflagellate cysts (de Vernal et al. 2005). Moreover, a new Holocene oxygen isotope data synthesis based on planktonic foraminifera is presented (Waelbroeck et al., 2005) and a stimulating contribution by Morey et al. (2005) discusses the distribution of planktonic foraminifer assemblages in surface sediments as a function of multiple environmental variables rather than exclusively related to SST. The series of papers addressing glacial surface ocean conditions is followed by a study describing the termination of the last glacial period in the Pacific (Kiefer and Kienast, 2005) and this MARGO special issue ends with two contributions dealing with the issues of mapping techniques for sparsely and non-homogeneously distributed proxy data (Schäfer-Neth et al., 2005) as well as their comparison with results from climate model experiments (Paul and Schäfer-Neth, 2005).

This preface briefly summarises the recommendations and common standards agreed at two MARGO workshops which form the innovative guidelines for the new compilations presented herein, and which will serve as the internationally agreed base for the overall multi-proxy synthesis of the last glacial SST reconstruction. For further information on the MARGO guidelines, their application to the new compilations and the individual data sets the reader is referred to the MARGO website (http://www.pangaea.de/projects/MARGO) and to the individual articles in this volume. These guidelines evolved from the major aims of MARGO, as formulated at the first meeting in 2002.

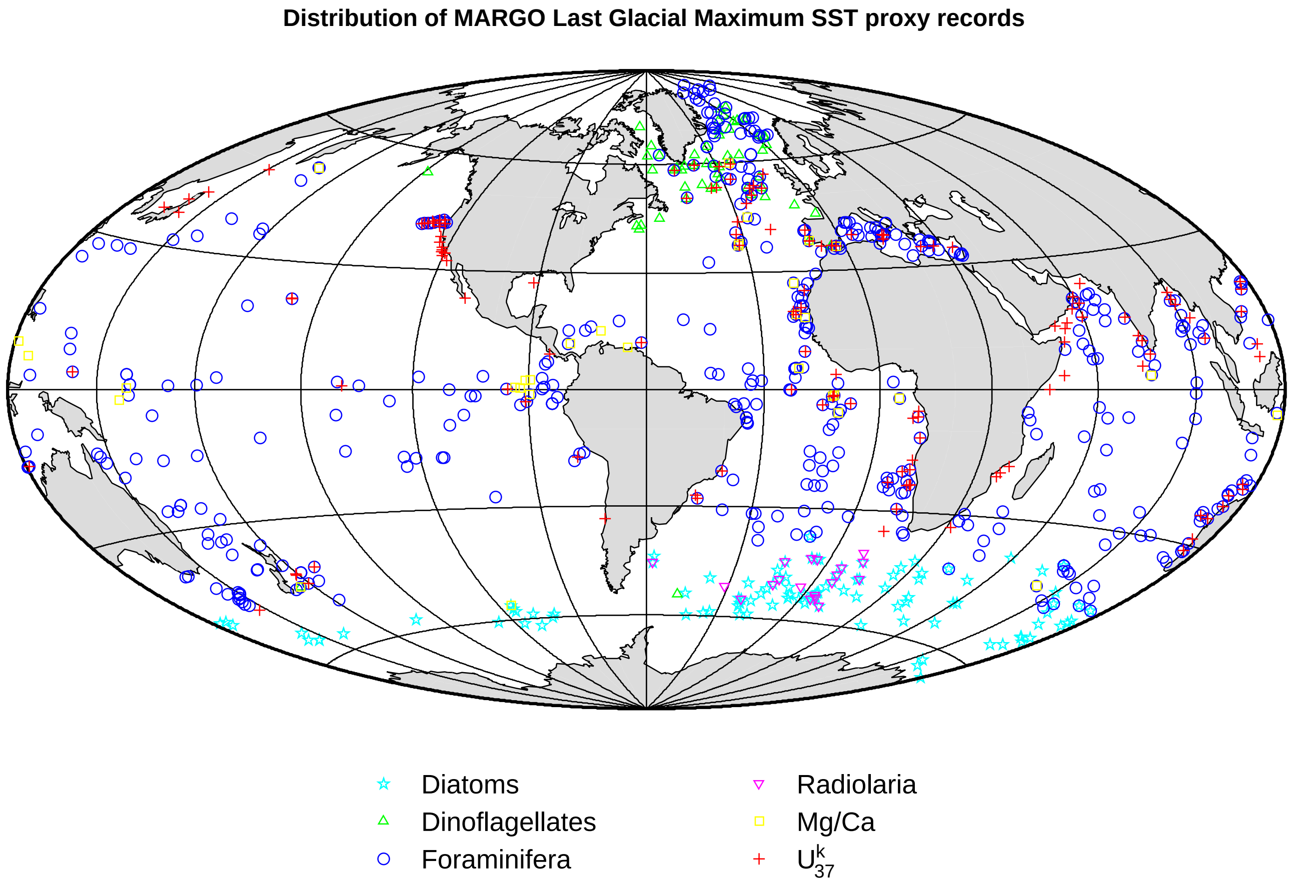

Fig. 1. The location of proxy records of LGM SST included in the MARGO reconstructions. The alkenone data are from Rosell-Melé et al. (2004). All other proxy data are presented in this volume.

- Compilation of new calibration datasets using consistent criteria for sample quality, and assignment and definition of modern SST values to each calibration sample.
- Compilation of new LGM SST reconstructions for each proxy, based on the new calibrations, providing age quality assessment for each sample using harmonised criteria.
- Assessment of the feasibility of a single, multi-proxy, LGM SST reconstruction.

In parallel, the oxygen isotopic composition of planktonic foraminifera has been included among the MARGO target proxies of glacial surface ocean conditions. Although one cannot use oxygen isotope data alone to deduce palaeotemperatures, compiling a new dataset for this proxy has numerous advantages

- Combining planktonic oxygen isotope values with independent SST estimates makes it possible to derive the isotopic composition of surface water, which is related to surface salinity and thus yields information on the hydrological cycle (e.g., Duplessy et al., 1991; Lea et al., 2000);
- Oxygen isotopes give a first approximation of the surface density of the ocean as the oxygen isotopic composition of planktonic foraminifera is a function of salinity and temperature;
- An increasing number of ocean circulation numerical models compute the isotopic composition of calcite explicitly (e.g., Paul et al., 1999), and these models can be directly validated by comparison of their output with foraminifer isotopic composition;
- Finally, a large amount of oxygen isotope data is currently available on planktonic foraminifera from recent and glacial sediments (e.g., Duplessy et al., 1981, 1991; Billups and Schrag, 2000; Schmidt and Mulitza, 2002), which provides a unique opportunity to test the consistency of the regional SST estimates based on different methods and proxies.

The MARGO oxygen isotope dataset now consists of over 2100 measurements from recent sediments (Waelbroeck et al., 2005) and 410 data points from LGM sediments with thorough age control that have been checked for internal consistency. The LGM dataset will be analysed in conjunction with the envisaged revised global LGM SST compilation.

According to the MARGO recommendations, seasonal SST reconstructions as well as annual temperatures are provided wherever possible. This is the case with all transfer function techniques using planktonic foraminifera, dinoflagellate cysts, radiolarian and diatom assemblages, while the geochemical SST reconstructions provide annual mean estimates (alkenones) or summer SST (Mg/Ca). To cater for a proper comparison of single proxy reconstructions we agreed on common use of World Ocean Atlas version 2 (WOA, 1998; 1° grid version) as modern reference and calibration data. The WOA98 dataset has benefited from error reduction as compared to previous versions while no significant new data were included. Seasonal and/or annual temperatures for the sample sites were extracted for 10 m water depth using a common data extraction tool (http://www.palmod.uni-bremen.de/~csn/woasample.html).
For seasonal temperatures three-month averages of January–March (northern winter) and July–September (northern summer), and 12-months average for annual SST are used. Temperature at sample sites is computed as the area-weighted average of the four WOA temperature points surrounding the sample location; WOA data points marked as land were omitted from the averaging.

Sea-ice extent is one of the most elusive properties of the ocean in terms of the prospect of its accurate reconstruction from geological records, yet it is a crucial parameter of climate models and its knowledge is essential for assessment of the different oceanographic mechanisms that could be at play in a given region. The MARGO group has, therefore, recommended this variable should be reconstructed as far as is possible and encourage further research in this field. In this issue, Gersonde et al. (2005) present an updated reconstruction of patterns of summer and winter sea-ice extent in the Southern Ocean reconstructed from the distribution patterns of diatom sea-ice indicator species. In the Northern Hemisphere, deVernal et al. (2005) and Kucera et al. (2005) produced updated estimates of glacial sea-ice extent in the Nordic Seas based on dinocyst and planktonic foraminifer assemblages; both indicated ice-free summers in the Norwegian Sea.

MARGO adopted the same definition of the LGM interval or chronozone as in Mix et al. (2001): 19–23 cal kyr BP (ka). The definitions of the levels of certainty are identical as well:

- *LGM Chronozone Level 1*: Chronologic control based either on annually counted layers extending through the LGM chronozone, or two radiometric dates within the interval, such as U/Th dates or reservoir-corrected 14 C-yr dates adjusted to the calendar scale using the CALIB software (Stuiver et al., 1998).
- *LGM Chronozone Level 2*: Chronologic control based on two bracketing radiometric dates of any kind within the interval 12–30 ka (i.e., within marine oxygen-isotope stage 2), or by correlation of non-radiometric data to similar regional records that have been dated to match the level 1 protocol (for example, $\delta^{18}O$ stratigraphy).
- *LGM Chronozone Level 3*: Chronologic control based on other stratigraphic constraints (for example, a regional lithologic index such as %$CaCO_3$) that are correlated to similar records dated elsewhere to match the level 2 protocol.

In addition, it was recommended to label samples with no stratigraphic control as level 4.

For the purpose of improved calibration of transfer functions and calibration equations used in MARGO with respect to WOA98, the MARGO working group also attempted to better constrain the quality of "modern" or "core-top" samples. Therefore, the Late Holocene chronozone was defined in a similar way: 0–4 cal kyr BP, with the following levels of certainty:

- *LH Chronozone Level 1, 0–2 ka*: Chronologic control based either on annually counted layers covering the last 2 ky, or one radiometric date (such as U/Th dates or reservoir-corrected 14 C-yr dates converted into calendar age) within the interval 0–2 ka.
- *LH Chronozone Level 2, 0–4 ka*: Chronologic control based on one radiometric date of any kind within the interval 0–4 ka, or stained benthic foraminifera with sedimentation rate higher than 5 cm/ky.
- *LH Chronozone Level 3, 0–4 ka*: Chronologic control based on one radiometric date of any kind within the interval 4–8 ka or specific stratigraphic control (for e.g., % *G. hirsuta* left coiling) indicating that the sample belongs to the interval 0–4 ka.
- *LH Chronozone Level 4, 0–4 ka*: Chronologic control based on other stratigraphic constraints (for e.g., $\delta^{18}O$ stratigraphy, or a regional lithologic index such as %$CaCO_3$) indicating that the sample belongs to the interval 0–4 ka.

In addition, it was recommended to label samples with no stratigraphic control as Level 5, and to report the 0–4 ka and 0–2 ka intervals separately when Level 1 is achieved.

Table 1
Conversion of MARGO/EPILOG Holocene and LGM Chronozone boundary ages using the INTCAL98 calibration curve from Stuiver et al. (1998)

Calendar age	Reservoir age–corrected ^{14}C age
2 ka ± 0.1 kyr	2.05 ^{14}C kyr BP ± 0.1 kyr
4 ka ± 0.1 kyr	3.6 ^{14}C kyr BP ± 0.1 kyr
19 ka ± 0.1 kyr	15.9 ^{14}C kyr BP ± 0.35 kyr
23 ka ± 0.1 kyr	19.4 ^{14}C kyr BP ± 0.4 kyr

The definition of the Holocene and LGM Chronozone intervals in terms of reservoir age-corrected ^{14}C ages is shown in Table 1. In high latitudes (beyond 40°N and 40°S), reservoir ages significantly increase during the LGM with respect to modern values (Sikes et al., 2000; Waelbroeck et al., 2001). As the LGM reservoir age is generally not well defined, this induces very large uncertainties on calendar dates derived from radiocarbon dates. The reliability of the radiocarbon dates from LGM high-latitude samples is thus lower than that for dates derived from low- or mid-latitudes samples.

Given the perspective for a single multi-proxy reconstruction for the glacial surface ocean conditions which should be the final product of MARGO and considering the individual proxy compilations presented in this volume, we would like to end this preface with some general thoughts addressing the challenge that the compilation of a unique multi-proxy SST/SSS/sea-ice data set or map presents, and on the possible strategies to do so. Given the current array of proxies available to reconstruct SST it might appear that the reconstruction of these parameters could be achieved with more certainty than ever before. This would have been the case if coinciding SST estimates were obtained by all proxies, but unfortunately this is not what always happens. There are only a few comprehensive studies on the comparison of different proxy SST estimates. One of these is the study carried out by Bard (2001). One of its chief conclusions is that overall SST proxies agree on the amplitude of changes at low and mid-latitudes. However, a level of disagreement between proxies must be expected because each approach reflects different past environmental conditions. The estimates depend on the ecology and biology of each source organism as well as the statistical approaches used to calibrate the proxy. The uncertainties are intrinsic to each approach, as each calibration is empirically derived, based on data sets of different size and with contrasting spatial coverage. The sedimentary data is usually calibrated against "modern conditions" but there is an incomplete knowledge of the ecology and biology of the source organisms and incomplete information on oceanographic conditions to derive "modern SST" as registered in the sediments. A proxy measured in a sediment sample also represents an integrated signal over time and space of the sedimentation of the chemical or microfossil parameters on which the approach is based. This will also be different for each proxy given that the remains of each source organism will sediment differently as a function of density and size of particles, among other factors.

In addition, the environmental information inferred from each approach may relate to more than one climatic parameter. This may be a general property of the proxy, as in the case of $\delta^{18}O$ in calcareous tests of foraminifera, or occurring just in specific circumstances, which means that certain approaches are geographically constrained. For instance, $U^{K}_{37'}$ is not reliable in low-salinity environments, foraminiferal transfer functions are questioned in upwelling regions, diatom and radiolarian-based approaches are vulnerable in areas where sediments are undersaturated in silica, dinoflagellate cysts are not found at present in many open ocean environments where they were common in the last glacial.

Each approach also has key uncertainties that must be resolved to clarify the meaning of the temperature estimates inferred in each case. In the case of the alkenones this possibly relates to the depth and time of production of the signal, and the role of sedimentary processes in laterally mixing the alkenone inputs. In the case of the use of microfossils abundances the Achilles heel is in the understanding of the ecology of each fossil group, its precise relationship to the desired environmental parameter and the validity of this relationship in space and through time. For the Mg/Ca measurement in planktonic foraminifera the key pending issue is probably on the development of worldwide valid calibration, the role of vital effects in the calibration, and the imprint of calcite dissolution in the deep ocean. Finally, for $\delta^{18}O$ in calcareous tests the challenge is to establish in each studied region the relative importance of the environmental factors that influence the isotopic signature. In conclusion, all proxy approaches provide slightly or substantially different SST estimations, and the meaning of what is "sea surface" and "temperature", and for which season in each case, is still a matter of debate.

The compilation of global SST reconstruction maps which summarise the information from all approaches available may thus appear too much of a daunting challenge at present. It is a key issue to decide if any single approach should be given more credibility than others. But given that all proxies are fraught with uncertainties taking this a priori assumption on a general basis seems unjustified. A multi-proxy compilation of SST for the same depth and season is also impossible to obtain at present. Maps like those produced by CLIMAP are only feasible on a single-proxy basis. Once accepted that no single proxy is "right" and "right everywhere", the joint interpretation of multiple maps to infer SST during the last glacial is not trivial. We cannot provide the solution here, but in our effort to advance in updating CLIMAP reconstructions, it may be useful to think about the purpose of generating the compilations and who will be the end-users of such products. Given the current shortage of resources it may be more efficient to focus efforts on some strategies rather than others to achieve short-term progress whilst maintaining long-term goals in sight. Rather than waiting for years to provide a consensus multi-proxy map of SST for the LGM, some intermediate products could be assembled that still represent a genuine advance in our understanding of the LGM climate, and be of use to the community. For instance, why is it necessary, in contrast to being desirable, to provide a single multi-proxy SST map? If multi-proxy maps of SST cannot be derived, what could still be useful to advance our understanding of climate change? If multiple maps are provided for different approaches, how may they be interpreted by different users?

The second challenge in such an interdisciplinary research field is the flow of information between different communities, such as data producers and users like climate modellers. It is our perception that issues that may be taken for granted among some groups may be ignored by others even if the general field of work is the same, in our case climate research. Few individuals work in the transition between disciplines and the flow and processing of information between research areas is not always smooth and unbiased by each individual's perception. We decided to find out as objectively as possible, as far as we were able to, the perception and opinion on some of the issues outlined above by constructing a questionnaire directed to climate modellers. Its aim was to dispel some doubts on how the palaeo-maps were perceived, their possible uses, and obtain suggestions on how to provide useful mapping outputs that would represent an improvement on the state of the art and be valuable to other users than those in the MARGO project. Of course, we all knew, or thought we knew, the answers to some issues, but the answers were not always the same and were based on our restricted circle of contacts. The questionnaire was publicised among the palaeoclimate modelling community and was returned by North American, European and Japanese modellers from 11 groups, which represent more than half of the participants in the Palaeoclimate Modelling Intercomparison Project (http://www-lsce.cea.fr/pmip2/). These groups are engaged in almost all cases in 3D general circulation modelling, and although those that provided a reply identified themselves, it was our commitment to maintain the anonymity of the participants. A summary and discussion of the results of the exercise are shown on the MARGO web site (http://www.pangaea.de/projects/MARGO). Perhaps, the key (and not unexpected) message that one can draw from the questionnaire replies is that palaeomaps will be more useful to modellers, the simpler they are in their graphical representations and the better explained the proxy approaches are. The former means that fancy coloured maps are good for wall displays and as teaching aids, but that raw and gridded data are more useful for science. The latter means that the better described the constraints in the interpretation of the proxies, and the advantages and shortcomings of each approach, are the better use will be made of the data by those that need them.

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