Overview of Glacial Atlantic Ocean Mapping (GLAMAP 2000)

M. Sarnthein,[1] R. Gersonde,[2] S. Niebler,[3] U. Pflaumann,[1] R. Spielhagen,[4]
J. Thiede,[2,4] G. Wefer,[3] and M. Weinelt[1]

[1]   GLAMAP 2000 presents new reconstructions of the Atlantic's sea surface temperatures (SST) at the Last Glacial Maximum (LGM), defined at both 21,500–18,000 years B.P. ("Last Isotope Maximum") and 23,000–19,000 years B.P. (maximum glacial sea level low stand and orbital minimum of solar insolation; EPILOG working group; see *Mix et al.* [2001]). These reconstructions use 275 sediment cores between the North Pole and 60°S with carefully defined chronostratigraphies. Four categories of core quality are distinguished. More than 100 core sections provide a glacial record with subcentennial- to multicentennial-scale resolution. SST estimates are based on a new set of almost 1000 reference samples of modern planktic foraminifera and on improved transfer-function techniques to deduce SST from census counts of microfossils, including radiolarians and diatoms. New proxies also serve to deduce sea ice boundaries. The GLAMAP 2000 SST patterns differ significantly in crucial regions from the *CLIMAP* [1981] reconstruction and thus are important in providing updated boundary conditions to initiate and validate computational models for climate prediction.   *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 5415 Planetology: Solid Surface Planets: Erosion and weathering; *KEYWORDS:* Last Glacial Maximum, sea surface temperature reconstruction, paleoceanography, time slice definition, accuracy of age control

1. Introduction

[2]   The broad meridional and narrow zonal extension of the Atlantic from high southern to high northern latitudes is a major factor in forcing the thermohaline circulation (THC) of the global ocean (model of *Toggweiler and Samuel* [1998]) and the climate system of the adjacent continents. The specific configuration of the Atlantic margins results in a strong advection of warm surface water into northern high latitudes. The cooling of this surface water which is more saline than anywhere else in high-latitude oceans triggers extensive deep water formation in the Nordic Seas, and thus drives the onset of global deep water circulation and drives the cross-equatorial heat transfer today characteristic of the Atlantic [*Schmitz*, 1995]. Different from the North Atlantic, the modern South Atlantic is characterized by the lateral incursion of surface currents, in the southeast by the advection of warm surface water from the Indian Ocean via a seasonal extension of the Agulhas Current, and in the southwest by the incursion of the cold Antarctic Circumpolar Current (overview of *Berger and Wefer* [1996]).

[3]   Sea surface temperatures (SST) of the Last Glacial Maximum (LGM) reflect the most recent scenario of full glaciation in the Pleistocene [*Teller*, 1987; *Svendsen et al.*, 1999]. Accordingly, the LGM is considered a well defined climatic end-member of Quaternary global change, contrasting with the present conditions characterized by Northern Hemisphere ice sheets of only limited extent. LGM objectives of particular interest are to assess (1) high-latitude variations in sea ice cover, (2) the intensity of past deep water formation in the northern North Atlantic, (3) the amount and seasonality of cross-equatorial heat advection from the central and southern Atlantic into the Nordic Seas, and (4) the corresponding extent of the West Atlantic heat pool. Additional objectives include an evaluation of (5) the resulting directions and strength of major wind systems and of both equatorial and coastal upwelling, and (6) the structure and location of oceanic frontal systems of the Antarctic Circumpolar Current (ACC), and its relation to (7) the reduction and/or cessation of the Indian-Atlantic warm water path through the Agulhas current.

[4]   In a pioneer approach, Climate Long-Range Investigation, Mapping, and Prediction (CLIMAP) presented for the first time distribution maps of seasonal SST of the LGM North Atlantic [*McIntyre et al.*, 1976] and global ocean at "18 ^{14}C ka" [*CLIMAP Project Members*, 1976, 1981]. The glacial SST estimates were based on census data of various microfossil assemblages from deep sea sediment cores, census data that were calibrated to the SST of modern surface water via a set of transfer functions based on principle component analysis and a multiple regression approach, the Imbrie-Kipp technique (I-K technique) [*Imbrie and Kipp*, 1971; *Kipp*, 1976]. Over the last 20 years the CLIMAP-LGM temperature maps have provided the only consistent array of global boundary conditions different from today. They have formed a unique data set for initiating numerical ocean models which simulate past

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[1]Institut für Geowissenschaften, University of Kiel, Kiel, Germany.
[2]Alfred Wegener Institut, Bremerhaven, Germany.
[3]Fachbereich Geowissenschaften, University of Bremen, Germany.
[4]Geomar Kiel, Kiel, Germany.

climates, and vice versa, for testing the output of coupled General Circulation Models (O-GCMs) with the potential of predicting future climate change.

[5] According to *CLIMAP* [1981], the glacial-to-intergla-cial SST anomalies barely exceed -2 (± 1.5)°C in the tropics. In equatorial upwelling regions they may have reached just in excess of -4°C. However, these low CLIMAP SST anomalies may be biased. They do not fit the various land-based paleotemperature data deduced from strongly lowered snow lines [*Bowler et al.*, 1976] and major vegetation changes in the tropics [*Frenzel et al.*, 1992; *Rind and Peteet*, 1985], as summarized by *Anderson and Webb* [1994]. Moreover, West Atlantic SST records deduced from Sr/Ca and δ^{18}O ratios in corals off Barbados [*Guilderson et al.*, 1994] (though recently debated by *Martin et al.* [1999]) reveal LGM SST anomalies of -5 (± 0.5)°C, which are much higher than those found for this region by *CLIMAP* [1981]. Likewise, a recent transfer-function approach using a CABFAC matrix of Pleistocene foraminiferal assemblages in ten core-top samples for SST calibration has resulted in tropical glacial temperatures which are lowered by up to 6°C in the "tongue" of the westward flowing equatorial current [*Mix et al.*, 1999]. Accordingly, to help resolve this long-standing controversy about glacial tropical SSTs, a thorough revision of the transfer-function techniques using a truly broad matrix of modern core-top samples is required to reconstruct microfossil-based SSTs with a generally agreeable degree of reliability.

[6] A further controversy concerns the CLIMAP recon-struction of the Greenland-Icelandic-Norwegian Seas. Here *CLIMAP* [1981] proposed extremely low glacial SST and an annually persistent sea-ice coverage. However, this scenario is opposed to recent microfossil and stable isotope records which indicate at least seasonally ice-free conditions during the LGM [*Hebbeln et al.*, 1994; *Sarnthein et al.*, 1995; *Weinelt et al.*, 1996].

[7] The German Glacial Atlantic Ocean Mapping (GLA-MAP 2000) Project presents a collection of papers [*Weinelt et al.*, 2003; *Pflaumann et al.*, 2003; *Nørgaard-Pedersen et al.*, 2003; *Niebler et al.*, 2003; *Gersonde et al.*, 2003; *Sarnthein et al.*, 2003] that display various sets of new and rigorously revised seasonal SST estimates and other proxy data of sea surface conditions during the LGM. The proxy data are estimated from an array of 275 densely sampled, well preserved, and well dated marine sediment records from Atlantic sites between 60°S and 85°N (Figure 1) [cf. *Vogelsang et al.*, 2001]. This close-meshed grid of sampling sites is sufficient to resolve past mesoscale structures in the surface ocean. Our reconstruction serves the purpose of constraining more precisely the actual range of glacial-to-interglacial SST and circulation changes in the entire Atlantic, and may help to reconcile the apparent discrepancies amongst tropical temperature records obtained from the sea surface and the adjacent continents,

such as discussed by *Mix et al.* [1999]. Most importantly, the GLAMAP 2000 data set provides up-to-date boundary conditions and validation data for 3-D global circulation and climate models, first employed in the experiments of *Grieger and Niebler* [2003] and *Paul and Schäfer-Neth* [2003].

[8] As compared to *CLIMAP* [1981], our approach is based (1) on a more precise age definition and age control of the LGM time slice($-$s), (2) on various new transfer techniques to deduce SST from microfossil census counts such as the Modern Analog Technique (MAT) (*Hutson* [1977]; similarity maximum-modern analog technique (SIMMAX-MAT); *Pflaumann et al.* [1996]), in addition to the I-K technique using log-transfer techniques [*Zielinski et al.*, 1998] and improved statistical computer programs [*Sieger et al.*, 1999], and (3) a more precise calibration of the microfaunal census data to modern SST at 10 m water depth from the "objectively analyzed" hydrographic data set of *Levitus and Boyer* [1994] of the entire Atlantic.

2. Choice of the LGM Time Slice and Age Control

[9] To permit isochronous sampling of the LGM Atlantic, the GLAMAP 2000 working group agreed (in May 1997) on using a joint definition of the LGM time slice, within which all SST estimates at each single site are averaged (without weighting). A first definition of the LGM chro-nozone is based on the "Last benthic oxygen Isotope Maximum" (LIM; N. J. Shackleton, second EPILOG con-ference, October 2000) in the Atlantic ocean and on maximum planktic δ^{18}O values in the northern North Atlantic, assuming that these maxima correspond to a maximum volume of global ice sheets. In North Atlantic sediment records with decadal-to-centennial resolution [*Sarnthein et al.*, 1995; *Voelker*, 1999; *Mix et al.*, 1999; *Weinelt et al.*, 2003], the LIM interval defined in this way shows almost stable δ^{18}O values from $\sim$18 to 15 ^{14}C ka (corrected for 400 years ^{14}C reservoir effect; or until 14.5 ^{14}C ka; N. J. Shackleton, personal communication, 2000), equal to $\sim$21,500 to 18,000 calendar (cal) years B.P. or somewhat younger [*Stuiver et al.*, 1998]. The LIM or GLAMAP 2000 time slice ends with the onset of the Heinrich-1 stadial event.

[10] In the western equatorial and South Atlantic, how-ever, several sediment records pose an irreconcilable prob-lem to this LGM definition. They instead show an earlier shift toward lighter planktic δ^{18}O values during the LIM time slice in parallel with a lead in deglacial warming from 18 to 15 ^{14}C ka [*Ruehlemann et al.*, 1999; *Gersonde et al.*, 2003], thus documenting an interhemispheric contrast of climate trends during the late LGM.

[11] The international EPILOG working group produced a second, slightly older definition of the LGM chronozone

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Figure 1. (opposite) Map of GLAMAP 2000 authors' areas of responsibility for stratigraphic and microfossil-based SST data (full dots): GEOMAR = *Nørgaard-Pedersen et al.* [2003] (open dots show cores with planktic δ^{18}O records only); IfG = *Pflaumann et al.* [2003]; GeoB = *Niebler et al.* [2003] (open dots show supplementary data of *Mix* [1986]); AWI = *Gersonde et al.* [2003] (SST records deduced from siliceous microfossils are marked by asterisks). Thermal equator is hatched.
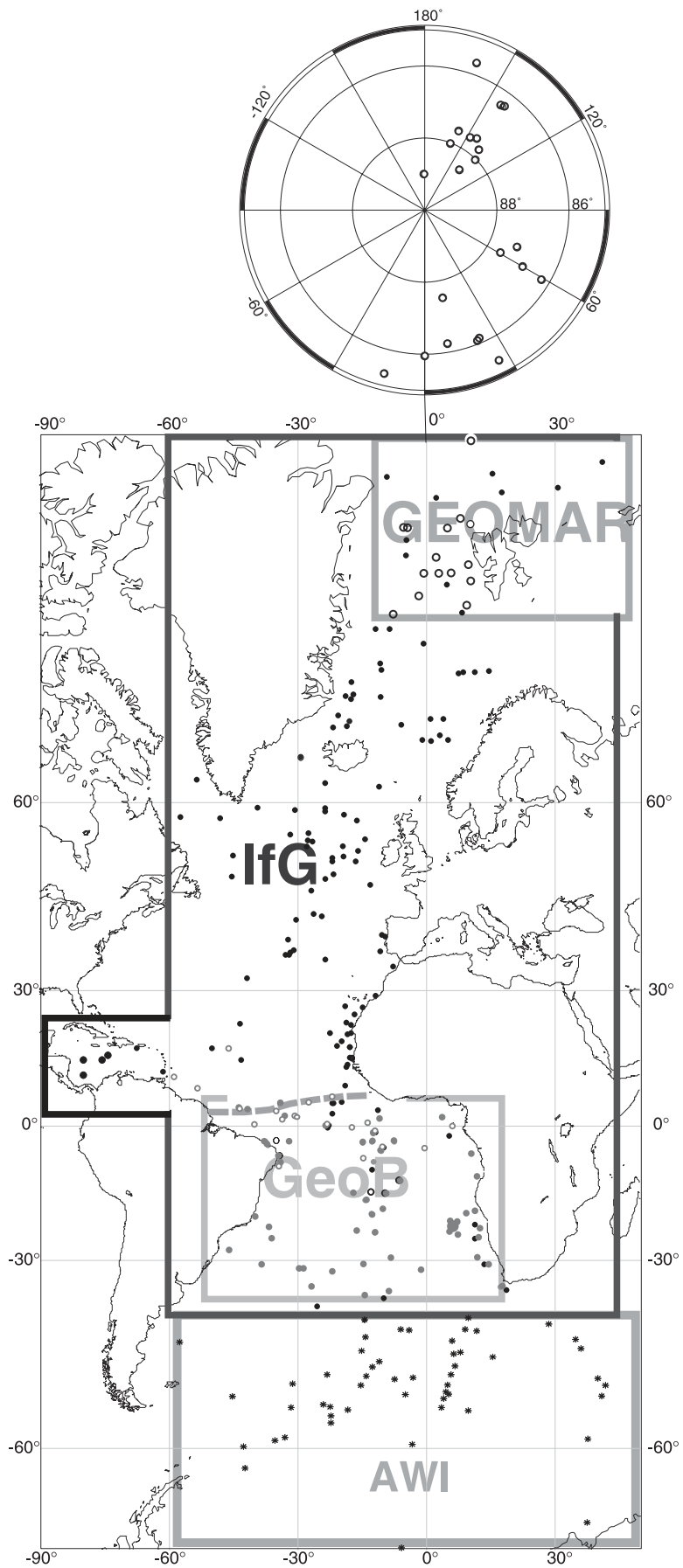
("Level 1") at 19.5–16.0 ^{14}C ka, equal to 23,000–19,000 cal years B.P. (first conference in May 1999; *Mix et al.* [2001]). This definition is based on the insolation minimum at 65° for summer near 21,000 ± 2000 cal years B.P. and on various paleoclimate records from the Atlantic, Antarctica, and Greenland. This alternative definition of the LGM gains support from evidence for the lowest glacial sea level stand on the north Australian shelf, which may reflect the maximum in global ice volume at >18.0–16.5 ^{14}C ka [*Yokoyama et al.*, 2000]. However, the extent and dating of this sea level low stand remain controversial, especially when compared with a recent sea level record from the nearby Sunda Shelf [*Hanebuth et al.*, 2000].

[12] Acknowledging that slight differences in the LGM definition exist, some GLAMAP 2000 reconstructions employ for comparison both the GLAMAP 2000 and EPILOG age definition of the LGM, in part with interesting results [*Pflaumann et al.*, 2003]. Moreover, *Weinelt et al.* [2003] discuss North Atlantic SST variability on decadal-to-centennial timescales over the entire glacial δ^{18}O stage 2 (25.6–12.0 ^{14}C ka, equal to 29,000–14,000 cal years ago). In the new GLAMAP 2000 reconstruction of North Atlantic SST [*Pflaumann et al.*, 2003], the EPILOG "Level-1" time window was reduced to 22,500–19,000 cal years B.P. to exclude the second warm episode of DO interstadial 2 which lasted from 23,700–22,000 cal years B.P. (based on the GISP2 timescale; *Grootes and Stuiver* [1997]). On the other hand, a final small warm excursion near 22,200 cal years was integrated in the reconstruction.

[13] The primary age control for the GLAMAP 2000 cores is based on δ^{18}O stratigraphy. However, many cores from southern high latitudes do not provide a continuous δ^{18}O stratigraphy. Here, abundance records of the radiolarian *Cycladophora davisiana* and/or of diatom species (e.g., *Eucampia antarctica*) are employed, the chronostratigraphy of which is time calibrated by δ^{18}O records and AMS ^{14}C dating [*Howard and Prell*, 1992; *Gersonde et al.*, 2003].

[14] More than one third of the sediment records are dated by AMS ^{14}C ages which are ^{14}C reservoir-corrected by ~400 years according to *Stuiver et al.* [1986] and *Bard* [1988]. The AMS ^{14}C ages have been converted to calendar ages by CALIB-1998 back to ~18,000 ^{14}C years B.P. [*Stuiver et al.*, 1998], and further back by tuning North Atlantic sediment records to the GISP2 timescale [*Voelker et al.*, 1998; 2001]. Core sections without ^{14}C age control were correlated to ^{14}C-dated neighbor cores by means of high-resolution structures in the δ^{18}O records. Stratigraphic details of >120 cores from the North and Central Atlantic are documented by *Vogelsang et al.* [2001].

3. Differential Accuracy of Age Control

[15] Our reconstructions only rely on core sections where the LGM interval was clearly identified in (largely published) δ^{18}O curves or in siliceous microfossil records. On the basis of sediment accumulation rates, dating precision, and differential sampling and time resolution, the quality of our SST estimates varies from one site to another. According to the integrated effect of these variables on the SST

estimates, we classified the marine sediment records into four categories [cf. *Vogelsang et al.*, 2001].

[16] 1. Category-I cores comprise 133 well-dated sections with sedimentation rates of >3 cm/ka and sample spacings of <5–10 cm. Approximately 75% of Category-I cores have rates of >5 cm/ka, 15% of the cores have rates >20 cm/ka. Category Ia: 50% of the Category-I records which are ^{14}C dated. Category Ib: Category-I cores, not ^{14}C dated.

[17] 2. Category II comprises 87 cores with sedimentation rates of 1.5–3.0 cm/ka, occasionally ^{14}C dated (Category IIa). Category IIb includes siliceous ooze sections from the Southern Ocean with medium to very high sedimentation rates (>1.5 to >20 cm/ka), but lacking δ^{18}O and ^{14}C stratigraphy. In these core sections age control is based on defined structures in siliceous-microfossil abundance records [*Gersonde et al.*, 2003].

[18] 3. Category III records (55 cores) show sedimentation rates of less than 1.5 cm/ka, a smoothed SST signal, and are occasionally ^{14}C dated. Here the densely sampled δ^{18}O maxima and/or siliceous microfossil abundance records are generally adequate to define the position of the LGM via comparison with the records of neighbor sites. Cores of this quality category were employed to increase the spatial density of SST data from the Mid Atlantic ridge and in (Arctic) sea regions largely sea-ice covered, where sedimentation rates are generally low.

[19] 4. Category IV records, which have a poor δ^{18}O stratigraphy, low sedimentation rates, and a smoothed SST signal, were rejected (and not included in the total of 275 records).

[20] The differential impact of bioturbational mixing, which is a function of the carbon/nutrient flux near the seafloor [*Trauth et al*, 1997], is not considered in this classification. *Weinelt et al.* [2003] present a special study of the intraLGM SST variability, also examining the effects of centennial-scale climate change in ultrahigh-resolution sediment cores.

4. Reconstruction of Isotherms, Seasonality, and Temperature Anomalies

[21] The GLAMAP 2000 paleotemperature reconstructions are based on nearly 1000 reference samples of modern planktic foraminifera counts in the Atlantic, and a number of different transfer techniques using microfossil (planktic foraminifers, diatoms, radiolarians) census data as described in this group papers [*Gersonde et al.*, 2003; *Niebler et al.*, 2003; *Pflaumann et al.*, 2003; *Weinelt et al.*, 2003]. Pertinent results from Uk37- and Mg/Ca-based SST estimates are discussed for comparison. In southern high latitudes (south of ~40°S), SST values were only reconstructed for (southern) summer because sediment trap data in this region suggest that microfossils and their signals are generated during summer only [*Abelmann et al.*, 1999; *Gersonde and Zielinski*, 2000].

[22] In contouring the paleotemperature maps, the isolines were derived from strictly linear interpolations (triangulation) between SST estimates of the irregularly distributed neighbor sites. In rare cases of controversial SST estimates, Category-I data were preferred to Category-II and -III data,

respectively. Minor deviations from the local SST average are considered to reflect a sort of cumulative standard error of sample analysis, laboratory counting, and stratigraphy. The results show that the LGM temperature estimates are internally highly consistent.

[23] Near to the equator, *Pflaumann et al.* [2003] ascribed the SST values of the "cold season" to Northern Hemisphere summer (i.e., to July–September) up to 5°N, that is the latitude of the modern thermal equator (Figure 1). Similarly, warm SST up to 5°N were ascribed to Northern Hemisphere winter (January–March).

[24] Sea-ice margins were defined by various techniques with largely consistent results, as described in the papers of *Gersonde et al.* [2003], *Sarnthein et al.* [2003], *Nørgaard-Pedersen et al.* [2003], and *Pflaumann et al.* [2003].

[25] Similar to *CLIMAP* [1981], maps of LGM temperature anomalies were constructed using a point-by-point subtraction of LGM SST estimates minus Modern SST of *Levitus and Boyer* [1994], which were interpolated from the 1° by 1° grid for each GLAMAP 2000 site. Seasonality maps of SST were derived from the subtraction of caloric summer and winter SST values. The difference maps between the GLAMAP 2000 and CLIMAP reconstructions of the LGM SST patterns in the Atlantic were deduced from interpolating the GLAMAP 2000 sites into the CLIMAP SST distribution pattern using several different techniques which are described in detail in the papers on the different regions of the Atlantic. The complete data set of the GLAMAP 2000 project is available from the PANGAEA paleoclimate databank (http//www.pangaea.de) and will be summarized by the GLAMAP 2000 Project Members in a separate paper (GLAMAP 2000 Project Members, manuscript in preparation, 2003).

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R. Gersonde and J. Thiede, Alfred Wegener Institut, Postfach 120161, D-27570 Bremerhaven, Germany. (gersonde@AWI-Bremerhaven.de; jthiede@awi-bremerhaven.de)

U. Pflaumann, M. Sarnthein, and M. Weinelt, Institut fuer Geowissenschaften, University of Kiel, Olshausenstr. 40, D-24098 Kiel, Germany. (up@gpi.uni-kiel.de; ms@gpi.uni-kiel.de; mw@gpi.uni-kiel.de)

S. Niebler and G. Wefer, Fachbereich Geowissenschaften, Postfach 330440, University of Bremen, D-28334 Bremen, Germany. (niebler@uni-bremen.de; gwefer@zfn.uni-bremen.de)

R. Spielhagen, Geomar, Wischhofstr. 1-3, D-24148 Kiel, Germany. (rspielhagen@geomar.de)