The response of the Subantarctic Pacific to climate change: Reconstructing dust flux and biological productivity during the last glacial cycle

GISELA WINCKLER¹, ROBERT F ANDERSON¹, JIWOON PARK¹, ROSEANNE SCHWARZ¹, JENNIFER LAMP¹, ELIZABETH SHOENFELT¹, KATHARINA PAHNKE², TORBEN STRUVE², GERHARD KUHN³, MARC WENGLER³, FRANK LAMY³

¹ Lamont-Doherty Earth Observatory of Columbia
University, Palisades, New York, United States
² Institute for Chemistry and Biology of the Marine Environment (ICBM), Oldenburg, Germany
³ Alfred Wegener Institute Helmholtz-Center for Polar and Marine Research Bremerhaven

The scarcity of iron limits marine productivity in about a quarter of the global ocean. Of these high nutrient low chlorophyll (HNLC) regions, the Southern Ocean is the region where variations in iron availability can have the largest effect on Earth’s carbon cycle through its fertilizing effect on marine ecosystems, both in the modern and in the past.

Whereas recent work in the Subantarctic South Atlantic (Martínez-Garcia et al., 2009, 2014, Anderson et al., 2014) suggests that dust-driven iron fertilization lowered atmospheric CO₂ by up to 40 ppm in the latter half of glacial cycles of the late Pleistocene, the other sectors of the Southern Ocean remain poorly constrained, including the Pacific Sector, that accounts for the largest surface area of the Subantarctic Southern Ocean.

Here we report records of dust deposition, iron supply and export production (using opal, excess Ba, TOC fluxes) from a set of cores from the Subantarctic Pacific (PS75, Lamy et al 2014). We test how tightly dust and biological productivity are coupled over glacial/interglacial and millennial timescales in the Subantarctic Pacific and explore controls on productivity and potential impacts on the carbon cycle.
Subantarctic Pacific iron fertilization during the last ice age

ALFREDO MARTÍNEZ-GARCÍA¹, DANIEL M. SIGMAN², FRANK LAMY¹, ANJA STUDER¹, RALF TIEDEMANN¹, GERALD H. HAUG¹

¹ Max Planck Institute for Chemistry, (a.martinez-garcia@mpic.de)
² Princeton University
³ Alfred Wegener Institute

Paleoceanographic records from the Subantarctic Atlantic show that peak glacial times and millennial cold events were nearly universally associated with increases in dust flux, export production, and nutrient consumption (the last indicated by higher foraminifera-bound Δ¹⁵N). This combination of changes is uniquely consistent with ice age iron fertilization of the Subantarctic Atlantic. However, the impact of iron fertilization in other sectors of the Southern Ocean characterized by lower glacial dust fluxes than the Atlantic remains unclear. A series of recently published records from the Subantarctic Pacific indicate that dust deposition and marine export production were three times higher during glacial periods than during interglacials, consistent with enhanced iron fertilization. However, glacial dust and productivity fluxes remained significantly lower than in the Subantarctic Atlantic. Therefore, the potential impact of the observed dust and productivity changes on major nutrient consumption and carbon sequestration remains unclear. Here, we present new measurements of foraminifera-bound nitrogen isotopes in a sediment core located in the Subantarctic Pacific (PS75/56-1), which provide the first insights on the impact of iron fertilization in the largest Southern Ocean sector.
Reconstruction of Southern Ocean paleo-temperatures based on hydroxylated GDGTs along with changes in dust deposition and export productivity

S. Fietz\textsuperscript{1*}, S.L. Ho\textsuperscript{2}, C. Huguet\textsuperscript{3}, A. Rosell-Melé\textsuperscript{4,5}, A. Martínez-García\textsuperscript{6}

1 Department of Earth Sciences, Stellenbosch University, 7600 Stellenbosch, South Africa (*correspondence: sfietz@sun.ac.za)
2 Department of Earth Science, University of Bergen, 5007 Bergen, Norway
3 Departamento de Geociencias, Universidad de los Andes, Bogota, Colombia
4 Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, Bellaterra, Catalonia, Spain
5 Institució Catalana de Recerca i Estudis Avançats, Barcelona, Catalonia, Spain
6 Geological Institute, Swiss Federal Institute of Technology Zürich, Zürich, Switzerland

A robust understanding of past oceanographic variability in the Southern Ocean is important because of its role in modulating global climate change. Here we reconstructed past sea surface temperature based on indices derived from isoprenoid glycerol dialkyl glycerol tetraethers (GDGTs), both non-hydroxylated and the more recently discovered hydroxylated ones, in a 500 kyr sediment record (core PS2489-2) from the Atlantic sector of the Southern Ocean. The GDGTs are cell membrane lipids synthesized by Archaea and some Bacteria. The glacial-interglacial oscillations in paleo-temperatures derived from non-hydroxylated and hydroxylated GDGTs throughout the past 500 kyr mirrored phytoplankton export productivity and varied in time with dust and IRD input. However, despite a good correspondence between the reconstructed temperatures and known glacial-interglacial features, the amplitude of glacial-interglacial change in our reconstructed temperatures was much larger than that derived from alkenone and foraminifera assemblage records. Especially the reconstructed glacial temperatures were lower compared to their alkenone and foraminifera derived counterparts. We discuss the possible contribution of an eolian or ice edge related provenance of the hydroxylated GDGTs, difference in the recording season between respective source organisms, differences in archaeal depth habitat in glacial and interglacial periods, and a shift in the recording and export depth between glacials and interglacials.
SW Pacific export production since the Last Glacial Maximum: No evidence for iron fertilisation

ZANNA CHASE1, AXEL DURAND1, HELEN BOSTOCK2, SAMUEL JACCARD3, HELEN NEIL2, TARYN NOBLE1, ASHLEY TOWNSEND4

1 Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia Zanna.Chase@utas.edu.au; Axel.Durand@utas.edu.au; Taryn.Noble@utas.edu.au
2 National Institute of Water and Atmospheric Research, Wellington, New Zealand Helen.Bostock@niwa.co.nz; Helen.Neil@niwa.co.nz
3 Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, Switzerland samuel.jaccard@geo.unibe.ch
4 Central Science Laboratory, University of Tasmania, Hobart, Australia Ashley.Townsend@utas.edu.au

The stimulating effect of dust on export production (EP) has been clearly demonstrated for the Atlantic Subantarctic, on both orbital [1] and millennial [2,3] timescales. Here we infer EP since the LGM at four sites around New Zealand using 230-Thorium-normalised fluxes of biogenic opal, carbonate, excess barium, and organic carbon. In Subtropical Waters and the SAZ, biogenic fluxes have not changed markedly since the LGM. The only exception is a site currently north of the subtropical front. Here we suggest the subtropical front shifted south over the core site between 18 and 12 ka, driving increased EP. At all sites, lithogenic fluxes were greater during the LGM compared to the Holocene due to a combination of increased aeolian and glaciogenic inputs. From these observations, we propose that even though increased glacial dust deposition may have relieved iron limitation within the SAZ around New Zealand, the availability of silicic acid limited diatom growth and thus any resultant increase in carbon export during the LGM. Therefore, silicic acid concentrations have remained low since the LGM. This result suggests no change in the co-limitation of EP by silicic acid and iron in the SAZ around New Zealand since the LGM.

Southern Ocean High-nutrient, low-chlorophyll status during the last deglaciation: Insights from new N and Si isotope records

M. Dumont¹, L. Pichevın¹, R. Ganeshram¹

¹ School of Geoscience, University of Edinburgh, Edinburgh, UK

Since the last glacial maximum (LGM), the Southern Ocean shifted from an efficient nutrient utilization state driven by stratification and high dust-borne iron input, into the high-nutrient, low-chlorophyll (HNLC) conditions of today. This change in the nutrient status of the ocean surface, arguably, reduced the efficiency of the biological pump in the Southern Ocean and may have contributed significantly to the observed glacial-interglacial atmospheric pCO₂ variability. In addition, the last deglaciation was marked by increased deep water overturning and CO₂ outgassing through the Southern Ocean, which has been linked to the observed deglacial rise in global atmospheric pCO₂. However, the sparse records from the Southern Ocean have yet to provide a coherent description of the biogeochemical changes that affected the Southern Ocean during the deglacial transition and, consequently, how the biological pump responded to the deglacial upwelling events.

Here we present new diatom-bound δ¹⁵N and δ³⁰Si as nutrient utilisation proxies from three cores with highly-resolved deglacial intervals distributed across the modern polar front of the under-sampled Indian Sector of the Southern Ocean. These records show the decoupling between Si and N utilisation and dust-borne iron input across the deglacial transition. This decoupling is most apparent in our records that are close to the modern polar front and suggests that the HNLC status of the region was not realised until after the global atmospheric pCO₂ had plateaued at the end of the glacial termination, lagging documented declines in dust fluxes to Antarctica by thousands of years. We will explore possible causes of the dust – Si/N utilisation decoupling, including nutrient isotopic source signal changes and the potential contribution of non-dust iron inputs, as well as discuss the implications of these findings on the magnitude of the Southern Ocean CO₂ source during the deglaciation.
THE POLAR OCEANS AND ATMOSPHERIC CO₂

Gerald H. Haug1,2, Alfredo Martinez-Garcia1, Anja Studer1, Abby Ren3, Mathis Hain3, Samuel L. Jaccard4, Ralf Tiedemann5, and Daniel M. Sigman3

1Max-Planck Institute for Chemistry, Mainz, Germany, gerald.haug@mpic.de
2Department of Earth Sciences, ETH Zürich, Switzerland
3Department of Geosciences, Princeton University, Princeton, USA
4Institute of Geological Sciences, University of Bern, Bern, Switzerland
4Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany.

We argue for a pervasive link between cold climates and polar ocean stratification. In both the Subarctic North Pacific and the Antarctic Zone of the Southern Ocean, ice ages were marked by low productivity. The accumulated evidence from sediment cores points to an increase in density stratification that reduced the supply of nutrients from the ocean interior into the sunlit surface in both of these regions. The last ice age was associated with stratification of the Antarctic and the subarctic North Pacific. This link also applies to longer time scales, including the onset of extensive northern hemisphere glaciation 2.7 million years ago, which was concurrent with stratification of the Subarctic North Pacific and the Southern Ocean. A mechanism is provided by the non-linear relationship between the temperature of seawater and its density: cooling of the ocean will decrease the role that temperature plays in the density structure of the polar water column, allowing a freshwater cap to cause greater density stratification. Nutrient-rich polar ocean regions such as the Antarctic and the Subarctic Pacific represent a “leak” in the biological pump, allowing deeply sequestered carbon dioxide to escape back into the atmosphere, and stratification of these regions largely stops that leak. Thus, the link between climate cooling and the stratification of nutrient-rich polar regions represents a positive feedback in the climate system, raising atmospheric carbon dioxide during warm periods and reducing it during cold periods.
Iron Fertilization of the Eastern Equatorial Pacific linked to Heinrich Stadial Events

FRANCO MARCANTONIO1, MATTHEW LOVELEY1, MARILYN WISLER1, JENNIFER HERTZBERG2, MATTHEW W. SCHMIDT3, MITCH LYLE4

1 Department of Geology & Geophysics, Texas A&M University, College Station, TX 77843, USA
2Department of Marine Science, University of Connecticut, Groton, CT 06340, USA
3Department of Ocean, Earth & Atmospheric Sciences, Old Dominion University, Norfolk, VA 23529, USA
4College of Earth, Ocean, and Atmospheric Sciences, Oregon State University Corvallis OR 97331, USA

The Equatorial Pacific Ocean is one of three main high-nutrient, low-chlorophyll zones of the global ocean. Within these zones, utilization of the macronutrients phosphate and nitrate during phytoplankton growth is likely limited by the micronutrient iron. Given the Equatorial Pacific’s prominent role in biogeochemical cycling of carbon, the variability of the iron supply to the Equatorial Pacific may contribute significantly to the drawdown of atmospheric CO2 and, therefore, influence global climate change. Although it is well established that the supply of iron to the Equatorial Pacific through the dissolution of mineral aerosol (dust) is greater during glacial periods on Milankovitch timescales, recent research argues against coincident increases in export production [1, 2]. On millennial timescales in the eastern Equatorial Pacific, changes in surface productivity seem to be associated with the timing of either North Atlantic Heinrich Stadial (HS) events or Antarctic Warm Periods, and are thought to be related to changes in nutrient delivery caused by variations in the ventilation of Southern Ocean intermediate waters [3, 4]. Using 232Th fluxes as a proxy for dust fluxes, we show for the first time that increased delivery of dust to the EEP is coeval with virtually all HS events (HS 1-7) during the last glacial period (MIS 2-4). Furthermore, using authigenic U and xsBa fluxes as productivity proxies, we suggest that episodes of increased biological productivity are coincident with each millennial pulse of increased dust flux. We contrast the millennial and orbital variability differences, and suggest an atmospheric role, manifested through shifts in the Intertropical Convergence Zone, for the connection between the low latitude EEP and cold North Atlantic HS events.

The Atlantic Meridional Overturning Circulation Through the Mid–Pleistocene Transition

Goldstein, S.L.1, Pena, L.D.2, Jaume-Seguí, M.1, Kim, J.1, Yehudai, M.1, Knudson, K.1, Basak, C.1, Hartman, A.E.3, Lupien, R.4

1Lamont-Doherty Earth Observatory, Columbia University, NY, USA
2Department of Earth and Ocean Dynamics, University of Barcelona, Spain
3USGS, Columbia, MO, USA
4Department of Geological Sciences, Brown University, RI, USA

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The Atlantic Meridional Overturning Circulation is a major means for distributing heat between the tropics and the high latitudes, and thus its temporal variability has major impacts on ice age cycles. We present a summary of work in-progress to generate two-dimensional profiles of the AMOC from the North Atlantic to the Southern Ocean, at time slices over the past ~2 Ma, from Nd isotopes in Fe-Mn-oxide encrusted foraminifera and fish debris. Our sites show a consistent N-S gradient in the North Atlantic signal strength, which varies temporally at each site, providing strong evidence that we are following the AMOC (with one exception). Moreover, the data show strong evidence that the $\epsilon$Nd of the North Atlantic end-member remained similar to today through this time interval.

The interval includes the Mid-Pleistocene Transition (MPT), marking the change in glacial-interglacial periodicity from ~40 to ~100 kyr cycles, and which occurred between ~1.3-0.7 Ma. Pena and Goldstein (Science, 2014), from data in two South Atlantic cores, concluded that the AMOC experienced an unprecedented “crisis” between ~950-850 ka (MIS 25-21), which generated the climatic conditions that intensified cold periods, prolonged their duration, and stabilized 100 kyr cycles. Our new results document impact of the “AMOC crisis” over the entire Atlantic basin. The sites show the same history, and are consistent with southern-sourced waters filling the deep Atlantic over that period. An $\epsilon$Nd excursion in the North Atlantic just prior to the AMOC crisis, during MIS 26, indicates a spike of Canadian or European Shield material into the N Atlantic, and evidences a northern hemisphere trigger for the AMOC crisis and the transition to 100 kyr glacial cycles. The data support important changes in the overturning circulation during the MPT, and greater glacial-interglacial variability in the 100 kyr world compared with the 40 kyr world.
Indian Ocean circulation changes over the Middle Pleistocene Transition.

BENJAMIN F. PETRICK¹, G. AUER², D. DE VLEESCHOUWER³, B. A. CHRISTENSEN⁴, C. STOLFI⁴, L. REUNING³, A. MARTINEZ-GARCIA¹, G. HAUG¹, T. BUCKLEY⁵, S. J. GALLAGHER⁶, C. S. FULTHORPE⁷, K. BOGUS⁸, IODP 356 SHIPBOARD SCIENCE PARTY

¹ Max-Planck-Institut für Chemie, Mainz (b.petrick@mpic.de)
² Institute of Earth Sciences, University of Graz
³ MARUM - Center for Marine Environmental Science
⁴ Adelphia University, USA.
⁵ Geological Institute, RWTH Aachen University
⁶ School of Earth Sciences, University of Melbourne
⁷ Institute for Geophysics, University of Texas at Austin
⁸ Ocean Discovery Program, Texas A&M University

The Mid-Pleistocene Transition (MPT; ~1.4 – 0.4 Ma) represents a climatic shift towards climate cycles at a quasi-100-kyr frequency. High-resolution data exists covering the MPT from globally distributed archives, but there is only sparse evidence on changes in heat exchange between the Pacific and Indian Oceans. Deciphering the influence of this heat exchange via the Indonesian Throughflow (ITF) is an important step in understanding the causes of the MPT. The Leeuwin Current off Western Australia is directly influenced by the ITF and can therefore be used to reconstruct ITF variability during the MPT.

We present the first continuous reconstruction of changes in the Leeuwin Current during the MPT using data from IODP Expedition 356 Site U1460. The site is located at 29°S in the path of the current. We reconstruct paleoenvironmental variability by combining XRF, organic geochemistry, ICP and XRD data with shipboard data, to reconstruct Leeuwin Current and ITF variability. High sedimentation rates (~30 cm/ka) at Site U1460 provide the opportunity for high-resolution reconstruction of the MPT.

Initial analyses show that productivity off Western Australia intensified after the MPT, indicated by increased primary productivity related to increased nutrient levels, from 900-600 ka. There is also increased amount of SST variability after 900ka suggesting a more dynamic Leeuwin current and that glacial periods had a weaker Leewin current. Our results suggest, that these changes after the MPT might be related to global changes and suggest conections between changes in Indian Ocean circulation and the south Atlantic Ocean.
Cosmogenic $^{10}\text{Be}/^{9}\text{Be}$, normalized to stable $^{9}\text{Be}$, is used extensively for generating age models for ferromanganese (FeMn) crusts. This is based on the assumption that the input of both isotopes to the oceans has been relatively constant over the timescales of concern. $^{10}\text{Be}$ is derived from atmospheric production which precipitates directly to the oceans, while stable $^{9}\text{Be}$ is derived from continental weathering. While this assumption appears to hold true generally, the $^{10}\text{Be}/^{9}\text{Be}$ ratio recorded in an archive could deviate under special circumstances, such as for crusts deposited near marine gateways which had different configurations in the past compared with today. Changes in the origin of the water bathing a crust may cause changes to the recorded $^{10}\text{Be}/^{9}\text{Be}$ ratio that are completely unrelated to the decay of $^{10}\text{Be}$, or changes to the inputs of either isotope.

The modern difference in the natural $^{10}\text{Be}/^{9}\text{Be}$ ratio of Mediterranean and Atlantic waters, $1.0x10^{-8}$ and $6.1x10^{-8}$ respectively,

, is resolvable and well-constrained. $^{10}\text{Be}/^{9}\text{Be}$ data for FeMn crust 3514-6, derived from high resolution subsampling of this crust, show clear and distinct discrepancies, generating reversals in apparent age. Crust 3514-6 was deposited on the Lion Seamount, approximately 900 km due west of the Strait of Gibraltar. This location is bathed by Mediterranean Outflow (MO), a water mass which is known to have deviated in terms of flow and plume height,

, due to both gateway and climate changes. We interpret the discrepancies in the $^{10}\text{Be}/^{9}\text{Be}$ record as periods of time when MO did not bathe crust 3514-6. During the LGM, the MO plume is thought to have moved at greater depth; our data indicate that a similar deepening of flow may have occurred near the intensification of northern hemisphere glaciation $\sim$3 Ma. Furthermore, gateway changes are recorded consistent with a blockage in the Gibraltar gateways prior to 5.33 Ma. Our findings demonstrate that, under special circumstances, the $^{10}\text{Be}/^{9}\text{Be}$ ratio records paleoceanographic information.

Pyrite sulfur isotopes reveal glacial-interglacial environmental changes.

V. PASQUIER1, P. SANSJOFRE1, M. RABINEAU1, S. REVILLON2, J. HOUGHTON3, D.A. FIKE3

1 IUEM, UMR CNRS 6538 « Laboratoire Géosciences Océan », Université de Bretagne Occidentale, 29280 Plouzane, France. virgil.pasquier@univ-brest.fr, pierre.sansjofre@univ-brest.fr, Marina.Rabineau@univ-brest.fr.
2 SEDISOR, IUEM, UMR CNRS 6538 « Laboratoire Géosciences Océan », Place Nicolas Copernic, 29280 Plouzane, France. sidonie.revillon@sedisor.eu.
3 Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130, United States. jhoughton@levee.wustl.edu, dfike@levee.wustl.edu.

The sulfur biogeochemical cycle plays a key role in regulating Earth’s surface redox through diverse abiotic and biological reactions that have distinctive stable isotopic fractionations. As such, variations in the sulfur isotopic composition ($\delta^{34}S$) of sedimentary sulfate and sulphide phases over Earth history can be used to infer substantive changes to the Earth’s surface environment, including the rise of atmospheric oxygen. Such inferences assume that individual $\delta^{34}S$ records reflect temporal changes in the global sulfur cycle; this assumption may be well grounded for sulfate-bearing minerals, but is less well established for pyrite-based records. Here, we investigate alternative controls on the sedimentary sulfur isotopic composition of marine pyrite by examining a 300 m drill core of Mediterranean sediments deposited over the past 500,000 years and spanning the last five glacial-interglacial periods. Because this interval is far shorter than the residence time of marine sulfate, any change in the $\delta^{34}S_{pyr}$ record necessarily corresponds to local environmental changes. The stratigraphic variations (>76.8‰) in the isotopic data reported here are among the largest ever observed in pyrite, and are in phase with glacial-interglacial sea level and temperature changes. In this case, the dominant control appears to be glacial-interglacial variations in sedimentation rates. These results suggest that there exist important but previously overlooked depositional controls on sedimentary sulfur isotope records, especially associated with intervals of substantial sea level change. This work provides important perspective on the origin of variability in such records and suggests novel paleoenvironmental information can be derived from pyrite $\delta^{34}S$ records.
Modelling Abrupt Climate Change during the Last Deglaciation

PAUL J VALDES

1School of Geographical Sciences, University of Bristol

Abrupt climate change events are a common feature of glacial periods and during the last deglaciation (21 – 10 kaBP) yet we still lack a full understanding for the causes and consequences of these events, and have limited ability to successfully simulate them. Rapid cooling events (such as Heinrich events) have been the focus of many studies. However, ice-core records indicate that abrupt warming events (such as Dansgaard-Oeschger events), which may take place in a few decades or less, are more representative of the palaeo record. Furthermore, although a clear understanding is still lacking, recent modelling efforts suggest that atmospheric dynamics could be more important in shaping these abrupt events than previously thought. The talk will review the various oceanic and atmospheric mechanisms which have invoked to explain abrupt events. We will show that the atmosphere can play an important role in events but that the ocean (and sea ice) remain fundamentally important. Rapid cooling events are better simulated than warming event, with a particular challenge being to successfully simulate the rapidity of the warming.
Glacial Climate Stability

GREGOR KNORR¹, XU ZHANG², GERRIT LOHMANN³, STEPHEN BARKER⁴

¹Alfred Wegener Institute Helmholtz-Center for Polar and Marine Research, Bremerhaven D-27570, Germany (gregor.knorr@awi.de)
²Alfred Wegener Institute Helmholtz-Center for Polar and Marine Research, Bremerhaven D-27570, Germany (xu.zhang@awi.de)
³Alfred Wegener Institute Helmholtz-Center for Polar and Marine Research, Bremerhaven D-27570, Germany (gerrit.lohmann@awi.de)
⁴School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK (barkers3@cf.ac.uk)

Various climate archives suggest that abrupt climate changes are an intrinsic characteristic of glacial cycles. Especially millennial-scale climate variability and Dansgaard-Oeschger events have been linked to changes in the Atlantic meridional overturning circulation (AMOC). To reproduce the associated abrupt transitions between weak and strong AMOC states a common trigger mechanism is related to the timing of North Atlantic freshwater perturbations that is mainly motivated by unequivocal ice-rafting events during Heinrich Stadials (HS). However, recent studies suggest that the Heinrich ice-surging events are triggered by ocean subsurface warming associated with an AMOC slow-down. Furthermore, the duration of ice-rafting events does not systematically coincide with the beginning and end of the pronounced cold conditions during HS.

In this context we show that both, changes in atmospheric CO₂ and ice sheet configuration can provide important controls on abrupt glacial/deglacial climate shifts, using a coupled atmosphere-ocean model. Our simulations reveal that gradual changes in Northern Hemisphere ice sheet height and atmospheric CO₂ can act as a trigger of abrupt climate changes. Furthermore, the interplay between changes in ice volume and atmospheric CO₂ determines that windows of AMOC bi-stability exist during intermediate conditions between peak glacial and interglacial states. This fits to data observations that e.g. MIS 3 was characterised by pronounced millennial scale climate activity while the last glacial maximum and the Holocene interglacial were not. Since millennial-scale changes in CO₂ are themselves thought to be linked to AMOC changes (with a weakened AMOC giving rise to a gradual CO₂ increase and vice versa), our results suggest that CO₂ might also represent an internal feedback to AMOC changes by enabling rapid transitions between contrasting climate states without the necessity to invoke additional processes like North Atlantic ice rafting events.
The sensitivity of Nordic Seas upper-ocean stratification to freshwater input

BENOIT THIBODEAU¹, HENNING A. BAUCH², THOMAS F. PEDERSEN³ AND ANDREAS SCHMITTNER⁴

¹The University of Hong Kong, Hong Kong; bthib@hku.hk
²Alfred Wegener Institute c/o GEOMAR, Kiel, Germany
³University of Victoria, Canada
⁴Oregon State University, USA

The Nordic Seas (Greenland, Iceland, and Norwegian Seas) are a site of open ocean convection that play an essential role in the Atlantic Meridional Overturning Circulation (AMOC), which profoundly affects surface heat transfer in the Northern Hemisphere, deep-ocean ventilation, and the global climate. Despite its global importance to Earth’s climate, the fate of open-ocean convection is still unresolved, especially regarding the potential effects of freshwater inputs from the demise of the Greenland ice sheet. While it is generally accepted that freshwater would drastically decrease the surface water density, thus preventing convection, there are still gaps in our understanding of the sensitivity of this system to freshwater input.

By coupling sedimentary δ¹⁵N measurement with planktic foraminiferal abundance we highlighted that decreased nutrient utilization during past interglacials (MIS 5e and 11) where concurrent to colder condition at around 50-150 m depth in the water column compared to the Holocene. Since these periods are thought be generally warmer and characterized by an active AMOC we hypothesized that the colder condition at sub-surface were indicative of freshwater input, probably linked with the demise of ice-sheet from the preceding glaciations, which are generally thought to be larger than MIS 2. This hypothesis is coherent with the isotopic composition of alkenones used to reconstruct salinity, which suggest the presence of freshwater in the sub-surface layer. To explain both δ¹⁵N and foraminiferal assemblages we thus suggest the presence of a thick summer mixed-layer of meltwater origin that limited nutrient utilization. Modeling was used to test this hypothesis.

Thus, variation in Nordic Seas upper-ocean stratification between the three last interglacials highlights the sensitivity of the summer mixed-layer to large freshwater input. However, our results also raise questions about the exact link between upper-ocean stratification and convection in the Nordic Seas.
Past dynamics of Atlantic Ocean overturning: A multi-proxy view on three key intervals

JULIA GOTTCHALK1,2, LUKE C. SKINNER2, CLAIRE WAELBROECK3, DAVID A. HODELL2, CHRISTOPH NEHRBASS-AHLES4, SAMUEL L. JACCARD1

1Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, CH (julia.gottschalk@geo.unibe.ch, samuel.jaccard@geo.unibe.ch)
2Godwin Laboratory for Palaeoclimate Research, Department of Earth Sciences, University of Cambridge, UK (lcs32@cam.ac.uk, dah73@cam.ac.uk)
3Laboratoire des Sciences du Climat et de l’Environnement, LSCE/IPSL, CNRS-CEA-UVSQ, Université de Paris-Saclay, Gif-sur-Yvette, F (claire.waelbroeck@lsce.ipsl.fr)
4Climate and Environmental Physics, Physics Institute and Oeschger Centre for Climate Change Research, University of Bern, CH (nehrbass@climate.unibe.ch)

Changes in deep convection in the North Atlantic are often considered a major driver of past global climate variability. Based on marine proxy evidence of carbonate ion saturation- and bottom water [O2] changes in the South Atlantic, we provide insights into important aspects of the Atlantic meridional overturning circulation (AMOC) from three key intervals: First, we provide evidence for persistent perturbations of the AMOC strength and/or geometry during almost every Dansgaard-Oeschger (D-O) event of the last glacial period, highlighting the existence of fast oceanic teleconnection mechanisms and a close link between rapid overturning changes and past millennial-scale climate variability. Second, we show evidence for similar AMOC changes during the penultimate glacial period that also show a systematic relationship to variations in bottom water [O2] at our study site. Our data do not only highlight the persistence of instabilities of Atlantic overturning during older glacial periods, but also point to a connection between Atlantic- and Southern Ocean overturning and deep South Atlantic respired carbon storage, with possible implications for atmospheric CO2 changes. Lastly, although interglacial climate conditions are generally considered as more ‘stable’ than during glacial periods, we show evidence for recurrent and significant reductions in bottom water ventilation in the South Atlantic at times of higher-than-present local sea surface temperatures during the last interglacial. This may indicate possible feedback mechanisms between instabilities of the cryosphere and the strength of deep water formation in the Atlantic Sector of the Southern Ocean in a warmer-than-present climate.
Deglacial deep water circulation and end member Nd isotope changes in the subpolar North Atlantic

P. Blaser1, J. Lippold2, M. Gutjahr1, J. M. Link1, F. Pöppelmeier2, M. Frank3, N. Frank1

1Institute of Environmental Physics, Heidelberg University, Germany, contact: patrick.blaser@iup.uni-heidelberg.de
2Institute of Earth Sciences, Heidelberg University, Germany
3GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany

Neodymium (Nd) isotopes have become a valuable proxy for the reconstruction of past water mass provenance and mixing. Accurate interpretation of Nd isotope palaeo records, however, requires a precise knowledge of the Nd isotope signatures of the water mass end members. North Atlantic Deep Water (NADW) is the major water mass ventilating the deep Atlantic Ocean today. However, whether the Nd isotope composition of NADW and its glacial counterpart remained constant or how much it varied during glacial cycles is actively debated. The subpolar North Atlantic is both the source region of NADW, as well as an area of very dynamic water mass mixing, which responded sensitively to climatic changes such as enhanced freshwater input and surface water temperatures. Furthermore, it is a region with highly variable weathering inputs in terms of Nd isotope compositions.

Aiming to provide improved (de-)glacial end member compositions, we reconstructed the deep water Nd isotope composition from several sites across the deep subpolar North Atlantic during the transition from the last glacial to the Holocene. Our results suggest that water mass exchange between the deep eastern and western basins was limited during the Last Glacial Maximum, possibly due to the weakened admixture of overflow waters from the Nordic Seas. Vigorous exchange between the two basins was established during the mid Holocene, evident through homogenised Nd isotope signatures across the two basins. Moreover, the Nd isotope composition of the deep boundary currents evolved towards more radiogenic isotope signatures in both basins during the mid to late Holocene.

This continued transition from undariogenic to radiogenic deep boundary currents during the Holocene provides evidence for changes in the Nd isotope compositions of NADW end members. It could thus be the cause for simultaneous changes observed further south in the deep West Atlantic at the Bermuda Rise.
Deglacial water mass mixing in the 
Drake Passage on millennial to 
centennial timescales

D.J. Wilson1*, T. Struve1,2, T. Van de Flierdt1, T. Chen1, A. Burke4, L.F. Robinson3

1 Dept. of Earth Science and Engineering, Imperial College 
London, UK (*david.wilson1@imperial.ac.uk) 
2 Max Planck Research Group for Marine Isotope 
Geochemistry, ICBM, University of Oldenburg, Germany 
3 School of Earth Sciences, University of Bristol, UK 
4 Dept. of Earth and Environmental Sciences, University of 
St. Andrews, UK

Deep-sea corals have emerged as a valuable archive for tracer reconstructions of the Late Pleistocene oceans. Unlike many paleoceanographic archives, they record conditions on (sub-)centennial timescales, can be absolutely dated using uranium series, and are relatively abundant at mid-depths of the Southern Ocean. These properties lead to the opportunity for a direct comparison between interior ocean changes and high-resolution globally-distributed climate records such as those from speleothems and ice cores.

Here we address the sequence and timing of changes in the intermediate to mid-depth Southern Ocean during the millennial climate events of the last deglaciation. In particular, by combining new neodymium (Nd) isotope data with existing radiocarbon evidence on deep-sea corals collected from the Drake Passage [1, 2], we focus on water mass variability and its role in deglacial carbon cycling.

Despite in some cases only modest glacial-interglacial changes in Nd isotopes, there is striking variability on millennial to centennial timescales. In addition, and in contrast to the modern Southern Ocean water column, latitude and water depth were significant factors in the deglacial evolution of Nd isotopes recorded by deep-sea corals. Comparing the records from different seamounts and water depths therefore provides additional insight into the rapidly changing ocean structure.

A further intriguing feature of some of the records is a correspondence between Nd isotope variability and rapid jumps in atmospheric carbon dioxide [3]. By considering the detailed pattern and timing of these changes, we attempt to determine the possible atmospheric or oceanic mechanisms operating, and to distinguish the importance of northern versus southern hemisphere forcing.

Intermediate water temperature and radiocarbon records from the North Atlantic and Southern Ocean across the most recent glacial termination

SOPHIA K. HINES1, JOHN M. EILER2, JESS F. ADKINS3

1Caltech, USA, *Corresponding author: shines@caltech.edu
2Caltech, USA, eiler@gps.caltech.edu
3Caltech, USA, jess@gps.caltech.edu

Intermediate waters play an important role in global heat transport; therefore, changes in intermediate water circulation can strongly impact global climate over glacial-interglacial transitions. We present intermediate water clumped isotope temperature and radiocarbon timeseries spanning the most recent glacial termination, based on deep-sea Desmophyllum dianthus corals. North Atlantic and Southern Ocean radiocarbon records are variable and close to the contemporaneous atmosphere during Heinrich Stadial 2, scattering around their modern ocean offsets. During the LGM and the early part of Heinrich Stadial 1, radiocarbon values are more depleted and less variable. During the late part of Heinrich Stadial 1, radiocarbon values are more variable again, but still depleted. During the ACR/Bolling-Allerød, radiocarbon values in the Southern Ocean and North Atlantic are enriched compared to their modern ocean offsets and highly variable, especially in the Southern Ocean. North Atlantic and Southern Ocean temperature records drop during Heinrich Stadial 2 from relatively warm values of ~8 and 6.5 °C, respectively at 26 ka to cooler values of ~4.5 °C at 23 ka. Southern Ocean temperatures rise again during the LGM to ~7 °C, drop through the middle of Heinrich Stadial 1, and rise again before the start of the Bolling. There is a gap in the North Atlantic record during the LGM, but temperatures also rise from the middle to the late part of Heinrich Stadial 1. Through this interval, the North Atlantic is also consistently colder than the Southern Ocean. These intermediate-depth warming trends during Heinrich Stadial 1 are consistent with other intermediate-depth warming trends during this time documented in the Equatorial Atlantic (Weldeab et al., 2016) and North Atlantic (Thiagarajan et al., 2014).
Dueling Transects show enhanced $\delta^{13}$C and $\delta^{18}$O differences between the South Atlantic and South Pacific during the last glaciation: The deep gateway hypothesis

ELISABETH L. SIKES$^1$, KATHERINE A. ALLEN$^2$ & DAVID C. LUND$^3$

$^1$ Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ 08901, USA sikes@marine.rutgers.edu

$^2$ School of Earth and Climate Sciences, University of Maine, Orono, ME 04469, USA, katherine.a.allen@maine.edu

$^3$ Department of Marine Sciences, University of Connecticut Avery Point, Groton, CT 06340, USA, david.lund@uconn.edu

Deep ocean circulation during the Last Glacial Maximum (LGM) was characterized by shoaling of northern sourced waters that is considered a primary cause of enhanced vertical gradients in $\delta^{13}$C and $\delta^{18}$O in the deep ocean. High-resolution depth transects of $\delta^{13}$C and $\delta^{18}$O in Cibicidoides spp. from the Southwest Pacific and Southwest Atlantic basins record northern and southern sourced deep waters changes during the LGM and deglaciation. The Atlantic between $\sim$1.0 and 2.5 km was more than 1‰ enriched in $\delta^{13}$C than the Pacific and remained thus through the deglaciation. During the LGM, Atlantic $\delta^{18}$O was $\sim$ 0.5‰ more enriched than the Pacific below 2.5 km and this implies independent deep water sources. We attribute this to a ‘deep gateway’ effect whereby northern sourced waters shallower than the Drake Passage sill were unable to flow south into the Southern Ocean; a net meridional geostrophic transport cannot be supported in the absence of a net east-west circumpolar pressure gradient above the sill depth. We surmise that from the LGM through the early deglaciation, shoaled northern-sourced waters were unable to escape the Atlantic and contribute to deep water in the Southern Ocean.
New constraints on Atlantic Meridional Overturning Circulation changes during the past 40 ky from combined $^{231}\text{Pa}/^{230}\text{Th}$, benthic $\delta^{13}\text{C}$ and $^{14}\text{C}$ benthic-planktonic ventilation ages

LISE MISSIAEN$^1$, CLAIRE WAELBROECK$^1$, SYLVAIN PICHAT$^2$, ARNAUD DAPOIGNY$^1$, FRANÇOIS THIL$^1$, LORNA FOLIOT$^1$, LUKAS WAKER$^1$, IRKA HAJDAS$^3$, EVELYN BÖHM$^1$, NATALIA VAZQUEZ-RIEVEROS$^1$, SANTIAGO MOREIRA$^1$

$^1$LSCE, CEA-CNRS-UVSQ-Université Paris-Saclay, Bât 12
Avenue de la Terrasse, F-91198 Gif-sur-Yvette
(lise.missiaen@lsce.ipsl.fr)
$^2$LGL-TPE, Université de Lyon-ENS de Lyon-Université
Lyon 1, 46 Allée d’Italie F-69 364 Lyon cedex 7
$^3$Laboratory of Ion Beam Physics, HPK, H29 Otto-Stern-Weg 5 CH-8093 Zürich

The Atlantic Meridional Overturning Circulation (AMOC) is a major component of the climate system through its impact on low to high latitude heat transport and CO$_2$ air-sea exchange. Despite numerous studies, its role in abrupt climate changes of the last glacial period is still poorly constrained. This study aims at better understanding the evolution of the AMOC by combining, within the same core, different circulation proxies such as the sedimentary $^{231}\text{Pa}/^{230}\text{Th}$, which documents changes in the water masses flow rate, benthic $\delta^{13}\text{C}$ which reflects the ventilation state of bottom water and paired benthic-planktonic $^{14}\text{C}$ measurements which indicate deep and shallow water masses ages.

We present new multi-proxy time series from North Atlantic core SU90-08 (43°N, 30°W, 3,080 m) for the last 28 ky and around Heinrich Stadial (HS) 4. $^{231}\text{Pa}/^{230}\text{Th}$ exhibits lower values for the Last Glacial Maximum (LGM) compared to the rest of the dataset. This suggests stronger flow rate at the LGM than during the Holocene above the core site. $^{231}\text{Pa}/^{230}\text{Th}$ also suggests slightly reduced circulation over HS 1 and HS 4. Benthic $\delta^{13}\text{C}$ displays slightly depleted values for HS 4 and very depleted values from 27 ky cal BP to the onset of the deglaciation. This would imply that deep water mass that bathed this location at the LGM was poorly ventilated while $^{231}\text{Pa}/^{230}\text{Th}$ over the same period indicates that the circulation was vigourous. We will discuss the apparent decoupling between $^{231}\text{Pa}/^{230}\text{Th}$ and benthic $\delta^{13}\text{C}$ during the LGM in the light of benthic and planktonic $^{14}\text{C}$ ages spanning the last 25 ky.
Rapid changes in Pacific seawater carbonate chemistry during the last glacial termination

KATHERINE A. ALLEN¹*, ELISABETH L. SIKES², ROBERT F. ANDERSON³

¹ School of Earth and Climate Sciences, University of Maine, Orono, ME 04469, USA (correspondence: katherine.a.allen@maine.edu)
² Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ 08901, USA
³ Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA

Past variations in seawater carbonate ion concentration ([CO₃²⁻]) may be derived from B/Ca of benthic foraminiferal calcite, ultimately providing constraints on past amounts and mechanisms of ocean carbon storage. We present results from a depth transect composed of three sediment cores spanning 1.2 – 2.5 km water depth in New Zealand’s Bay of Plenty. B/Ca of the benthic foraminifer Cibicidoides wuellerstorfi is used to reconstruct [CO₃²⁻] at the three core sites for the past ~30 ky. Large shifts in [CO₃²⁻] (30-40 µmol/kg) occur at the intermediate-water site (1.2 km) between 17-9 cal ky BP, similar in timing and magnitude to previously published results from the 1.6 km core [1]. Both [CO₃²⁻] and δ¹³C of the deeper sites (1.6 and 2.5 km) experience a permanent shift towards higher values between 25-10 cal ky BP. Broad covariation of Cibicidoides δ¹³C with [CO₃²⁻] derived from B/Ca suggests that the amount of isotopically light, respired CO₂ in deep waters is decreasing during the deglaciation. Depth profiles of [CO₃²⁻] for 2 ky time slices indicate a steeper intermediate-deep [CO₃²⁻] gradient during the glacial than the Holocene. At our Southwest Pacific sites, [CO₃²⁻] exhibits more dramatic changes than observed in the equatorial Pacific [2], perhaps indicating a more dynamic response of South Pacific water masses to shifts in Southern Ocean-atmosphere circulation and/or changes in the operation of the biologic pump during the deglaciation.

**CO₂ storage and release in the deep Southern Ocean on millennial to centennial timescales**

J.W.B. Rae¹, A. Burke¹, L.F. Robinson², J.F. Adkins³, T. Chen², C. Cole¹, E.F.M. Littley¹, D.C. Nita¹, P. Spooner², B. Taylor

¹School of Earth and Environmental Sciences, University of St Andrews, UK (jwbr@st-andrews.ac.uk)
²Bristol Isotope Group, School of Earth Sciences, University of Bristol, UK
³Division of Geological and Planetary Sciences, California Institute of Technology, USA

The carbon content of the deep Southern Ocean is widely thought to control atmospheric CO₂ on glacial-interglacial timescales, but few direct tests of this hypothesis exist. Here we present new deep sea coral boron isotope data that reflect the pH – and thus CO₂ chemistry – of the deep Southern Ocean over the last 40,000 years. At sites most influenced by deep Southern waters we find a close relationship between ocean pH and atmospheric CO₂: during intervals of low CO₂ ocean pH is low, reflecting enhanced ocean carbon storage; during intervals of rising CO₂ ocean pH rises, reflecting loss of carbon from the ocean to the atmosphere. In contrast at shallower sites we find extremely rapid (centennial-scale) pH decrease during abrupt CO₂ rise, reflecting the transfer of carbon from the deep to the upper ocean and atmosphere. These data thus confirm the importance of the deep Southern Ocean in ice age CO₂ change, and demonstrate that deep ocean CO₂ release can occur as a dynamic feedback to abrupt climate change on centennial timescales.
Determining changes in North-Atlantic carbon cycling across abrupt climate events.


1 School of Earth and Environmental Science, Irvine Building, University of St Andrews, St Andrews, KY16 9AL, UK. (*correspondence: rg200@st-andrews.ac.uk).
2 School of Geography, Archaeology and Palaeoecology, Queen's University Belfast, Belfast, BT7 1NN.
3 School of Ocean and Earth Science, University of Southampton Waterfront Campus, European Way, Southampton, SO14 3ZH, UK.
4 Department of Animal and Plant Sciences, Alfred Denny Building, University of Sheffield, Sheffield, S10 2TN, UK.
5 School of Earth and Ocean Sciences, Cardiff University, Main Building, Park Place, Cardiff, CF10 3AT.
6 Laboratoire des Sciences du Climat et de l’Environnement (LSCE), CEA/CNRS-INSU/UVSQ, Gif-sur-Yvette Cedex, France.

Intervals of rapid climate change have long been linked to different modes of meridional overturning circulation (MOC), with slowdown driving rapid cooling. Some of these cooling events are also associated with the enhanced discharge of icebergs from the Laurentide ice sheet and a rise in atmospheric CO2. While a number of records have shown evidence for a change in the strength and configuration of the MOC in the North Atlantic across abrupt climate events, there are limited studies determining how this would affect the partitioning of carbon between the surface and deep ocean. Here we use coupled measurements of the boron isotope ($\delta^{11}$B) and radiocarbon ($^{14}$C) composition of foraminifera to trace carbon cycling in the North Atlantic and its exchange with the atmosphere over the last deglaciation. The importance of the overturning circulation strength on the magnitude of surface water radiocarbon reservoir ages in the North Atlantic means that this parameter is sensitive to changes in deep-water formation through time. Meanwhile, boron isotopes provide insights into Atlantic carbon storage and release through millennial scale climate events. We present new high-resolution radiocarbon reservoir age estimates from four cores in the north Atlantic: ODP Site 983, Site 980, DAPC2 and EW9302-2JPC coupled with $\delta^{11}$B from ODP Site 980. Based on the new data, we present a model of ocean circulation and carbon cycling during millennial scale climate events that is consistent with the shifts observed in radiocarbon, $\delta^{11}$B and $\delta^{13}$C over the deglaciation.
Episodic dumping of ice rafted organisms on the Amundsen shelf, Antarctica

MINKYOUNG KIM\textsuperscript{1} EUN JIN YANG\textsuperscript{2} HYUNG JEEK KIM\textsuperscript{3} DONGSEON KIM\textsuperscript{3} SANGHOON LEE\textsuperscript{2} JEOMSHIK HWANG\textsuperscript{1}

\textsuperscript{1}School of Earth and Environmental Sciences/Research Institute of Oceanography, Seoul National University, Seoul, South Korea
\textsuperscript{2}Korea Polar Research Institute, Incheon, South Korea
\textsuperscript{3}Korea Institute of Ocean Science & Technology, Ansan, South Korea

We found the Parborlasia corrugatus, a common benthic species, were intercepted episodically in the sediment trap cups, deployed 130 and 567 m above the sea floor, respectively, on bottom tethered moorings in the sea ice zone and near the Dotson Ice Shelf inside the Amundsen Sea Polynya in the Amundsen Sea.

The organic carbon flux derived from the P. corrugatus was equivalenced to 40 % and 500 % of the corresponding organic carbon flux of fine sinking particles. A likely mechanism may be acquisition of these organisms by anchor ice on the McMurdo Sound, and/or the ice scouring by fast ice along the coastline of Bear Peninsula and eastern coast of the Amundsen Shelf. Considering the probability of the individuals being caught by the sediment traps, the transport of benthic organisms by this mechanism may be prevalent in this region.
Heinrich Stadial 1 caused by acceleration of Eurasian deglaciation
~18.5 ka

RUZA IVANOVIC¹, LAUREN GREGOIRE¹, ANDREW WICKERT², ANDREA BURKE³, PAUL VALDES⁴

¹School of Earth and Environment, University of Leeds, UK. r.ivanovic@leeds.ac.uk, l.j.gregoire@leeds.ac.uk
²Department of Earth Sciences, University of Minnesota, USA. awickert@umn.edu
³Department of Earth and Environmental Sciences, University of St. Andrews, UK. ah276@st-andrews.ac.uk
⁴School of Geographical Sciences, University of Bristol, UK. p.j.valdes@bristol.ac.uk

Heinrich Stadial 1 (~18-15 ka) is characterised by slow Atlantic Meridional Overturning Circulation (AMOC) and relatively cold Northern Hemisphere temperatures. Until recently, such conditions were largely attributed to the effect of North Atlantic surface freshening from enhanced iceberg calving (Heinrich Event 1). However, climate models have repeatedly struggled to simulate Heinrich Stadial 1 using realistic iceberg-derived freshwater fluxes, and it has recently been shown that Heinrich Event 1 began well after the onset of the AMOC slow down and northern cooling, and thus could not have caused it.

We ran the ICE-6G.C (VM5a) global ice sheet reconstruction through a high resolution drainage network routing model to produce fully-distributed meltwater discharge for the period spanning 21-17 ka. We then used the resultant global, transient meltwater flux to force the coupled ocean-atmosphere-vegetation General Circulation Model HadCM3, which was otherwise set up according to conditions at 21 ka.

The model simulates a 20% reduction in maximum AMOC strength in response to accelerated Eurasian ice sheet melt delivered to the Arctic Ocean, starting ~18.5 ka. This in turn drives North Atlantic sea surface and surface air cooling of 1-5 °C, with even greater cooling occurring over regions with increased sea ice cover. Surface air temperature anomalies are largest during the Boreal Winter, but sea surface temperature changes are less seasonal. More widely, Eurasia cools by 1-3 °C, and the Southern Hemisphere undergoes weak warming of under +1 °C. The simulated climate matches a suite of geochemical climate proxy indicators, including Pa/Th measures of AMOC strength, alkenone-derived North Atlantic sea surface temperatures, Greenland ice core surface air temperatures, and precipitation changes inferred from Hulu Cave speleothems and Cariaco Basin reflectance data.
Laurentian Channel bottom water temperature as a proxy for AMOC intensity

CHRISTELLE NOT and BENOIT THIBODEAU

1 The University of Hong Kong, Hong Kong; cnot@hku.hk

It was recently suggested that the AMOC dramatically weakened during the last century, which is thought to be exceptional during the last millenium. This weakening should translate into a decrease in the strength of the Labrador Current (LC), the Labrador Subarctic Slope Water (LSSW) and the recirculation gyre in the western North Atlantic. Consequently, this should allow the Gulf Stream to penetrate onto the East Canadian shelf. Interestingly, this change should be recorded by Laurentian channel bottom water, which take its source at around 450 meters depth.

We observed strong similarity between the instrumental temperature of the Laurentian channel bottom water and the AMOC-index for the last 70 years. In addition, recent warming in the Laurentian Channel was attributed to a change in the proportion of water masses entering the channel, namely an increase proportion of Atlantic Temperate Slope Water (ATSW). Interestingly, the increase of the ATSW was seen in annually-resolved δ¹⁸O from corals off the East Canadian coast suggesting the increased presence of nutrient-rich water during the last century, a unique feature of the last millennium.

Thus, we believe that temperature of the Laurentian channel bottom water can serve as a robust proxy to reconstruct the AMOC intensity. This present a crucial advantage: temperature is a relatively straightforward parameter to reconstruct and δ¹⁸O of benthic foraminifera was proven a solid temperature proxy for this water mass.

Here we used sediment record from the Laurentian Channel to investigate the presence of warm water originating from the Gulf Stream and thus the AMOC intensity. Our results suggest that the last century warming is unprecedented not only for the last millennium but for the last 6 000 years.

Glacial-Interglacial Gradients in Biogenic Export Fluxes along a Meridional Transect in the Southern Indian Ocean

LENA M. THÔLE1,2, SAMUEL L. JACCARD1, JÖRG LIPPOLD2, ALFREDO MARTÍNEZ-GARCÍA3, ALAIN MAZAUD4, ELISABETH MICHEL4

1Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland. lena.thoele@geo.unibe.ch
2Institute of Earth Sciences, University of Heidelberg, Germany.
3Max Planck Institute for Chemistry, Climate Geochemistry Department, Mainz, Germany.
4Laboratoire des Sciences du Climate et de l’Environnement (LSCE), Gif-sur-Yvette, France.

For the earth’s climate during glacial-interglacial cycles, the partitioning of CO2 between the ocean and atmosphere is crucial. The Southern Ocean, in particular, proves to play a major role, as variations in both physical and biogeochemical processes have the potential to regulate the uptake and release of CO2. First, vertical mixing intensities close to the Antarctic continent bring CO2-and nutrient-rich waters to the surface ocean contributing to release CO2 to the atmosphere; on the other hand, export production transports CO2 to the ocean interior, where it can be sequestered for centuries. Combined, these processes can partially explain pCO2 trends recorded in Antarctic ice cores. However, different zones in the Atlantic sector of the Southern Ocean show different trends of export production for glacial/interglacial periods demanding for separate investigations.

To further test these hypothesis, we present new sediment records from the Southern Indian Ocean, a region that has yet been largely undersampled, adding up to existing records for a more complete picture of past Southern ocean dynamics. We report 230Th-corrected biogenic opal, carbonate and alkenone fluxes on two highly resolved sediment cores in the polar and subantarctic zone, respectively, to reconstruct changes in export production since the penultimate glacial period. Additionally, redox-sensitve trace metals that reflect the oxygenation state of deep waters provide additional evidence allowing to reconstruct changes in deep ocean ventilation. This combined approach will give important new constraints to further document changes in the efficiency of the biological pump accompanying changes in the dynamics in the Southern Indian Ocean and allow for comparisons with previously published records from the South Atlantic.
Goldschmidt2017 Abstract

Geochemical tracing of varying northern vs. southern water-masses contributions in the sub Antarctic Atlantic ocean (MD07-3076) since the last glacial maximum.

FRANÇOIS BENY¹, VIVIANE BOUT-ROUMAZEILLES², GARETH DAVIES³, ALOYS BORY, JULIA GOTTSCALK, LUKE SKINNER, CLAIRE WAEELBROECK, ELISABETH MICHEL, ALAIN MAZAUD, MARION DELATTRE, ROMAIN ABRAHAM

¹beny.francois@gmail.com
²Viviane.bout@univ-lille1.fr
³g.r.davies@vu.nl

The Southern Ocean (SO) is a key area for the understanding of the carbon cycle. Being today a sink today, it acted as a source of atmospheric CO2 during the last glacial maxima. The interest of constraining the deep water masse variations through time is then obvious. The variation of deep oceanic circulation in the Atlantic sector of the SO during the last climatic cycle have been widely studied. However, only a few studies focused on the sediment load of these water masses and on their terrigenous signal although these parameters enable to reconstruct the dynamic components of deep ocean circulation. Here, we propose to reconstruct the particle ‘source to sink’ in the SO during the last climatic cycle in order to characterize the dynamical variations of the main water masses. These first results are based on grain-size distribution, clay mineralogy, and Sr and Nd isotopic composition of distinct grain-size fractions of the sediments. This study shows (1) a decrease of the contribution of Southern-borned water masses (i.e. Circumpolar Deep Water, Antarctic Bottom Water) associated with an increase of the North Atlantic Deep Water during the deglaciation; (2) a strong impact of the continental climate conditions (hydrolysis) over the South American sediment delivery to the ocean during the Holocene; (3) unexpected sedimentological and geochemical variations during Heinrich Events suggesting strong and brutal modifications of North Atlantic Deep Water vs. AntArctic Bottom Water contributions during these periods.
The glacial-Holocene evolution of water masses in the Bay of Bengal based on δ18O and δ13C analyses

R. MA*1, S. SEPULCRE1, L. LICARI2, F. BASSINOT3, Z. LIU4, N. KALLEL2 AND C. COLIN1

1GEOPS, Université Paris-Sud, CNRS, Université Paris-Saclay, Rue du Belvédère, Bât. 504, 91405, Orsay, France (*correspondence: rui-fang.ma@u-psud.fr)
2CEREGE, Aix-Marseille Université –Europole de l’Arbois - BP80, 13545 Aix-en-Provence cedex 4, France
3IPSL–LSCE, CEA CNRS UVSQ, UMR 8212, F-91190 Gif Sur Yvette, France
4State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China
5Université de Sfax, Faculté des Sciences, Laboratoire GEOGLOB, BP 802, 3038 Sfax, Tunisia

The Indian Ocean is an important area to understand the global ocean circulation, especially for intermediate water masses (IW). We combined benthic foraminiferal stable isotope records (δ13C and δ18O) and statistical analyses of benthic assemblages from Core MD77-176 (14°30’5N, 93°07’6E, 1375 m [1]) to reconstruct changes in the IW in the Bay of Bengal since the Last Glacial Maximum (LGM).

δ18O and δ13C analysis were performed on Cibicidoides pachyderma, C. wuellerstorfi and Uvigerina peregrina. The δ18O values range between 1.66 to 3.61‰, with a maximum during the LGM, a marked decrease at 12.7 ka and lower values during the Holocene. Coeval variations are observed between planktonic [1] and benthic δ18O records during the LGM, whereas inverse trends exist during the Late Deglaciation and across the Holocene. The δ13C values vary from -0.46 to 0.54‰ and are lower during the LGM, at 12.54 and 9.82 ka, and higher during the Holocene. The records tend to show, therefore, that during the Holocene, the IW were better ventilated than during the LGM, suggesting a change in the source of IW and/or in the circulation rate. Changes in assemblages are in good agreement with the geochemical records, suggesting a higher oxygen concentration and lower nutrients contents, associated to an oligo- to mesotrophic environment during the Holocene. However, negative shifts in the δ13C are observed during the Holocene, linked to a lower oxygen concentration and/or meso- to eutrophic conditions, reflecting events of poorer IW ventilation and/or water pulses from another source. Future analysis (elemental ratios and 14C) will help to decipher the mechanisms ruling past changes in the IW at the core site.

Northern North Atlantic sea ice, temperature, and carbon cycle interactions through the Common Era using coralline algae

E. ANAGNOSTOU1,2*, B. WILLIAMS3, P. MOFFA-SANCHEZ4, G.L. FOSTER5, W.H. ADEY6, I. WESTFIELD2 AND J. RIES2

1 ETH Zurich, 25 Clausiusstrasse, ZH 8092, Switzerland  
(*correspondence: eleni.anagnostou@erdw.ethz.ch)  
2 Marine Science Center, Northeastern University, 430 Nahant Rd, Nahant, MA 01908, USA  
(j.ries@northeastern.edu, i.westfield@northeastern.edu)  
3 Claremont McKenna-Pitzer-Scripps College, 925 N. Mills Ave, Claremont, CA 91711, USA  
(bwilliams@kecksci.claremont.edu)  
4 Cardiff University, Cardiff CF10 3AT, UK  
(moffasanchezp1@cardiff.ac.uk)  
5 Ocean and Earth Science, European Way, Southampton SO14 3ZH, UK (gavin.foster@noc.soton.ac.uk)  
6 National Museum of Natural History, Smithsonian Institution, Washington, DC 20013, USA (adeyw@si.edu)

The growth rate of Arctic and Subarctic coralline alga Clathromorphum compactum has been linked to sea ice extent, considering its dependence to temperature and light, at least in the short term. In this new study, we focus on two newly developed proxies in aquaria linking the boron isotopic composition of the algal high magnesium calcite skeleton to seawater pH and its Mg/Li ratio to seawater temperature. We applied these proxies on algae collected from two locations: one within the Canadian Arctic and the other on the Labrador Coast influenced by the Arctic Labrador Current. At both locations we see significant changes in pH and temperature over the last ~600 years. In the earlier part of our record, within the Medieval Warm Period and the Little Ice Age, these changes are linked to sea ice growth and retreat. Post 1850 CE, boron isotopes and Mg/Li ratios document a progressive ocean acidification and warming signal. This trend was interrupted by further decline in sea ice extent and increase in Greenland meltwater, that enhanced algal growth in the region, resulting in increasing seawater pH. During the same time, the algal Mg/Li ratios indicate cooler temperatures in the Labrador region, potentially linked to the coeval Atlantic Meridional Overturning Circulation decline post ~1950. We will discuss our seawater pH and temperature reconstructions in light of changes in growth and calcification, ocean warming and acidification, and variations in North Atlantic atmospheric and oceanic circulation.
Intensification of Antarctic Ocean stratification at the end of the mid-Pleistocene transition

A.P. HASENFRATZ¹, S.L. JACCARD², A. MARTÍNEZ-GARCÍA³, D.A. HODELL⁴, D. VANCE⁵, S. BERNASCONI¹, H.F. KLEIVEN⁶, D.M. SIGMAN, G.H. HAUG¹

¹ Geological Institute, ETH Zurich, Switzerland
² Institute of Geological Sciences, Univ. of Bern, Switzerland
³ Max Planck Institute for Chemistry, Mainz, Germany
⁴ Godwin Laboratory for Paleoclimate Research, Univ. of Cambridge, UK
⁵ Institute of Geochemistry and Petrology, ETH Zurich, Switzerland
⁶ Department of Earth Science, Univ. of Bergen, Norway
⁷ Department of Geosciences, Princeton Univ., USA

The causes of the mid-Pleistocene transition (MPT; ~1.2 to 0.7 million years ago), when the climate cycles shifted from 41- to ~100-kyr periodicities, are not fully understood. Many of the proposed hypotheses involve global cooling and an associated decline in glacial atmospheric CO₂. Whereas evidence suggests that the ice ages prior to the transition were characterised by atmospheric CO₂ concentrations 30–40 ppmv higher than today, the mechanisms accounting for the CO₂ drawdown remain unclear. Here we use surface- and bottom-dwelling foraminifera from the Antarctic Ocean to reconstruct the vertical density gradient of the past 1.5 million years, a process crucial in controlling the partitioning of CO₂ between the ocean interior and the atmosphere. We found that an abrupt increase in glacial stratification occurred towards the end of the MPT, coinciding with the emergence of the dominant high-amplitude 100-kyr glacial cycles. While iron fertilization in the Subantarctic Ocean likely played a major role in enhancing oceanic carbon sequestration, we propose that the reconstructed changes in the Antarctic Ocean were instrumental in finalising the transition to more prolonged and severe ice ages, allowing Northern Hemisphere ice sheets to survive periods of obliquity-paced summer insolation maxima.
The radiocarbon fingerprint of different Meridional Overturning Circulations

J. E. DENTITH1*, R. F. IVANOVIC1, L. J. GREGOIRE1, J. C. TINDALL1, AND L. F. ROBINSON2

1School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK (*correspondence: eejed@leeds.ac.uk)
2School of Earth Sciences, University of Bristol, Bristol, BS8 1RJ, UK (Laura.Robinson@bristol.ac.uk)

Changes in the strength and structure of the Atlantic Meridional Overturning Circulation (MOC) may have played a key role in abrupt palaeoclimatic transitions and could result in significant climatic impacts in the future. Carbon isotopes can be used to infer palaeoceanographic circulation changes. However, discrepancies exist in the interpretation of isotopes in geological archives. By directly simulating isotopic tracer fields within complex numerical models, tracer concentrations can be compared to observations rather than the more uncertain climatic interpretations. We simulate the radioactive isotope $^{14}$C in the ocean component of the FAMOUS General Circulation Model to study large-scale ocean circulation, the oceanic carbon cycle, and air-sea gas exchange. This abiotic tracer implementation accounts for the effects of air-sea gas exchange, advection and radioactive decay. The model was spun-up for 10,000 years to allow $^{14}$C concentrations in the deep ocean to equilibrate. Here, we evaluate the model’s ability to reproduce $^{14}$C distributions in the pre- and post-bomb eras. We find that the model is able to reproduce the main features of observed $\Delta^{14}$C in the surface ocean, zonal means and depth profiles. We also use the isotope-enabled model to investigate the surface climatologies and $^{14}$C fingerprint of different MOC stability regimes, as identified by net freshwater import into the Atlantic ($F_{\text{w}}$). The overall aim is to improve our understanding of palaeoceanographic circulation changes at the Last Glacial Maximum (21,000 years ago) and during the last deglaciation (21,000-11,000 years ago).
Sedimentary δ\(^{13}\)C\(_{\text{org}}\) and pigments in coastal ponds of Ross Sea, East Antarctica and their paleoenvironmental implication

XIAODONG LIU*, QIANQIAN CHEN, YANGYANG WEI, JING JIN, YAGUANG NIE

Institute of Polar Environment, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui, P R China (ycx@ustc.edu.cn)

The carbon isotopic compositions of total organic matter (δ\(^{13}\)C\(_{\text{org}}\)) and photosynthetic pigments in lake algae are important proxies for identification of organic matter source and reconstruction of paleoenvironmental records because they can be well preserved in Antarctic lacustrine sediments after deposition. δ\(^{13}\)C\(_{\text{org}}\) measured in the freshwater algae samples from the coastal ponds of Ross Sea region were very high up to about −12‰. The sedimentary δ\(^{13}\)C\(_{\text{org}}\) values from different ponds of Ross Sea were very different, indicating the different source of sedimentary organic matter. Some lacustrine sediments had relatively high δ\(^{13}\)C\(_{\text{org}}\) almost in accordance with that of the studied lake algae, indicating organic matter predominantly sourced from aquatic algae, while the obviously low δ\(^{13}\)C\(_{\text{org}}\) values in some sediment profiles evince significant influence from penguin guano with algae as the secondary source. Based on the identification of sedimentary organic matter in the ponds, the sedimentary pigments had been analyzed for the sediment samples with different organic source using high performance liquid chromatography coupled with atmospheric pressure chemical ionisation mass spectrometry (HPLC-APCI-MS). The results showed that the pigment concentrations including chlorophyll a, chlorophyll b, zeaxanthin, echinenone, canthaxanthin, β-carotene, fucoxanthin, diadinoxanthin, peridinin and alloxyanthin displayed large fluctuation against depth, and most of them showed almost consistent change trends. Based on the CHEMTAX analyses, we tentatively reconstructed the sedimentary record of algal community change and examined the possible effects of seabird activity on lake primary productivity and algal community structure. The results showed that chlorophyta, cyanophyta and diatom were the dominant species, and the input of penguin droppings promoted the growth of algae, especially for the chlorophyta, and thus increased lake primary productivity. The nutrient input derived from penguin droppings could cause the change of algal community structure in the coastal ponds and lakes of Antarctic region.
Out of the woods – driftwood provenance as a proxy for Holocene Arctic sea ice dynamics

G.M. Hole¹, M. Macias-Fauria¹, D. Porcelli²

¹School of Geography and the Environment, University of Oxford, Oxford, UK. (*correspondence: georgia.hole@ouce.ox.ac.uk)
²Department of Earth Sciences, University of Oxford, Oxford, UK.

The rapid decline in Arctic sea ice extent, age and thickness is well documented, with such changes due to cause far-reaching impacts. At present unknowns remain of the nature of the spatio-temporal Arctic sea ice fluctuations of the Holocene preceding satellite observation, limiting the extrapolation of modern trends to predictions of future change. The use of driftwood as a novel proxy utilises the knowledge base from previous work that has shown it to be a robust proxy for sea-ice reconstructions in the Arctic [1], with driftwood transport and deposition determined by sea ice and surface current dynamics. Or work utilises the use of isotopic analysis of driftwood tissue, specifically using Strontium 87Sr/86Sr radiogenic isotope ratios, which have been previously explored for provenance studies as a useful geochemical tracer due to not being significantly fractionated by biological processes such as incorporation into wood tissue [2, 3]. Combined with a framework of potential source Strontium signatures, this enables a spatial link between the deposited driftwood and its originating growth site, leading to a robust reconstruction of the wood-bearing sea ice dynamics. Combined with links between ice movement with the expansion and contraction of the Arctic Ocean circulations of the Beaufort Gyre and Transpolar Drift, the method enables a proxy-based reconstruction of Arctic sea ice and broader climatic states throughout the Holocene.

REFERENCES
Modern and Holocene hydrological variations of the NE Atlantic inferred from Nd isotopic composition analyzed on seawater and deep-sea corals

C. Colin1*, L. Bonneau1, Q. Dubois-Dauphin1, E. Pons-Branchu2, E. Douville2, N. Tisnerat-Laborde2, M. Elliot3, M. Douarin1, F. Mienis4, N. Frank5, D. Swingedouw6, F. Eynaud6

1Laboratoire GEOPS, Université de Paris-Sud, Université Paris-Saclay, France (correspondence: christophe.colin@u-psud.fr)
2LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
3LPGNantes, Université de Nantes, France
4Royal Netherlands Institute for Sea Research (NIOZ), Den Burg, Netherlands
5Universität Heidelberg, Im Neuenheimer Feld 229, 69120 Heidelberg, Germany
6EPOC, UMR CNRS 5805, Université de Bordeaux, France

The North Atlantic plays a major role in the European climate via the Atlantic Meridional Overturning Circulation (AMOC) that is intimately tied to the salt and heat budget in the north Atlantic gyres. The strength of the subpolar gyre as well as the northern limit of MSW and subtropical waters are important components of mid-latitude Atlantic climate variability that are in turn linked to the atmospheric circulation and freshwater fluxes from the Arctic. However, little is known about the sensitivity of the gyres and boundary currents to wind stress and freshwater perturbations over long time-scale such as the Holocene. HAMOC (Holocene North Atlantic Gyres and Mediterranean Outflowing dynamical through Climate Changes) is an integrated multidisciplinary climate research project that take up the challenges of improving present knowledge of the AMOC variability and links with the Mediterranean outflow during the Holocene. Here, we present a new set of εNd data obtained on seawater and precisely dated cold-water corals (U/Th dating) collected in the NE Atlantic to reconstruct the re-circulation of water occurs through basin scale, gyres circulations and boundary currents at surface and at mid-depth. More particularly, we will show the interest to use εNd proxy to reconstruct the eastward extension and strength of the subpolar gyre water as well as the northern limit of MSW and subtropical gyre waters in the NE Atlantic.
Climate-related formation of cold-water coral mounds in the Alboran Sea since the mid-Pleistocene transition

T. KRENGEL1,2,*, C. WIIENBERG3, D. HEBBELN3, J. ARPS2, R. EICHSTAEDTER3, N. FRANK1,2

1Institute for Earth Science, University of Heidelberg, Germany (tkrengel@iup.uni-heidelberg.de)
2Institute of Environmental Physics, University of Heidelberg, Germany
3MARUM-Center for Environmental Sciences, University of Bremen, Germany

Framework forming cold-water corals (CWC) such as Lophelia pertusa and Madrepora oculata have built giant seabed structures such as ridges and mounds in the southern Alboran Sea (East Melilla coral province) at depths ranging from 230 m (Dragon Mounds) to 450 m (base of Brittlestar Ridge). In 2014, these coral mounds and ridges were drilled using the Bremen Seafloor Drill Rig (MeBo), providing up to 70-m-long cores of coral-bearing sediment. Here, we present results of coral ages obtained from two MeBo cores: Dragon Mound (35°18.6’ N; 2°34.9’ W, 236 m), which was fully penetrated down to its base at 62 m depth, and the Brittlestar Ridge (35°26.1’ N; 2°30.8’ W, 329 m) whose core encompasses roughly half of its overall height of 150 m. Using high precision Th/U dating and Sr-Isotope stratigraphy, the discontinuous nature of coral mound formation is revealed. The more than 200 dated corals, mostly of pristine preservation, show a remarkable mound aggradation pattern back to ~500 ka, marked by a 100-kyr cyclicity. Periods of sustained coral proliferation seem coincident to warm climates with vertical mound aggradation rates of up to 140 cm/kyr. In contrast, during cold climate periods corals occurred in strongly reduced numbers likely hampering mound growth. Based on these results, we assume that the initial formation of the largest mounds, such as Brittlestar, started during the mid-Pleistocene transition some 0.8 to 1.2 Million years ago. What caused mound growth to begin and the key environmental factor which influence it remain to be discovered.
Changes in North Atlantic deep water provenance across glacial Terminations during the past one million years


1 Institute of Environmental Physics, Heidelberg University, Germany (*correspondence: jasmin.link@iup.uni-heidelberg.de)
2 GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany
3 Institute of Earth Sciences, Heidelberg University, Germany
4 LSCE, Gif-sur-Yvette, France

The Atlantic Meridional Overturning Circulation (AMOC) plays a key role in the global heat balance and was subject to substantial changes during the Pleistocene. Dramatic variations in the density structure and deep water circulation patterns in the Atlantic occurred across glacial-interglacial cycles and themselves exerted a strong influence on climate.

We present a record of deep water mass provenance in the Northwest Atlantic covering the last one million years, with a special focus on glacial-interglacial transitions. To this end, we reconstructed dissolved deep water Nd isotopic compositions from the authigenic fraction of bulk sediments of ODP Site 1063 on the Bermuda Rise for glacial Terminations T-IV, -V, and -VII to -XII and compare these to published records of T-I, and –II [1-4]. This allows us to better characterize the state and potential role of the AMOC during major climate transitions since the late Early Pleistocene.

Following the Mid-Pleistocene Transition (MPT), the glacial maxima are characterized by comparable peak glacial Nd isotopic signatures, whereas interglacials commonly exhibit most unradiogenic signatures during the early interglacial and become more radiogenic afterwards.

In contrast to the other terminations, MIS 11 following T-V shows a sustained extremely unradiogenic isotopic signature pointing to contributions from a different deep water source. Moreover, AMOC transitions recorded within terminations before and during the MPT will be discussed.

Dust flux variations in last 800,000 years: changes of Platinum group elements and Pb isotopic compositions at Dome C EPICA ice cores, Antarctica


1Korea Polar Research Institute (*correspondence: sdhur@kopri.re.kr)  
2National University of Mongolia, Mongolia  
3Inha University, Korea  
4Curtin University of Technology, Australia  
5The Ohio State University, USA  
6University of Venice, Italy  
7Saint Martin d’ Hères Cedex, France

Trace elements and Platinum group elements (PGE) concentrations and lead isotopic compositions were measured from the EPICA (European Project for Ice Coring in Antarctica) Dome C ice core, covering a period from ~570 kyr BP to ~800 kyr BP, by inductively coupled plasma sector field mass spectrometry (ICP-SFMS) and thermal ionization mass spectrometry (TIMS) for trace elements and platinum group elements (PGEs), and Pb isotopic compositions, respectively. The main trend of trace element and other proxy concentrations match well defined insoluble dust concentration profile. It shows that mineral dust was the dominant source of trace elements to East Antarctica whatever the period. For In, Tl, Bi and F- the volcanic proxies were partially increased with higher 206Pb/207Pb during the period from ~690 kyr BP to ~740 kyr BP. Although Pb concentration variations coincide with crustal dust, the Pb isotopic compositions do not coincide with crustal dust. It means that the Pb isotopic compositions were influenced by volcanic input or other materials that periods. Mean concentrations of Ir and Pt for the glacial periods were approximately two times higher than their mean concentrations for the interglacial periods. Concentration ratios (Ir/Pt) and crustal enrichment factors (EFc) of Ir and Pt indicate that atmospheric PGE in Antarctica may be originated dominantly from non-crustal sources. These geochemical and isotopic evidence suggest that changes in relative contribution of crustal dust, volcanic and extraterrestrial input to Antarctic ice during period from ~570 kyr BP to ~800 kyr BP.
Evolution of deep-water circulation in the Indian-Atlantic ocean gateway since late Miocene from authigenic neodymium isotope records

N. LATHIKA1*, WALIUR RAHAMAN1, SIDNEY R HEMMING2, MELOTH THAMBAN1, IAN R HALL3, LEAH J LEVAY4 AND EXPEDITION 361 SCIENTIFIC PARTY

1NCAOR, Goa, India (*lathika@ncaor.gov.in)
2LDEO, Columbia University, USA
3Cardiff University, UK
4IODP, Texas A&M, USA

The Agulhas Current is the largest western boundary current in the Southern Hemisphere [1] exporting warm and saline water from tropical Indian Ocean to the Atlantic, thereby playing a vital role in controlling the thermohaline circulation (THC) and global climate. To understand the influence of Agulhas Current system on Atlantic Meridional Overturning Circulation (AMOC), it is important to understand the past deep-water circulation variability in this region.

Authigenic Neodymium isotope (En_d) is a potential proxy to trace past deep water circulation as it is unaffected by any biological and physical processes [2]. In this study, we are reporting the initial data on Nd isotope in foraminiferal shells and fish teeth, hand-picked from the sediment recovered during the IODP Expedition 361 [3] from the Agulhas Plateau (Site U1475). This site is located on the Southwestern flank of Agulhas Plateau (41° 25.61ʹ S; 25° 15.64ʹ E) through which North Atlantic deep water (NADW) enters into the southern Indian Ocean and hence is suitable for understanding the variability of NADW export. The En_d record will help to elucidate the major changes in the deep-water circulation in the Indian-Atlantic gateway during major climate transitions since late Miocene.

Glacial intensification of the Benguela Current

N. FRANK1, C. ROESCH1, A.-M. WEFING2, C. WIENBERG3, M. LAUSECKER1, J. FÖRSTEL1, A. SCHRÖDER-RITZRAU1, S. THERRE1, R. FRIEDRICH4, J. ARPS1, D. HEBBEN5, C. DULLO5, A. FREIWALD6

1 Institute of Environmental Physics, Heidelberg University, Germany (Norbert.Frank@iup.uni-heidelberg.de)
2 Laboratory of Ion Beam Physics, ETH Zürich, Switzerland
3 MARUM, Center for Marine Environmental Sciences, Bremen, Germany
4 Klaus-Tschira- Laboratory for Radiometric Dating Methods, CEZ - Mannheim, Germany
5 GEOMAR, Helmholtz Centre for Ocean Research, Kiel, Germany
6 Marine Research Department, Senckenberg am Meer, Wilhelmshaven, Germany

The Benguela current feeds cold and nutrient rich waters into the south Atlantic gyre fueling high rates of phytoplankton growth. Its strength is tidily coupled to the southern hemisphere atmospheric circulation and surface ocean recirculation. Framework forming cold-water corals such as Lophelia pertusa and Madrepora oculata develop north of today's Angola-Benguela Front on the so called Scary Mounds (9°49.331'N; 12°46.565'E; 338m): U-series dating of fossil fragments from these mounds now reveals that corals also developed during the past 33'000 years, hence, including times of global warm and glacial climate conditions. Based on the coral skeletons [Li]/[Mg] ratio and its radiocarbon content, we show first evidence of strong glacial cooling by 6.5±2°C and radiocarbon aging (R = 900±100 years) of tropical thermocline waters. The coral mounds are situated well below the highly dynamic surface layer near today's 10°C isotherm, and are predominantly influenced by the northward advection of thermocline waters through the Benguela current. We interpret the massive cooling and significant aging of thermocline waters as a glacial intensification of the Benguela Current system driven by an enhanced Hadley circulation. In addition, the northward advected glacial mid-depth water from the Antarctic circumpolar current must have been colder and radiocarbon aged as well.
Tracing dust sources in the Atlantic Southern Ocean during the last 160 ka

OPHÉLIE LODYGA¹, ², SYLVAIN PICHAT¹, ², ALFREDO MARTÍNEZ-GARCÍA² AND STEVE GALER²

¹ Laboratoire de Géologie de Lyon, ENS de Lyon, CNRS UMR 5276, 69007 Lyon, France
² Max Planck Institut for Chemistry, Climate Geochemistry, 55128 Mainz, Germany

The Southern Ocean is a “high-nutrient low-chlorophyll” area where iron availability is a key component to primary productivity, which in turn influences the carbon cycle. The main supply of iron to the Atlantic Southern Ocean is dust, originating mostly from South America. During ice ages the increased dust supply to the Southern Ocean enhanced the primary productivity, which then influenced the CO₂ leakage.

Both iron concentration and bioavailability in dust depend on the type of material the dust derives from. Thus identifying potential source areas would allow a better characterization of the iron supplied to the ocean.

Lead, Sr, and Nd isotopic signatures of the detrital fraction in marine sediments are powerful tools to trace dust sources. Here, we have studied core ODP 1090, a well-documented core located in the east Atlantic sector of the Southern Ocean. In particular a tight connection between the dust inputs and the atmospheric CO₂ variations has been identified in this core. We will measure Pb, Sr, and Nd isotopic compositions over the last 160 ka with an average resolution of 5 ka. Preliminary results show large variations in the $^{87}$Sr/$^{86}$Sr ratios: 0.711 to 0.719. These values mostly fall in the field of South American sources; however contributions from Australia or South Africa cannot be excluded. We will measure Pb and Nd isotopic compositions to further precise the origins of dust.
Nd Isotopes in the North Atlantic endmember of the AMOC over the last 1.3 Ma

Jaume-Seguí, M.¹, Goldstein, S.L.¹, Pena, L.D.², Kim, J.¹, Yehudai, M.¹, Knudson, K.¹, Basak, C.¹, Hartman, A.E.³, Lupien, R.⁴

¹Lamont-Doherty Earth Observatory, Columbia University, NY, USA
²Department of Earth and Ocean Dynamics, University of Barcelona, Spain
³USGS, Columbia, MO, USA
⁴Department of Geological Sciences, Brown University, RI, USA

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The Atlantic Meridional Overturning Circulation is an important means for distributing heat between the tropics and the high latitudes, and its temporal variability has major impacts on ice age cycles. As part of a project to generate profiles of the AMOC from the North Atlantic to the Southern Ocean at time slices over the past ~2 Ma, we have analyzed Nd isotopes in Fe-Mn-oxide encrusted foraminifera and fish debris in DSDP Site 607 (41°00’N, 32°58’W, 3,427 m) on the western flanks of the Mid-Atlantic Ridge and ODP Site 1063 (33°41´N, 57°37´W, 4,584m) in the abyssal plain near the Bermuda Rise. Thus both Sites are in the deep western North Atlantic basin, and were targeted to constrain the variability of εNd in the North Atlantic endmember.

Our data show that εNd-values of Site 607 during interglacials are consistently close to the modern day NADW value of εNd ~ -13.5, as well as literature values for Fe-Mn crusts. During glacials, Site 607 shows more positive εNd values than interglacials, averaging ~ -12 prior to the Mid-Pleistocene Transition and ~-11 since the MPT. Moreover, the glacial-interglacial εNd variability covaries with benthic δ¹³C, and both are consistent with a small component of Southern-sourced water reaching the site during glacial. During the MPT “AMOC crisis” of Pena and Goldstein (Science 2014), Site 607 shows more positive εNd-values between MIS 25 and 21 indicating a strong and lasting incursion of southern waters into the deep North Atlantic. In contrast to the Site 607data, the values in Site 1063 fluctuate wildly, showing extreme εNd during some interglacials, reaching values of εNd ~ -20 several times. Its most extreme εNd value is ~ -27 during MIS 28, while during MIS 28 the values in Site 607 are between -13 and -14, like modern day NADW.

We conclude that the Site 607 εNd interglacial data represents the North Atlantic endmember of the AMOC, which has remained similar to the value of NADW today, and the higher values during glacials reflect incursion of southern waters into the deep north Atlantic. At the same time, the Site 1063 data do not appear to represent the North Atlantic AMOC endmember, but appear to show local or regional effects, whose mechanism is not yet explained. We are currently working to identify their cause.
Physical and biological controls on phytoplankton blooms in the Amundsen Sea Polynya

HILDE OLIVER*, PIERRE ST-LAURENT, ROBERT SHERRELL, PATRICIA YAGER

1University of Georgia Department of Marine Sciences, Athens, GA 30602
2Center for Coastal Physical Oceanography, Old Dominion University, Norfolk VA 23508
3Rutgers, The State University of New Jersey, New Brunswick, NJ 08901

In the Southern Ocean, no region is more productive (per square meter) than the Amundsen Sea Polynya (ASP) [1]. We sought to determine the mechanisms behind the intense phytoplankton blooms with a physical-biogeochemical model (ROMS), with particular focus on the role of the delivery of glacial meltwater to the polynya from adjacent ice sheets, as a part of the NSF-funded INSPIRE project, the successor to ASPIRE (Amundsen Sea Polynya International Research Expedition). We compared model results with observations from the cruise ASPIRE 2010-11, during which the inception and rise of the bloom was well documented. With the model, we can determine how variability in stratification, wind mixing, and lateral iron inputs between potentially delivered with glacial meltwater, can influence the bloom’s conditions between different stations. With the model, we observe how these factors influence light and nutrient limitation, timing of the blooms, chlorophyll concentration, primary productivity, and carbon export.

Biogeochemical controls on the Mn distribution in Arctic Ocean sediments

LUDVIG LÖWEMARK

1Department of Geosciences, National Taiwan University, Taiwan. ludvig@ntu.edu.tw

Paleoceanographic and paleoenvironmental studies in the Arctic Ocean are hampered by the scarcity of calcareous nanno- and microfossils, making age modeling complicated. In order to construct a chronostratigraphic framework for late Quaternary cores from the Arctic Ocean, alternative stratigraphic tools have been developed. One promising avenue for the correlation between cores is the use of glacial-interglacial swings in the Mn content that allows cores to be correlated over large distances. However, Mn is a redox sensitive element easily influenced by biogeochemical processes, both in the water column and in the sediment. An improved understanding of the biogeochemical processes that control the incorporation of Mn in the stratigraphic record is therefore crucial for the use of Mn as a chronostratigraphic tool. In this study, the diagenetic processes responsible for the dissolution and reprecipitation of Mn are explored, and independent ways of identifying hiatuses in the records are tested.
Goldschmidt2017 Abstract

Drake Passage deep-sea coral records of Southern Ocean ventilation during the last deglaciation

Tao Li1,2, Laura F. Robinson1, Tianyu Chen1, Albertine Pegrum-Haram1, Andrea Burke1, Peter T. Spooner1, George Rowland1, Ana Samperiz1, James Rae3, Maria Prokopenko5, Timothy Knowles6

1Bristol Isotope Group, School of Earth Sciences, University of Bristol, UK
2MOE Key Laboratory of Surficial Geochemistry, School of Earth Sciences, Nanjing University, China
3School of Earth and Environmental Sciences, University of St Andrews, UK
4Department of Geography, University College London, UK
5Department of Geology, Pomona College, California, USA
6Bristol Radiocarbon Accelerator Mass Spectrometry Facility, University of Bristol, UK

Changes of circulation pattern in the Southern Ocean have been invoked to explain a significant portion of the increase in the atmospheric carbon dioxide during the last deglaciation. However the accurate timing and thus underlying mechanisms of these changes are still controversial, requiring knowledge of different water masses movements with absolute age constraints. Aragonitic scleractinian deep-sea corals, recovered from a broad range of depths in the Drake Passage, provide a unique opportunity to investigate Southern Ocean ventilation with precise U-Th age control. A rapid age-screening technique achieved by coupling a laser system to MC-ICPMS enables us to get an approximate age distribution of the coral samples in order to select appropriate specimens for more accurate isotope-dilution age and radiocarbon age determination. Thus far more than 1500 deep-sea corals from the Drake Passage have been dated using this and other techniques. The reconnaissance age results show that deep-sea corals can be found across nearly the whole of the last deglaciation. With known radiocarbon contents and U-Th ages of the deep-sea corals, the ventilation state of different water masses in the past can be assessed based on their decay-corrected \(^{14}\)C activities. We are building on previous work to provide high-resolution \(^{14}\)C records covering the last 20,000 years from multiple locations including Cape Horn at a depth of 1000m, which is today bathed by Antarctic Intermediate Water (AAIW). With U-Th age control this high-resolution record is directly comparable to the Antarctic ice-core records, and can be used to help us better understand the Southern Ocean’s role in global climate and carbon cycle during the last deglaciation.
BIOGEOCHEMICAL CYCLING ON THE YERMAK PLATEAU DURING THE LAST TWO GLACIAL CYCLES

ALLYSON TESSIN1*, CHRISTIAN MÄRZ1, HANS-JÜRGEN BRUMSACK2, MATTHIAS FORWICK1, LUDVIG LÖWEMARK4, JENS MATTHIESSEN1, MATT O’REGAN6, BERNHARD SCHNEITGER2

1School of Earth and Environment, University of Leeds, UK (correspondence: a.c.tessin@leeds.ac.uk)
2Institut für Chemie und Biologie des Meeres, Universität Oldenburg, Germany
3UiT The Arctic University of Norway in Tromsø;
4Department of Geosciences, National Taiwan University
5Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany
6Department of Geological Sciences, Stockholm University, Sweden

Over the past several decades, Arctic sea ice extent has drastically decreased. Sea ice retreat is expected to continue, with model simulations predicting that the Arctic Ocean will become seasonally ice free within several decades. Changes in sea ice extent are likely to have significant effects on nutrient availability and, subsequently, primary productivity. Nutrient cycling in the Arctic Ocean is poorly constrained in the modern, and even less is known about how nutrient availability will evolve as sea ice continues to retreat. Sedimentary records of past biogeochemical cycling are, therefore, important to evaluate and predict the effects changing sea ice export and oceanographic conditions will have on nutrient cycling within the Arctic Ocean.

Here we present paired pore water and sediment analyses from multiple cores retrieved north of Svalbard near the modern summer sea ice margin during the 2015 TRANSSIZ expedition (“Transitions in the Arctic Seasonal Sea Ice Zone”). Based on preliminary age constraints, the longest of these cores (PS92/39-2) includes sediments from the penultimate glaciation (MIS 6) to the Holocene (MIS 1). Initial results indicate a series of high Fe delivery events during the record with Fe concentrations of up to 9.8 wt.% and Fe/Al ratios of up to 1.3. Tight coupling between Fe and P concentrations throughout the record suggests dynamic nutrient delivery and burial in the region during the last two glacial cycles. Our results also suggest that the last two deglaciations were characterized by distinctly different patterns of biogeochemical cycling, suggesting that oceanographic and sea ice dynamics may have produced different responses in nutrient cycling during glacial terminations 1 and 2.
Freshwater input, upwelling, and the evolution of Caribbean coastal ecosystems on the Central American Isthmus

E.L. Grossman¹*, J.A. Robbins¹, P.G. Rachello-Dolmen¹, K. Tao¹, D. Saxena¹, and A. O’Dea²

¹Department of Geology and Geophysics, Texas A&M University, College Station, TX 77843, USA
(∗correspondence: e-grossman@tamu.edu)
²Smithsonian Tropical Research Institute, PO Box 0843-03092 Balboa, Republic of Panama

Caribbean biota underwent major ecological and evolutionary transformation in the Plio-Pleistocene but a lack of detailed paleoenvironmental reconstruction prevents thorough resolution of cause and effect. To reveal ancient conditions in the southwestern Caribbean (SWC) we performed >4000 stable isotope analyses from 57 fossil serially-sampled gastropods. Specimens from 51-100 m paleodepth show a gradual increase in median δ¹⁸O of about 0.6‰ from ~4.25 to 1.6 Ma, similar to the pattern for open ocean G. sacculifer δ¹⁸O [1]. This trend reflects increasing Caribbean salinity resulting from the severance of interoceanic straits during the formation of the Central American Isthmus [1]. Specimens from 0-50 m paleodepth show similar δ¹⁸O ranges for ~5.0-3.0 Ma and today [2] despite increasing seawater δ¹⁸O with ice volume. This likely reflects the nearshore collection of modern specimens.

To quantify upwelling and freshwater input into Caribbean coastal shelf ecosystems over the last ~6 Ma, we use a ‘baseline’ approach that normalizes δ¹⁸O gastropod values to open-ocean δ¹⁸O from planktonic foraminifera. The influence of Pacific-like upwelling in the SWC was low and then negligible after 4.25 Ma. However, we discover that SWC coastal ecosystems were heavily influenced by seasonal freshening until ~2.5 Ma, after which time modern Caribbean conditions with low freshwater influence were established. The oligotrophic Caribbean and associated biota is therefore a result of not only oceanographic change causing declining upwelling, but also declining nutrients from terrestrial sources. We speculate that declining river-derived nutrients was the proximate driver of extinction and the proliferation of modern reef communities in the Caribbean after 2.5 Ma, and may have been caused by decreased rainfall due to a southward shift of the intertropical convergence zone with Northern Hemisphere glaciation.

Sedimentary mercury deposition in the southern Scotia Sea during the glacial stage

J. Kim\textsuperscript{1,2*}, D.I. Lim\textsuperscript{1,2}, H.I. Yoon\textsuperscript{3} and K.-C. Yoo\textsuperscript{3}

\textsuperscript{1}University of Science & Technology, Daejeon 34113, Republic of Korea (Correspondence: jhkim1010@kiost.ac.kr)
\textsuperscript{2}Korea Institute of Ocean Science & Technology, Ansan 15627, Republic of Korea
\textsuperscript{3}Korean Polar Research Institute, Incheon 21990, Republic of Korea

Polar regions have acted as an important atmospheric mercury (Hg) sink, especially during the cold climatic periods. In this respect, seasonal and glacial-interglacial Hg variations, associated with atmospheric mercury depletion events (AMDEs), were extensively documented in snowpack and ice cores \cite{Steffen2008, Jitaru2009}, but only a few attempts have been made to study the sedimentary Hg records in these zones. Here we present the first Hg variations in sediment cores from the southern Scotia Sea, Antarctic, covering the last glacial cycle. Sedimentary Hg concentrations in the cores varied considerably during the past climatic cycles (glacial-interglacial cycles); Hg concentrations ranged from 22 to 75 ng/g, which were primarily controlled by total organic carbon (TOC) contents. Interestingly, TOC-normalized enrichment ratio and flux of sedimentary Hg were higher and more variable during the glacial stage, compared with Holocene. Such elevated Hg level may be associated with large input of Hg enriched-saline water resulting from intense polynya formation in the Weddell Sea during the glacial, coupled with enhanced deposition of atmospheric Hg by dusts and sea-salts. Our result provides new insights into the Hg depositional processes in Antarctic environments, especially during the cold, glacial stages.

\begin{thebibliography}{99}
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ENSO and PDO cycles since Glacial times: a 55,000 year record of inter-annual and decadal variabilities from the Gulf of California

**Pichevin, L.E.*1, Ganeshram, R.S.1, J. Thurow2, A. Nederbragt3**

1 University of Edinburgh, Grant Institute, James Hutton Road, Edinburgh EH9 3FE, UK  
*Correspondence: laetitia.pichevin@ed.ac.uk  
2Department of Earth Sciences, University College London, London, UK  
3School of Earth and Ocean, Cardiff University, Cardiff, UK

Seasonal shifts between terrigenous (riverine) and biogenic inputs to the sea bed associated to disoxic conditions at intermediate depth lead to the rapid deposition and unaltered preservation of annually varved sedimentary sequences in the Gulf of California. These annually resolved sequences document shifts in marine upwelling/stratification and wet/dry conditions on land, which are both strongly controlled by El Niño Southern Oscillations (ENSO) today. Here we present a continuous 55,000 year long record of upwelling-induced biological productivity (biogenic silica and organic carbon) and water column deoxygenation (denitrification) in the Gulf of California at centennial timescales. Several (9) 200 year long, varved sections distributed from the Holocene to the last Glacial period and the millennial scale events of the deglaciation were selected from this long record, and both denitrification and productivity were measured with annual resolution. Spectral and wavelet analyses of the annually resolved records reveal the permanence of ENSO- and PDO-like (Pacific Decadal Oscillation) variabilities throughout the record with only minor deviations in the length of the ENSO and PDO periodicities since the last glacial period. The relative amplitudes of the ENSO- and PDO-like cycles however vary greatly throughout the 55,000 year sequence and exhibit a negative relationship: strong PDO are associated with weak ENSO cycles. While denitrification and deoxygenation respond more prominently to PDO-like variabilities, upwelling-induced productivity is related to the amplitude of ENSO. This is in agreement with the recent observations that today’s intermediate depth oxygen levels are influenced by North Pacific circulation changes (PDO paced) while upwelling-strength in the Pacific eastern boundary currents is strongly controlled by rapid atmospheric oscillations (ENSO).
Oceanographic mechanisms and penguin population increases during the Little Ice Age in the southern Ross Sea, Antarctica

LIANJIAO YANG¹, LIGUANG SUN¹*, STEVEN D. EMSLIE², TAO HUANG¹,³, YUESONG GAO¹, WENQING YANG¹, ZHUDING CHU¹ & YUHONG WANG¹

¹ Institute of Polar Environment, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, Anhui, China (ljyang@mail.ustc.edu.cn, *Correspondence: slg@ustc.edu.cn)
² Department of Biology and Marine Biology, University of North Carolina, 601 South College Road, Wilmington, NC 28403, USA (emslies@uncw.edu)
³ School of Resources and Environmental Engineering, Anhui University, Hefei 230601, Anhui, China (huangt@ahu.edu.cn)

Changes in the oceanic conditions associated with large-scale atmospheric forcing can exert substantial ecological impacts in the Southern Ocean, however, little is known on the coupling of atmospheric circulation, oceanic conditions, and marine ecology over a long time scale. Here, using ornithogenic sediments at Cape Bird, Ross Island, Antarctica, we inferred relative population changes of Adélie penguins in the southern Ross Sea over the past 500 years, and observed an increase in penguin populations during the Little Ice Age (LIA; 1500-1850 AD). We used cadmium content in ancient penguin guano as a proxy of ocean upwelling and identified a close linkage between penguin ecology and atmospheric/oceanic conditions. During the cold period of 1600-1825 AD, a deepened Amundsen Sea Low (ASL) led to stronger winds, intensified ocean upwelling, an enlarged Ross Sea and McMurdo Sound polynya, and thus higher food abundance and penguin populations. We propose a mechanism linking Antarctic marine ecology and atmospheric/oceanic dynamics which provides a new approach on understanding penguin ecological history that allows us to predict future changes with this species.