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Joint workshop

PALSEA - QUIGS

Climate, ice sheets and sea level during past interglacial periods

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Organizers: E. Capron, A. Rovere, R.E. Kopp

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Workshop rationale

The overarching goal of this workshop is to promote cross-cutting initiatives between members of PALSEA and QUIGS, two PAGES-funded working groups. In fact, while workshops from these two projects (and their predecessors) were successful and produced a relevant number of products, the commingling of ideas between the two groups was mostly the result of individual initiatives, and few scientists participated regularly in the activities of both groups. With this joint meeting, we aim to foster a more organized collaboration between PALSEA and QUIGS that is essential to solve a number of outstanding issues that have been identified by both working groups. These issues include:

- Can external (e.g. orbital) or internal (e.g. greenhouse gases) climate forcings explain the observed climate, ice-sheet and sea-level responses based on current knowledge of global physics?
- Does the relationship between interglacial climate and ice sheets/sea level change across the Quaternary? Are there interglacials other than MIS 5e and MIS 11 where we could attempt to link climate and sea level?
- How do interglacial sea-level highstands relate to interglacial high-latitude, global and tropical temperatures?
- Can we reach a firm conclusion on the magnitude of warming and the maximum sea level contribution for Greenland and Antarctic in MIS 5e?

Scientific program

Monday September 24th

8:45-8:55 Bob Kopp: Welcome

8:55-9:15 Alessio Rovere & Emilie Capron: The PALSEA and QUIGS working groups, introduction.

Session 1. Climate, Ice sheets and sea level during the Last Interglacial (Part 1) (Chairs: Natasha Barlow; Anne de Vernal)

9:15-9:35 Sarah Shackleton: Indirect and direct contributions of ocean warming to the MIS5e highstand.

9:35-9:55 Yarrow Axford: How much do we know about climate over Greenland during past warm periods?

9:55-10:15 Russell Drysdale: Nature and phasing of cross-hemispheric climate variability during the Last Interglacial based on Italian and New Zealand speleothem records.

10:15-10:35 Chronis Tzedakis: Climate instability in the North Atlantic and S Europe during the Last Interglacial.

10:35-11:00 *Coffee Break*

11:00-11:20 Emilie Capron: Amplitude and spatio-temporal structure of the Last Interglacial warmth in paleoclimatic records

11:20-11:50 Bette Otto-Bliesner (invited): Interglacial global and high-latitude temperatures and interglacial sea level climate modeling.

11:50-12:10 Feng He: Transient simulation of the last interglaciation and glacial inception in CCSM3.

12:10-12:30 Laurie Menviel: Oceanic circulation and sub-surface warming on the Antarctic continental shelf.

12:30-14:00 *Lunch*

Session 1. Climate, Ice sheets and sea level during the Last Interglacial (Part 2) (chairs: Jeremy Shakun; Chronis Tzedakis)

14:00-14:30 Alex Robinson (invited): The enigmatic past evolution of the Greenland ice sheet.

14:30-14:50 Anders Carlson: Radiogenic evidence on the behavior of West Antarctic ice during the last interglaciation.

14:50-15:20 Jacky Austerman (invited): Estimates of last interglacial global mean sea level from an extended sea level database and improved solid Earth models.

15:10-15:40 *Coffee Break*

15:40-16:10 Andrea Dutton (invited): New chronologies and links between episodic reef growth, meltwater pulses, climate and sea level variability during the Last Interglacial.

16:10-16:30 Natasha Barlow: The ability and limitations of geological archives to fingerprint the source of ice sheet melt.

16:30-16:50 Ian Goodwin: Last Interglacial meltwater signal from far-field sea-level, directional wave climate and proxy-climate.

16:50-17:20 Wrap-up of Session 1

Tuesday September 25th

Session 2. Climate, Ice sheets and Sea levels during older interglacials (Chairs: Jacky Austermann; Eric Wolff)

8:30-8:50 Lorraine Lisiecki: Interactions between ice sheets, orbital forcing and carbon dioxide during the MIS 13 interglacial.

8:50-9:10 Thomas Felis: Tropical Atlantic temperature seasonality during a mid-Pleistocene interglacial from southern Caribbean corals.

9:10-9:30 Anne de Vernal: Distinct climate and ocean conditions from one interglacial to another: example of MIS 31, 13, 11, 5e and 1 in the Labrador Sea.

9:30-9:50 Claude Hillaire Marcel: Record of high interglacial/interstadial sea-level intervals in sedimentary sequences from the central Arctic Ocean.

9:50-10:10 Yair Rosenthal: Hydrographic conditions in the North Atlantic polar region during "warmer-than-present" interglacials and their effect on the East Greenland Ice Sheet.

10:10-10:30 *Coffee Break*

10:30-10:50 Jeremy Shakun: Widespread Arctic permafrost thaw during Marine Isotope Stage 11 recorded by speleothems.

10:50-11:10 Isla Castaneda: Interglacials of the past 1.3 Ma in the terrestrial arctic: Insights from multi-proxy investigations at Lake El'gygytgyn (Far East Russia).

11:10-11:30 Montserrat Alonso Garcia: Pleistocene sea surface temperature and monsoonal regime variability in the Northern Indian Ocean (Maldives Sea) compared to the North Atlantic.

11:30-11:50 Oana-Alexandra Dumitru: Direct dating of Pliocene sea-level stands from western Mediterranean.

11:50-12:20 Wrap-up of Session 2.

12:20-13:30 *Lunch*

Session 3. Ice sheets and sea level during the Holocene (Chairs: Evan Gowan, Anders Carlson)

13:30-13:50 Pippa Whitehouse: Extensive retreat and re-advance of the West Antarctic ice sheet during the Holocene

13:50-14:10 Nicole Khan: What insights can the Holocene provide on previous interglacial sea levels?

14:10-14:30 Ben Horton Predicting marsh vulnerability to sea-level rise using Holocene relative sea-level data

14:30-14:50 Jennifer Walker: Reconstructing Holocene sea level in New Jersey using a new multi-proxy absence/presence (map) method

14:50-15:10 Wrap-up

15:10-15:30 *Coffee break*

Session 4. Posters (Chairs: Caroline Quanbeck, Deirdre Ryan)

15:30-16:00 Speed Poster presentations (3 min per poster). Each poster presenter will be given the floor and will have 2 slides to present in three minutes maximum the main points of their poster.

16:00-17:30 Poster session. Each poster presenter will remain near their poster for further discussions.

Public evening event

20:00-21:30 Chasing Ice – A Climate Change Documentary Screening and Panel Discussion https://stockton.edu/campus-center/

Enjoy a scientific evening with the public and your colleagues as together we screen "Chasing Ice". This 2014 News and Documentary Emmy® award for Outstanding Nature Programming is a story of one man's mission to change the tide of history by gathering undeniable evidence of our changing planet. Following the screening members of the audience will have the opportunity to interact through a moderated panel of international climate scientists and local New Jersey decision makers facing the increasing daily challenges posed by climate change. Refreshments and snacks will be served.

Wednesday September 26th

8:30-12:00 Visit to the salt-marshes near Galloway (Holocene sea-level indicators)

12:00-18:00 Visit of Pine Barrens (Late Pleistocene permafrost)

Thursday September 27th

8:30-8:45 Caroline Quanbeck and Deirdre Ryan: Presentation of the PAGES ECN working group

8:45-12.30 Discussion and wrap up

The objective of this discussion session is to write down the scientific questions and challenges that need to be tackled in the next 5 years. It will lay the groundwork for the preparation of an opinion/comment-type paper from the PALSEA-QUIGS community.

At the end of each session during the two first days of the workshop, the chairs will steer the "wrap-up" discussion towards the relevant questions/future challenges that the talks brought up, or that the audience feels relevant. We expect that each session will generate 5-6 main questions.

The last morning discussion session will be organized as follow:

8:45-9:15 We will refine/amend/add questions all together in a plenary session. We will decide on three „priority“ questions/challenges that we will tackle in breakout groups.

We already identified the following question as a priority that should be tackled by one breakout group:

"How do interglacial sea-level highstands relate to interglacial high-latitude, global and tropical temperatures? "

9:15-10:30 Three breakout groups with each to tackle one question-challenge/group of questions. For each question (set of questions) we will ask participant to think about:

(1) what time intervals or regions need to be targeted ?

(2) what proxies require development ?

(3) what model development are needed ?

10:30-10:50 Coffee break

10:50-12:10 Reports from each group to describe the essence of the discussion & feedbacks from the audience.

12:10-12:30 Wrap-up & discussion on future PALSEA-QUIGS join actions, e.g. writing groups to be defined for a community opinion paper, for reports in PAGES and INQUA newsletters, plans for submission of join sessions to upcoming conferences.

List of participants

Name	Affiliation
Alessio Rovere	MARUM, University of Bremen
Alex Robinson	Universidad Computense Madrid
Anders Carlson	Oregon State University
Andra Garner	Rutgers University
André Düsterhus	University of Hamburg
Andrea Dutton	University of South Florida
Anne de Vernal	University of Quebec
Ben Horton	NTU Singapore
Bette Otto-Bliesner	National Center for Atmospheric Research
Caroline Quanbeck	University of Florida
Chronis Tzedakis	University College London
Claude-Hillaire Marcel	University of Quebec
Dan Gilford	Rutgers University
Dario Domingo	University of Leeds
Deirdre Ryan	MARUM, University of Bremen
Emilie Capron	British Antarctic Survey and University of Copenhagen
Eric Wolff	Cambridge University
Erica Ashe	Rutgers University
Evan Gowan	Alfred Wegener Institute
Feng He	University of Wisconsin
Fiona Hibbert	Australian National University
Ian Goodwin	Macquarie University
Isla Castaneda	University of Massachusetts
Jacqueline Austermann	LDEO, Columbia University
James N Stanley	Rutgers University
Jamie McFarlin	Northwestern University
Jennifer Walker	Rutgers University
Jeremy Shakun	Boston College
Jerry McManus	LDEO, Columbia University
Ken Miller	Rutgers University
Kristen Joyse	Rutgers University
Larry Peterson	National Science Foundation
Laura Reynolds	Rutgers University
Laurie Menviel	University of New South Wales
Lorraine Lisiecki	University of California Santa Barbara
Marie France Loutre	PAGES / Bern University
Mark Demitroff	Stockton University
Michael Bender	Princeton University
Mick O'Leary	Curtin University
Montserrat Alonso Garcia	Centro de Ciencias do mar
Natasha Barlow	University of Leeds
Nicole Khan	NTU Singapore
Oana-Alexandra Dumitru	University of South Florida
Pippa Whitehouse	Durham University
Robert E. Kopp	Rutgers University
Russel Drysdale	University of Melbourne
Sarah Shackleton	University of California
Tamara Pico	Harvard University
Thomas Felis	MARUM, University of Bremen
Yair Rosenthal	Rutgers University
Yarrow Axford	Northwestern University

Venue information

Venue: Stockton Seaview Hotel & Golf Club

401 South New York Road, Galloway, NJ 08205

Check-In: Beginning at 4:00 PM EDT on 23 September 2018

Note: Each participant will be required to present a valid credit card and provide address and e-mail upon check-in in order to access the ancillary services of Seaview.

Check-Out: By 11:00 AM EDT on 27 September 2018

Note: Inquiries about special consideration for a later check-out may be made at the front desk; however, a $75.00 late check-out fee may apply

Amenities Included:

• Internet access in guestrooms

• In-room Coffee

• Unlimited use of fitness center, heated swimming pool, tennis and volleyball facilities

Seaview Policies:

• All function space is non-smoking

• Valet parking is available at a cost of $13.00 for overnight guests, and $6.00 for day guests

• Self-parking is available on a complimentary basis

• No food and/or beverage of any kind will be permitted to be brought into the hotel of any suite used as a hospitality suite by PALSEA participants. All food and beverage items served in the hotel's function rooms must be supplied and prepared by Seaview.

• A handling charge of $3.00 per small item will apply if deliveries are made to guest rooms

• Seaview is not responsible for any loss or damage to any samples, displays, property, or personal effects brought into Seaview, or for vehicles belonging to attendees and/or for the loss of equipment, exhibits, or other materials left in function rooms

Session 1. Climate, Ice sheets and sea level during the Last Interglacial

Indirect and direct contributions of ocean warming to the MIS5e highstand

Shackleton, S. (1); Severinghaus, J. (1), Baggenstos, D. (2); Bereiter, B. (2), Brook, E. (3); Menking, J. (3); Petrenko, V. (4); Dyonisius, M. (4); McConnell, J. (5); Bauska, T. (6); Rhodes, R. (6)

(1) University of California, San Diego; (2) University of Bern; (3) Oregon State University; (4) University of Rochester (5) Desert Research Institute (6) University of Cambridge

Pinning down the sources contributing to the Marine Isotope Stage 5e (MIS5e) highstand may be crucial to understanding the vulnerability of modern ice sheets to global warming. Today, ocean warming plays a direct role in sea level rise through thermal expansion, and may play an indirect role in future sea level rise through basal melting and subsequent mass loss from the Antarctic.

Using the novel proxy of noble gas ratios measured in ice cores, we reconstruct mean ocean temperature (MOT) change during late Termination II and MIS5e. We show that peak ocean temperatures were 1±0.3°C warmer than today, contributing ~0.6m to thermosteric sea level. This MOT maximum occurred at the end of the termination, coincident with peak Antarctic temperature.

We suggest that most of this enhanced warming was related to a delay in the resumption of the Atlantic Meridional Overturning Circulation and a bipolar seesaw response in global temperature change across Termination II. We also hypothesize that this early ocean warming contributed to enhanced mass loss from Antarctica in the earlier stages of MIS5e.

How much do we know about climate over Greenland during past warm periods?

Axford, Y., McFarlin, J.M., Lasher, G.E, Osburn, M.R.

Northwestern University

Climate over Greenland drives changes in mass balance of the Greenland Ice Sheet, and thus is an essential input to understanding past sea level changes. Yet there are surprisingly few quantitative constraints on temperatures over Greenland during past warm periods – particularly for the ice-marginal summer temperatures that drive ice sheet surface melt. We are applying paleolimnological proxies to this problem, with the goal of developing a network of temporally continuous, quantitative Holocene paleoclimate reconstructions from lakes around the ice sheet margin. Opportunities to reconstruct conditions of the Last Interglacial are more limited, but do exist in rare geologic settings. Here, we review quantitative reconstructions of summer temperatures around Greenland's margins for the early Holocene thermal maximum and the Last Interglacial, and contrast these reconstructions with representations of temperature in ice sheet model simulations of these past warm periods.

Nature and phasing of cross-hemispheric climate variability during the Last Interglacial based on Italian and New Zealand speleothem records

Drysdale, R. (1,2); Couchoud, I. (2,1); Hellstrom, J. (1); Zanchetta, G. (3)

(1) University of Melbourne; (2) Universite de Savoie-Mont Blanc; (3) Universita di Pisa

We compare precisely dated, high-resolution speleothem stable isotope records of the Last Interglacial (LIG) from Corchia Cave (Italy) and Nettlebed Cave (NZ). Post-termination warming first occurred in NZ, after which there was a period of synchronous bipolar warming of several thousand years. From 127 ka, we see major bipolar cooling, which first appears in NZ. The timing in both speleothem records may be indicative of the timing of meltwater releases from (first) Antarctica and (then) Greenland. This cooling heralded the beginning of a series of anti-phased, millennial-scale cooling/warming events through the remainder of the LIG. It appears that peak warming during the early LIG, which was warmer than present, may have triggered bi-polar ice-sheet melting, resulting in cooling episodes penetrating (at least) to the mid latitudes of both hemispheres. This seems to have paved the way for a weak 'interglacial version' of the bipolar seesaw. The LIG meltwater releases could account for the mid MIS5e sea-level jumps observed in some records.

Climate instability in the North Atlantic and S Europe during the Last Interglacial

Tzedakis, P.C. (1), Drysdale, R.N. (2,3), Margari, V. (1), Skinner, L. C. (4), Menviel, L. (5,6)

(1) Environmental Change Research Centre, Department of Geography, University College London, London, UK; (2) School of Geography, The University of Melbourne, Melbourne, Australia; (3) Laboratoire EDYTEM UMR CNRS 5204, Université Savoie Mont Blanc, F-73376 Le Bourget du Lac, France; (4) Department of Earth Sciences, University of Cambridge, Cambridge, UK; (5) Climate Change Research Centre and ARC Centre of Excellence for Climate System Science, University of New South Wales, Sydney, Australia; (6) Department of Earth and Planetary Sciences, Macquarie University, Sydney, Australia.

Considerable ambiguity remains over the extent and nature of millennial/centennial-scale climate instability during the Last Interglacial. This arises from the lower amplitude of interglacial variability compared to glacial, and the uneven resolution and poor chronological control of palaeorecords. Here, we address these issues by analysing marine and terrestrial proxies from a deep-sea sequence on the Portuguese Margin and combining results with an intensively-dated Italian speleothem record and climate-model experiments. The strongest expression of climate variability occurred during the transitions into and out of the interglacial. However, our records independently document a series of multi-centennial intra-interglacial arid events in southern Europe, coherent with cold water-mass expansions in the North Atlantic. The spatial and temporal fingerprints of these changes indicate a reorganization of ocean surface circulation, consistent with low-intensity disruptions of the Atlantic meridional overturning circulation.

Amplitude and spatio-temporal structure of the Last Interglacial warmth in paleoclimatic records

Capron, E. (1, 2); Govin, A. (3); Feng, R. (4); Otto-Bliesner, B. (4); Wolff, E. W. (5)

(1) British Antarctic Survey, Cambridge; (2) Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen; (3) LSCE/IPSL, Laboratoire des Sciences du Climat et de l'Environnement, Gif Sur Yvette; (4) Climate and Global Dynamics Laboratory, NCAR, Boulder; (5) University of Cambridge

The Last Interglacial (LIG, ~129-116 thousand years ago, ka) is the most recent time in Earth's history when global mean sea level was substantially higher than it is at present.

Quantifications of the amplitude and spatio-temporal structure of the LIG warmth are necessary to understand the sensitivity of polar ice sheets to climate change. However, such estimates are difficult to obtain mainly because aligning paleoclimatic records from various archives from around the globe is challenging.

In this talk we will synthesize recent insights on the Last Interglacial climate based on compilations combining temperature reconstructions from ice and marine archives in a coherent temporal framework. Quantitative estimates of the regional and global amplitude of the warmth throughout the Last Interglacial were produced based on the new data syntheses. Results suggest that across the globe (1) the maximum warmth was not synchronous and (2) the warmth amplitude was not homogeneous. We also provide a critical evaluation of the latest LIG surface climate data compilations and guidance on their use for comparison with climate model simulations and when assessing the link between sea level and climate changes during the LIG.

Interglacial global and high-latitude temperatures and interglacial sea level

Otto-Bliesner, B.L. (1); Brady, E. (1); Lofverstrom, M. (1); Feng, R. (2)

(1) National Center for Atmospheric Research; (2) University of Connecticut

The modeling of paleoclimate, using physically based tools, has long been used to understand and explain past environmental and climate changes, and is increasingly seen as a strong out-of-sample test of the models that are used for projection of future climate changes. Although the Last Interglacial (LIG, ~129 to ~116 ka) was discussed in the First Assessment Report of the IPCC, it gained more prominence in the IPCC Fourth and Fifth Assessment (AR4 and AR5) because of reconstructions highlighting that global mean sea level was at least 5 m higher (but probably no more than 10 m higher) than present for several thousand years. Thus, the LIG is recognized as an important period for testing our knowledge of climate-ice sheet interactions in warm climate states.

Recent data estimates suggest that global, annual surface temperature was likely ~0.8°C warmer than preindustrial. The ensemble of LIG time-slice simulations forced with the LIG orbital changes and Greenhouse gas concentrations, and assessed in the AR5, exhibit global annual surface temperature changes of 0.0 ± 0.5°C. These simulations capture the reconstructed patterns of Northern Hemisphere warming but the magnitude of the warming is only reached in summer. This calls into question the physics included in global climate models. An additional consideration is that long-term feedbacks (e.g. vegetation, ice sheets) are critical in addition to external (e.g. orbital) or internal (e.g. greenhouse gases) climate forcings for explaining the warmth of the LIG, and not fully considered in LIG climate model simulations. In this talk, I will review climate model simulations for the LIG to understand better the reasons for the warmth of the LIG.

Transient simulation of the last interglaciation and glacial inception in CCSM3

He, F. (1, 2); Clark P. U. (2); Carlson A. E. (2)

(1) University of Wisconsin-Madison; (2) Oregon State University

We will present the results from TraCE-LIG, the first transient synchronously coupled global climate simulation of penultimate deglaciation (Termination II), last interglaciation (LIG) and last glacial inception in CCSM3, which spans the periods between 140,000 years ago and 107,000 years ago (140 ka - 107 ka). TraCE-LIG is able to produce a climate optimum around 125 ka and a rapid glacial inception around 120 ka due to the gradual changes of orbital forcing. A detailed data/model comparison will be provided to support the simulated climate optimum around 125 ka and the rapid glacial inception around 120 ka. We will also discuss the possible mechanisms for the climate optimum and rapid glacial inception in TraCE-LIG. If time permitted, we will also discuss the similarities and differences between Termination I/Holocene and Termination II/last interglaciation by comparing the two transient simulations in CCSM3: TraCE-21K and TraCE-LIG.

Oceanic circulation and sub-surface warming on the Antarctic continental shelf

Menviel, L. (1,2)

(1) Climate Change Research Centre and ARC Centre of Excellence for Climate System Science, University of New South Wales, Sydney, Australia; (2) Department of Earth and

Planetary Sciences, Macquarie University, Sydney, Australia.

The Last Interglacial period (~129-116 ka) is an important period to understand as sea-level was 6 to 9m higher (Dutton et al., 2015), even though the atmospheric CO2 content was of ~280 ppmv (Schneider et al., 2013). Paleo-modelling and proxy data suggest that the Greenland ice-sheet contributed to a 2-3m sea-level equivalent (sle) at the LIG (Otto-Bliesner et al., 2006; Kopp et al., 2009, Stone et al., 2013, Yau et al., 2016), while the Antarctic ice-sheet could have contributed 3 to 7m sle (Kopp et al., 2009, Pollard & DeConto 2016). Despite a minimum in austral summer insolation at ~125 ka, the Antarctic ice-sheet extent probably reached a minimum at about 126-128 ka, thus suggesting that this disintegration of the Antarctic ice-sheet at the LIG could have been due to a sub-surface temperature increase of more than 4°C (Pollard & DeConto, 2016). Here, we will look into the processes that can lead to a sub-surface warming on the Antarctic shelf. A weakening of Antarctic Bottom Water formation increases stratification at the surface of the Southern Ocean, and leads to a significant sub-surface warming in the Southern Ocean (Menviel et al., 2010). The impact of changes in Southern Hemisphere westerlies on the oceanic circulation and on sub-surface temperatures in the Southern Ocean is also studied.

The enigmatic past evolution of the Greenland ice sheet

Robinson, A. (1)

(1) Universidad Computense de Madrid

Significant effort has gone into understanding past changes of the Greenland ice sheet (GrIS). Ice core and ocean sediment records, although sparse, have provided key data that give clues to the ice sheet's evolution and help to constrain ice sheet models. Ice sheet models of various degrees of complexity have been used to try to reproduce the data we have about the GrIS, and thus provide a more mechanistic picture of its role in the Earth system. In contrast to the Antarctic ice sheet, the GrIS is almost fully land-based today and it is strongly influenced by changes in the climate via surface mass balance. Thus in many ways its physics are easier to understand and model. However, developing a conclusive view of Greenland's past evolution, especially during warm periods, has been elusive until now. Here I take the Eemian Interglacial period (MIS-5) as an example and review the efforts to constrain the GrIS contribution to sea level during this time period. I will also propose what I consider to be important recent developments that may help this effort in the future, which include improvements to model physics and the inclusion of new processes, as well as the wealth of data available to constrain them.

Radiogenic evidence on the behavior of West Antarctic ice during the last interglaciation

Carlson, A.E. (1); Walczak, M.H. (1); Beard, B.L. (2); Laffin, M. (1); Stoner, J.S. (1); Hatfield, R.G. (1)

(1) Oregon State University; (2) University of Wisconsin-Madison

During the last interglaciation (LIG; ~129-116 ka), global mean sea level (GMSL) was at least 6 m above present and achieved this level early in the LIG. Based on evidence of only a modest contribution from the Greenland ice sheet to the LIG sea-level highstand of <2.5 m GMSL, it has been argued that the Antarctic ice sheets also contributed to higher-than-present GMSL during the LIG. However, evidence for such a contribution is so far lacking. Here we investigate the LIG behavior of the West Antarctic (WAIS) and Antarctic Peninsula (APIS) ice sheets using Sr, Nd and Pb radiogenic isotopes of silt in ODP Site 1096 in the Bellingshausen Sea. First, we confirm our interpretation of terrestrial rock radiogenic with continental shelf Sr-Nd data from 29 sediment samples that at least three radiometrically distinct terranes underlie the WAIS/APIS (new Pb data to be presented may lead to further differentiation). We then investigate silt source in Site 1096 over the last ~150 ka (age model from a unique foraminifera stable isotope record for Antarctic-proximal sediments). We will present these new down-core radiometric results. Initial Pb and Sr silt radiometric data suggest significant variations in silt source over the last 150 ka, particularly during the LIG.

Estimates of last interglacial global mean sea level from an extended sea level database and improved solid Earth models

Austermann, J. (1); Rovere, A. (2, 3); Lorscheid, T. (2, 3); Stocchi, P. (4); Mitrovica, J. X. (5); Huybers, P. (5)

(1) Lamont-Doherty Earth Observatory, Columbia University; (2) MARUM - Center for Marine Environmental Sciences, University of Bremen; (3) ZMT - Leibniz Centre for Tropical Marine Research; (4) NIOZ - Royal Netherlands

Institute for Sea Research, Coastal Systems (TX) and Utrecht University; (5) Harvard University

Estimating changes in global mean sea level, or equivalently ice volume, over the Last Interglacial (LIG) period requires a careful assessment of local reconstructions of sea level in conjunction with a model ensemble that captures the processes that distort local sea level relative to the global average. In this talk we will present results of pairing a large suite of solid Earth models with a new database of LIG sea level proxies. On the solid Earth side we extend traditional GIA models that explore Earth's viscosity and lithospheric thickness to exploring full uncertainties in ice sheet configurations leading into and during the LIG. We have shown that due to a feedback into the Earth's rotation axis these increased uncertainties also affect sea level in the far field. Ice histories are determined based on two approaches, (1) using benthic oxygen isotope records, deglacial ice geometries, and a variety of melt scenarios during the interglacial and (2) using an existing global ice-sheet chronology that was generated with the ANICE-SELEN coupled ice-sheet -- sea-level model. We further include models of dynamic topography, which is the topography that is supported by viscous flow and buoyancy variations in the Earth's mantle and lithosphere. We have shown that model predictions of this process are significantly correlated with observed sea level highstands and that they are consistent with preservation attributes across different sea level indicator types.

On the data side we use a new database of LIG sea level reconstructions, which includes new sea level interpretations based on the hydrodynamic limits of relative sea level indicators. This database is comprised of over 1000 data points that each account for uncertainties in the measurement and indicative meaning. We use observations along passive margins and their (gaussian and non-gaussian) uncertainties to score the different ice / Earth models in our model suite. This procedure allows us to identify the best fitting sea level scenarios during the LIG including an estimation of excess melt. We explore how well the data and model constrain melting of specific ice sheet as well as how changes in our input (such as only considering a subset of observations or models) propagate into our results.

New chronologies and links between episodic reef growth, meltwater pulses, climate and sea level variability during the Last Interglacial

Dutton, A (1)., Webster ,J.(2) , Eberli, G. (3), Vyverberg, K.L. (1), Edwards, R.L. (4), Zhang, P.(4), Pythoud, M. (5), Zwartz, D. (5)

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Over the past several decades several hypotheses have been put forward regarding the possibility of multiple peaks in global mean sea level during the Last Interglacial (LIG) sea level highstand. These peaks are variously defined by evidence for a rapid, yet ephemeral, rise or fall in sea level, and interpretations have ranged from 1-4 peaks in sea level during the 129 – 116 ka interval that defines the LIG highstand. Unfortunately, interpretations between localities, and sometimes at the same locality, differ from study to study. Some of these discrepancies may result from an improper connect-the-dot approach to coral age and elevation data without consideration for paleowaterdepth interpretations or reef facies context while others might be explained by local patterns in relative sea level resulting from processes such as glacial isostatic adjustment. In other cases, sedimentary (or other) evidence may have multiple possible interpretations that complicate straightforward conclusions.

Even if the controversy surrounding global mean sea level variability during the LIG can be resolved, the question remains as to what caused the(se) sea level oscillation(s). Given the millennial to sub-millennial scale suggested for these events, these perturbations would require rapid changes in the volume of grounded ice. Given that the timing of warming was asynchronous during the LIG (early in the Southern Hemisphere, later in the Northern Hemisphere), one possibility is that the sea level variability derives from growth/decay of either the Antarctic or Greenland ice sheet, that is then offset through a bipolar seesaw effect. Another possibility is that one of these polar ice sheets is sitting near a threshold that causes it to oscillate between two quasi-stable configurations. Yet another possibility is that residual ice from the Laurentide ice sheet did not fully melt until sometime during the LIG, providing another potential source of meltwater. Finally, some combination of these mechanisms may superimpose to create a complex history of global mean sea level changes.

Here we present evidence from a number of ongoing projects in the Seychelles, Florida Keys, Western Australia, Jamaica, and Mexico in combination with a review of evidence from sites around the globe regarding the timing and number of peaks in GMSL. Using a new chronology of episodic reef growth in the Seychelles, we are able to link the timing of these reef units with distinct pulses of meltwater into the North Atlantic. Our observations indicate that ice sheet retreat during the LIG may have been punctuated by stepwise meltwater release in the Northern Hemisphere that affected ocean circulation in the North Atlantic and created accommodation space for further reef growth.

The ability and limitations of geological archives to fingerprint the source of ice sheet melt

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Understanding the relative contribution of the ice sheets to late Quaternary sea-level highstands is vital to be able to understand how ice sheet mass balance has changed over time, and consequently better constrain forcing mechanisms. One of the primary means to do this, in periods where subsequent glacials have removed direct evidence of interglacial ice sheet extent, is through records of past sea level, in particular from far- and intermediate-field locations. Collection of MIS 5e sea-level data has been a priority for the PALSEA community, and has significantly refined our current understanding of the magnitude of the interglacial highstand (e.g. Dutton et al., 2015). However, to constrain how different ice-sheets have contributed to this highstand requires us to 'fingerprint' the pattern of melt. This requires a comprehensive spatial network of RSL records, in which are able to capture the transient nature of a sea-level fingerprint. To be able to reach a firm conclusion on the maximum contribution from Greenland and/or Antarctica to the MIS 5e highstand requires us to be confident in the ability of palaeo sea-level archives to record sub-millennial changes. This paper explores different geological archives of sea-level change in the far and intermediate field, and their potential to record centennial rates of relative sea-level change. To address this critical research gap we need to make significant progress in reducing the age and elevation uncertainties of some records, as well as being realistic as too the magnitude and duration of the signals that some archives are able to resolve. Innovative modelling approaches may be required to fill spatial and temporal gaps.

Last Interglacial meltwater signal from far-field sea-level, directional wave climate and proxy-climate

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Most of the geological record of Antarctic Ice Sheet extent during warmer interglacials has been lost due to glacial expansion and retreat cycles, and the ice-core record is geographically sparse. We take the novel approach of using the Southern Hemisphere (SH) far-field, coastal imprint of sea-level history (specifically the Australian region and Tierra del Fuego) to identify ice sheet instability during the last interglacial (MIS5). The unique sea level signal archived in the coastal sediments and morphology contains evidence for a pulse of meltwater input at a rate of ~1mm/year during the mid-late MIS5e of ~3 m of sea-level equivalent. The spatial pattern of the differential sea-level rise during MIS5e, after correction for Glacio-Isostasy is matched to the gravitational meltwater fingerprint (Hay et al., 2014) for each of the three polar ice sheets to determine the origin of the meltwater and hence, the source of ice sheet instability. Our results also have implications for determining the timing of ice sheet retreat in Antarctica and Greenland during MIS5e.

The MIS5e far-field coastlines also archive the evolution of directional wave climate and hence ocean windfields. At all sites where we reconstruct RSL we have inverse modelled the ocean wave and windfield history. Hence, we also report our progress in reconstructing the subtropical and mid-latitude SH SH atmospheric pressure and wind field evolution for MIS5e. We are working towards a coastal and climate proxy-data -model assimilation by using a Last Interglacial simulation together with a regionally distributed multivariate proxy dataset, to produce atmospheric reanalysis for 129 ka BP, 125 ka BP and 120 ka BP (after Goodwin et al., Clim. Dyn., 2013). Ultimately, we compare the atmospheric circulation patterns together with the meltwater fingerprint pattern to the MIS5e ice core record and the Antarctic shelf-sedimentary record of meltwater discharge, to investigate the climate drivers of ice sheet retreat.

Session 2. Climate, Ice sheets and Sea levels during older interglacials

Interactions between ice sheets, orbital forcing and carbon dioxide during the MIS 13 interglacial

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Nearly all models designed to simulate Late Pleistocene glacial cycles have trouble matching the pattern of climate change associated with interglacial Marine Isotope Stage 13 (~500 kyr ago). A comparison of climate records for this glacial cycle reveals decoupling between CO2 and ice volume (sea level) that likely arose due to specific characteristics of the ice sheets and orbital forcing at this time. A Late Pleistocene sea level stack (Spratt & Lisiecki, 2016) shows a two-step sea level rise during the transition into MIS 13. The small, initial sea level rise (~20 m) at 530 ka coincides with the majority of CO2 and global SST change, whereas the larger sea level rise (~40 m) at 500 ka is associated with much less CO2 change. The unusual pattern of ice sheet and CO2 change during this glacial-interglacial transition has the potential to provide important tests of Late Pleistocene climate models.

A simple relaxation model for glacial cycles that includes both ice volume and CO2 (García-Olivares and Herrero, 2013) simulates the two-step deglacial transition for MIS 13 when tuned to fit the sea level stack. In this model, decoupling between ice sheets and CO2 is caused by out-of-phase responses in ocean stratification and Antarctic ice cover. Weak Antarctic warming during the initial phase of deglaciation caused the Antarctic ice shelf to remain relatively wide and release less CO2 than usual. Additionally, the ice volume response to this CO2 pulse was muted by a large lag relative to Northern Hemisphere insolation. These factors lead the model to simulate a second CO2 pulse with greater impact on ice volume during the next precession maximum. Further investigation of this glacial-interglacial transition could yield unique constraints for quantifying ice sheet sensitivities to insolation and greenhouse gas forcing.

Tropical Atlantic temperature seasonality during a mid-Pleistocene interglacial from southern Caribbean corals

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Seasonality plays a fundamental role in Earth's climate, but the evolution of the annual cycle of temperature at Earth's surface is not well constrained during past interglacials - in particular for the tropical ocean, a key player in global climate dynamics. Fossil shallow-water corals provide a unique archive of temperature seasonality and sea level for the tropical ocean and can be precisely dated by the U-series method. Recent coral work from the Atlantic suggests that temperature seasonality of the tropical surface ocean is controlled mainly by orbital insolation changes during the Holocene and the last interglacial, even during periods of substantial climate perturbations and abrupt sea-level rise as suggested for 118 ka. However, comparable information for older interglacials is still lacking. We intend to reconstruct tropical Atlantic temperature seasonality during an earlier interglacial of the mid-Pleistocene, by utilizing corals drilled on an elevated reef terrace at Bonaire (southern Caribbean Sea). Our preliminary U-series datings suggest an age between MIS 13 (~500 ka) and MIS 17 (~700 ka), but we cannot exclude that this terrace could also represent MIS 11 (~400 ka). For Bonaire brain corals (Diploria strigosa) of the last interglacial, we have shown that the denser theca walls, the skeletal element commonly used for monthly Sr/Ca-temperature reconstructions, is less affected by post-depositional open-system behavior and better suited for U-series dating than bulk material. Extracting theca wall material combined with state-of-the-art MC-ICP-MS instruments and multi-faraday-cup techniques is thus a promising strategy to obtain reliable U-series ages for these older corals, assign this terrace to a specific interglacial of the mid-Pleistocene, and quantify tropical temperature seasonality and possibly sea level at that time.

Distinct climate and ocean conditions from one interglacial to another : example of MIS 31, 13, 11, 5e and 1 in the Labrador Sea

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IODP sites 1302/1303 (50°N-45°W) and 1305 (57°N-48°W), which are located along the continental margins of eastern Canada and southern Greenland, may be used to simultaneously address glacial activity (ice rafted debris – IRD) meltwater events (salinity), regional sea-surface temperature and vegetation/climate of adjacent land (pollen). Their records illustrate very different climate and ocean conditions during the study interglacials, which include marine isotope stages (MIS) 1, 5e, 11, 13 and 31. Results indicate that the last interglacial stands out as the warmest interglacial interval, in the NW North Atlantic, with sea-surface temperatures (SSTs) anomalies > + 5°C at both sites, although the almost continuous presence of ice rafted debris (IRD) and variations in salinity suggest meltwater discharge along the Greenland and Labrador margins. During MIS 11, SSTs were close or slightly lower than at present, but salinity was higher, and IRD close to nil, indicating limited meltwater supplies if any, and a complete stop in iceberg and/or sea ice drifting. Paleovegetation data and complete cessation of IRD suggest that MIS 11 could have been characterized by ice-sheet free Northern Hemisphere. MIS 13, in contrast, was characterized by large amplitude variations of SSTs, a generally low salinity and variable amounts of IRD and detrital inputs, suggesting active ice sheets in Greenland and northeast North America. Finally, MIS 31 appears to have been relatively warm, but with distinct microfossil assemblages that it might represents a situation without proper modern analogues.

Record of high interglacial/interstadial sea-level intervals in sedimentary sequences from the central Arctic Ocean

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Merging the Arctic Ocean climate history into the global Earth and Oceans climate system remains challenging due to the lack of robust chronologies of marine sedimentary sequences as well as to still equivocal proxy records of environmental changes. Over ridges notably, low and highly contrasted sedimentation rates, scarce biogenic remains ensuing from low productivity and/or poor preservation, oxygen isotope and paleomagnetic records differing from global stacks. All represent major impediments and result in major debates within the geoscientific community. In recent years, we put forth a stratigraphical frame for the late Quaternary sedimentary sequences (up to MIS 11) based on 230Th and 231Pa excess decay. In combination with exhaustive sedimentological and geochemical studies, records from the Lomonosov and Mendeleev ridges, this work indicates that fine sediment layers (with high initial excesses in 230Th and 231Pa) are tightly linked to high interstadial and interglacial sea levels, when Siberian shelves are submerged, leading to sea-ice (with resulting brines) production and export through an active Trans-Polar Drift. On one hand, these records provide the means to link sedimentary intervals to specific high sea-level windows, thus allowing to link the Arctic Ocean paleoclimate history to global records. On another hand, inventories of 230Th and 231Pa excesses during the recorded high sea-level intervals could help estimating the duration of these episodes, at least, up to MIS 9, possibly 11.

Hydrographic conditions in the North Atlantic polar region during "warmer-than-present" interglacials and their effect on the East Greenland Ice Sheet

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The climate of several previous interglacial periods, e.g., Marine Isotope Stage (MIS) 5e and 11, is of interest to scientists because it possibly shares many features with model projections of the future climate. Of specific interest are conditions during the "warmer-than-present" interglacials possible characterized by reduced Greenland Ice Sheet (GIS) and a higher sea level. In this study we combine high-resolution records of foraminiferal abundance with isotopic and elemental data from cores on the Eirik sediment drift, south of Greenland (MD03-2664 and IODP Site U1305), to reconstruct the surface hydrographic conditions in the North Atlantic polar region during the peak interglacials of MIS 5e, 7, 9 and 11. These records may offer new insights into the response of the polar region and the GIS to future warming and freshening and potential implications to ocean circulation and Earth's climate.

Widespread Arctic permafrost thaw during Marine Isotope Stage 11 recorded by speleothems

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Arctic permafrost contains a substantial stock of carbon that could be released to the atmosphere as CH_4 and CO_2 upon thawing, making it a potentially powerful amplifier of future warming. The sensitivity of permafrost to climate change is uncertain, however, and occurs on time scales longer than those captured by the instrumental record. Speleothems – cave precipitates deposited from flowing or dripping water – in currently frozen regions record past episodes of thaw, which can be used to assess the response of permafrost to long-term warmth. Here, we present 90 uranium-thorium ages on speleothems from across the North American Arctic, sub-Arctic and northern alpine regions to reconstruct a 500-kyr permafrost history. Widespread speleothem growth supports an episode of extensive permafrost thaw during the Marine Isotope Stage 11 interglacial about 400 ka, and suggests that it was the most intense interglacial of the past 500 kyr. Ice-core records of atmospheric greenhouse gases do not show elevated concentrations at these times, perhaps suggesting that the permafrost carbon pool remained largely intact, was smaller than today, or released gradually enough to be buffered by other reservoirs.

Interglacials of the past 1.3 Ma in the terrestrial arctic: Insights from multi-proxy investigations at Lake El'gygytgyn (Far East Russia)

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Long and continuous paleoclimate records from northeast Arctic Russia (Lake El'gygytgyn) provide new opportunities for understanding the sensitivity of Earth's high-latitude regions to greenhouse gas variability and changing orbital configurations as well as for studying associated climate feedbacks. Here we investigate temperature and vegetation change in the terrestrial Arctic using branched glycerol dialkyl glycerol tetraethers (brGDGTs) and plant leaf waxes, respectively, preserved in Lake El'gygytgyn sediments. We compare these new records to previously published geochemical and pollen data from Lake El'gygytgyn to assess the dynamics of glacial and interglacial periods during the past 1.3 Ma. This time interval allows for the investigation of the mid-Pleistocene transition (MPT) and the mid-Brunhes Event (MBT) in the terrestrial Arctic. Our organic geochemical temperature and vegetation reconstructions display strong glacial-interglacial variability and exhibit precessional and obliquity frequencies, respectively. We find that Marine Isotope Stages (MIS) 7c, 9, and 17 are the three warmest interglacials while MIS 4, 10 and 12 are the coldest glacial periods. However the intensity of these periods is not necessarily reflected in other proxies measured on the same samples. Instead, we demonstrate that the intensity and timing of climatic cycles, as well as the orbital signals that these records contain, varies by proxy type, even within the same sedimentary archive and when measured on the same samples. We suggest that high-resolution, multi-proxy analysis of paleoclimate archives is essential for improved understanding of the complexities of Earth's climate system as these differences provide valuable information about climate and environmental patterns and dynamics.

Pleistocene sea surface temperature and monsoonal regime variability in the Northern Indian Ocean (Maldives Sea) compared to the North Atlantic

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The Maldives Inner Sea is a natural sediment trap located in the northern Indian Ocean affected by the South Asian Monsoon (SAM) seasonal reversing wind pattern, which drives modern oceanography in the region. Moreover, variations in oceanic productivity and in the extension of the oxygen minimum zone (OMZ) in the northern Indian Ocean are intimately related to the SAM. Therefore, the Maldives Sea is a perfect location to study past changes in tropical climate and ocean circulation related to monsoon dynamics throughout the Pleistocene, and investigate the effects of the Mid-Pleistocene transition in this region.

In this work, we studied sediments from IODP Site U1467, drilled during IODP Expedition 359 in the Inner Sea of the Maldives, at a water depth of 487 m. Our study is focused on the last ~1.4 Ma, and mainly based on the analysis of organic compounds (lipid biomarkers) with the aim of reconstructing sea surface temperature (SST, using the alkenone unsaturation index, Uk'37), and estimating past surface ocean productivity (using total alkenone concentration) and bottom water oxygenation (BWO, using n-alcohol vs n-alkane rates). Additionally, data from scanning x-ray fluorescence (XRF) from this site provides information about the monsoon regime and the microfossil benthic communities have been used to support the interpretations of the BWO proxy.

At present, seasonal SST variation is rather small in The Maldives inner sea (less than 1ºC) and our reconstructed SST record also shows very small variability between glacial and interglacial periods (less than 1ºC). Our SST record shows rather warm temperatures before MIS 30, with not very significant variations between glacial and interglacial periods. After MIS 30, both glacial and interglacial temperatures show a decreasing trend until MIS 22, which represents the first interval with considerably colder SST. Between MIS 22 and 13, SST remains relatively warm, not showing large changes between glacial and interglacial periods. It is remarkable the absence of lukewarm interglacials during this interval. Bottom water oxygenation starts to increase during glacial periods at MIS 22, which is supported by the benthic ostracod assemblages. This indicates a contraction of the OMZ during glacial periods. Starting at MIS 12, glacial periods show colder SST again and glacial BWO increases, whereas the interglacial temperatures slightly decrease. The terrigenous elements (K, Fe, Al, Ti) from XRF suggest an increase in aridity at MIS 22, with stronger winter monsoon (higher aridity) during glacial periods. The comparison of our Indian Ocean reconstructions with other records, particularly those in the Atlantic Ocean, provides key information to improve our understanding of the evolution of global climate and ocean circulation during the Pleistocene.

Direct dating of Pliocene sea-level stands from western Mediterranean

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Throughout most of the Pliocene the atmospheric CO2 concentration was as high or even higher than today, and temperatures on Earth were above the preindustrial ones by as much as 4 °C. Since parts of the Greenland and the Antarctica ice sheets were not present, global mean sea level must have been higher than it is today. If a link between global ice volume, sea level, and CO2 concentration exists as suggested by recent studies, then the early to middle Pliocene climates are important for interpreting the path of future climate warming.

Repeated hydro- and glacio-isostatic-triggered sea-level oscillations left distinct horizons of calcite or aragonite phreatic overgrowths on speleothems (POS) at different elevations in the coastal caves of Mallorca Island, western Mediterranean. Here we present the first absolute U-Pb Pliocene ages of POS from a littoral cave in the northeastern part of the island. A key aspect of our results is the robust absolute chronology and the precise elevation of the POS. The six distinctive POS horizons extending between 22.5 and 32 m above present sea-level (mapsl) provide evidence of the behavior of relative sea-level during the Pliocene. The oldest sea-level stand at +32 mapsl yielded an age of 4.39 ± 0.39 Myr, whereas the youngest one formed 3.27 ± 0.12 Ma at 23.5 mapsl. These results represent the first U/Pb dated snapshots into the early to middle Pliocene sea-level variability. We will present ongoing work that considers the contribution of glacial isostatic adjustment and dynamic topography to the elevation of the POS in order to relate local sea level to the global mean. Our results suggest that the peak Pliocene sea-level high stand might have been prior to the mid-Pliocene Warm Period.

Session 3. Ice sheets and sea level during the Holocene

Extensive retreat and re-advance of the West Antarctic ice sheet during the Holocene

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Numerical models used to project future ice-sheet contributions to sea-level rise exploit reconstructions of post-LGM ice loss to tune model parameterizations. In the Weddell and Ross Sea sectors of Antarctica, ice-sheet reconstructions have assumed progressive grounding line retreat throughout the Holocene. Recent evidence from ice-penetrating radar and glacio-isostatic adjustment (GIA) observations have challenged this assumption. We provide evidence for the grounding line in these sectors retreating hundreds of kilometers inland of its present position, before Holocene isostatic rebound caused the grounding line to re-advance to its current position. Observational evidence for these changes includes (1) radiocarbon in sediment cores recovered from beneath Ross Sea Sector ice streams, indicating marine exposure at least 200 km inland of today's grounding line and (2) ice-penetrating radar observations of englacial structures preserved in a Weddell Sea Sector ice rise, indicating ice-shelf grounding and ice-rise expansion. We interpret these observations using an ensemble of ice-sheet simulations that reproduces widespread post LGM grounding line retreat inland of its current location and later re-advance. Modelled grounding line re-advance requires GIA-driven ice-shelf grounding on topographic highs. Our findings overturn the assumption of progressive Holocene grounding line retreat in the Weddell and Ross Seas and suggest that climate-initiated ice loss was reversed by GIA-driven stabilizing processes.

Whether these processes could reverse present-day Antarctic ice loss on millennial timescales depends on poorly-known bedrock topography, mantle viscosity and future ice-shelf extent.

What insights can the Holocene provide on previous interglacial sea levels?

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The current Holocene interglacial (the past 11.7 kyrs to present) offers the most abundant and highly resolved relative sea-level (RSL) reconstructions. The abundance of RSL data from this period, combined with the preservation of near-field glacial deposits, has contributed to the development of a relatively well-constrained history of ice-sheet retreat. Given the resolution of data during the Holocene, detailed sea-level reconstructions from this period are important for constraining local to regional processes. Glacial-isostatic adjustment (GIA) is the dominant process driving spatial variability during the Holocene, and therefore high-quality Holocene RSL data can provide important constraints for Earth model parameters representing the viscosity structure of the planetary interior and on the evolution of ice sheets through the glaciation/deglaciation process. The insights derived from the fit of GIA models to Holocene data in principle can then be applied to understand ice sheet evolution during previous interglacial periods. Here we present collocated Holocene-Last Interglacial (LIG) RSL records from Bermuda and the Caribbean to highlight the uncertainties that processes acting over different spatial and temporal scales contribute to sea-level equivalent estimates derived from RSL records. In addition, we explore the impact that Earth model parameters have on both Holocene and LIG timescales and how they may influence interpretation of ice sheet evolution.

Predicting marsh vulnerability to sea-level rise using Holocene relative sea-level data

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Tidal marshes rank among Earth's vulnerable ecosystems, because they will retreat if future rates of relative sea-level rise (RSLR) exceed marshes' ability to accrete vertically. Here, we assess the limits to marsh vulnerability by analyzing >780 Holocene reconstructions of tidal marsh evolution in Great Britain, which includes both transgressive (tidal marsh retreat) and regressive (tidal marsh expansion) contacts. The probability of a marsh retreat was conditional upon Holocene rates of RSLR, which varied between -7.7 and 15.2 mm/yr., because of the glacial isostatic response to the British-Irish ice sheet. Holocene records indicated that at RSLR rates ≥7.1 mm/yr. marshes are nine times more likely to retreat than expand, so that marsh retreat is nearly inevitable. Coupling probabilities of marsh retreat with projections of future RSLR suggests a major risk of tidal marsh loss in the 21st century. All of Great Britain has a >80% probability of a marsh retreat under Representative Concentration Pathway (RCP) 8.5 by 2100, with areas of southern and eastern England achieving this probability by 2040, because of the additional glacial isostatic subsidence.

Reconstructing Holocene sea level in New Jersey using a new multi-proxy absence/presence (map) method

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Most high resolution (decimeter- and decadal-scale) relative sea-level (RSL) records using salt-marsh microfossils as a proxy only extend through the Common Era, limiting our understanding of driving mechanisms of RSL change and how sea-level is influenced by changing climate. Records beyond the Common Era are limited by the depth of continuous sequences of salt-marsh peat suitable for high resolution reconstructions, as well as contamination by local processes such as sediment compaction. In contrast, sequences of basal peats have produced compaction-free RSL records through the Holocene, but at a low resolution (meter- and centennial-scale).

We devise a new Multi-proxy Absence/Presence (MAP) method to develop a mid-Holocene RSL stack for New Jersey. We stack 14 1-m basal peat cores that temporally overlap along a uniform elevation gradient above an incompressible basal sand. We analyzed three sea-level indicators in each of the 14 cores: foraminifera, testate amoebae, and δ13C. A modern dataset establishes the highest occurrence of foraminifera (HOF), the lowest occurrence of testates (LOT), and the C3/C4 vegetation boundary. To reconstruct RSL, this multi-proxy approach uses the timesaving presence/absence of forams and testates to determine the elevation of sediment that formed between HOF and LOT in each core. We use stable carbon isotope geochemistry to determine the C3/C4 vegetation boundary in each core. We develop age-depth models for each core using 3-5 radiocarbon dates. Radiocarbon dates place the basal sequences at least 4246-4408 cal yrs BP. The RSL records from each 1 m basal core are combined to create a stack for the mid Holocene to present. A short core with full counts

of forams and testates is used to test the new method and compare with the traditional foraminifera-based transfer function approach and the local tide gauge record. This method removes the issue of compaction to create a continuous and highly-resolved RSL record to address temporal changes and periods of climate and sea-level variability.

Session 4. Poster session

Ice cores and isotopic climate emulation to reconstruct the Last Interglacial Greenland Ice Sheet

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The Greenland Ice Sheet (GIS) contribution to the Last Interglacial (LIG) sea level high stand is uncertain. Published studies show wide range of LIG ice loss estimates, varying from 0.3 to 5.5 meters of sea level equivalent. Here we propose to combine, for the first time, a compilation of stable water isotopic (δ18O) information from Greenland deep ice cores with isotopic climate emulation to provide new constraints on GIS ice volume and configuration changes during the LIG. Greenland ice records show that between present-day and the LIG climatic optimum, there was a rise in δ18O of at least 2.5‰.

Isotopic LIG climate simulations are performed with a wide range of GIS morphologies. The outputs from the isotope-enabled climate model (HadCM3) are used to build an emulator of the response of δ18O to all possible changes in the shape and extent of the GIS at 125ka. By applying this rather novel emulation technique, we show that strong ice loss occurred over southern Greenland, possibly resulting in a two dome structure, with a small remnant dome covering the south of Greenland and a larger one in the north. We also demonstrate the sensitivity of the solution to DYE3 ice core data. This shows where the most valuable ice core data lies in order to reduce uncertainties on GIS ice volume change estimates during the LIG.

Reassessing global ice volume changes during interglacials and deglaciations: uncertainty and structure in sea level records

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Geologically recorded sea-level variations represent the sum total of all contributing processes, be it known or unknown, and may thus help in finding the full range of future sea-level rise. Significant sea-level-rise contributions from both northern and southern ice sheets are not unprecedented in the geological record and the most recent ~500,000 years offer a well-constrained range of natural scenarios from intervals during which ice volumes were similar to or smaller than present (i.e., interglacial periods), to intervals during which total ice volume was greater (i.e., glacial periods). Because the radiative forcing of climate associated with each of these intervals is known (or modelled), we can investigate the relationship between changes in sea level, ice volume (climate state), and radiative forcing. Initial results indicate that the rate of change in sea level depends on both pre-existing ice volume and radiative forcing of climate (e.g., Grant et al., 2014). Other work has found a sea-level sensitivity of several meters per degree of warming for intervals when temperatures were similar or slightly warmer than present (e.g., Kopp et al., 2009, Rohling et al., 2013).

We present a new synthesis of sea-level indicators, with particular emphasis on the geological and biological context, as well as the uncertainties of each record. Using this new compilation and the novel application of statistical methods (trans-dimensional change-point analysis, which avoids "overfitting" of noise in the data), we will assess global ice-volume changes, sea-level fluctuations and changes in climate through the Last Interglacial, the last deglaciation and the Holocene. Finally, we discuss the implications of these uncertainties on our ability to constrain past cryosphere changes.

How can we pin down what happened to the West Antarctic ice sheet in the last interglacial?

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Sea level records combined with constraints on the size of the Greenland ice sheet demand that 2-7 metres of sea level equivalent was lost from Antarctica at some point in the last interglacial. Given that the Antarctic warming during that period was similar to that expected in the next century, confirming this and pinning down the location of vulnerable ice seems critical. Most concern has centred on the West Antarctic Ice Sheet (WAIS), and it seems astonishing that we cannot yet point to any convincing evidence that WAIS either collapsed or survived. A key prediction of recent ice sheet models is that an early component of WAIS loss is the complete retreat of the Ronne and Ross Ice Shelves. Here I will discuss approaches to diagnosing the state of WAIS and of the Ice Shelves during the last interglacial. I will mainly describe the activities planned under the ERC project WACSWAIN.

In the field season 2018-19 we will drill a core to bedrock (620 m) at Skytrain Ice Rise, which sits behind the Ronne Ice Shelf. The ice there is nicely layered to the bed, and we have evidence that last interglacial ice will be preserved in the lowest 30 m of the ice. If the Ronne Ice Shelf retreated then this site, currently 600 km from ocean or sea ice would be only 50 km away. We will easily discern this in our ice chemistry and be able to put a date on any retreat and re-advance of the Ice shelf. Using other measurements such as water isotopes and air content we should also be able to diagnose changes to the WAIS itself. This poster is intended to serve as both a teaser for future research, and a challenge for people to come up with other methods to diagnose the very large changes many believe occurred but that has been enigmatically hard to demonstrate.

A global database of last interglacial sea-level elevations and geochronology: Work in progress

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The last interglacial period (marine isotope stage 5, sensu lato) is one of the most studied in terms of Quaternary sea-level history, not only due to the endurance of the record around the globe but also due to its significance for understanding the behavior of a climate system operating under warmer conditions than present. This understanding is vital for future global development in an era of increasing temperature and rising sea levels. To this end, the record is also applied to studies of sea-level variability, neotectonics, and ecology. The study of the Last Interglacial, as such, began with the recognition that fossil shorelines could be used to reconstruct past sea levels and the acceptance of the Glacial Theory by the end of the 19th century. Previously compiled databases of Last Interglacial studies tend to focus on a particular aspect of the record, e.g. neotectonics or a singular geochronological method such as U-series. This work presents current efforts to create the first comprehensive global database compiling last interglacial sea-level heights measured from a variety of physical indicator types and analyzed by a range of geochronological methods including multiple luminescence methods, U-series, electron spin resonance, amino acid racemization, and stratigraphic constraint. Global records have been subdivided into fourteen physical regions to facilitate recognition of locations of interest. Current work includes the evaluation of studies, as published in the literature, for sea-level estimates and the vertical accuracy of index points. Studies without fixed sea-level indicators and/or geochronological constraint will be rejected. The database will provide standardized descriptions of sea level index points, including its indicative meaning, as well as records of all geochronological data provided in the original work to facilitate reproduction and/or reassessment of the relative or numerical age as determined in the original study. A comprehensive list of all literature reviewed, including rejected studies, will be included. This work culminates in an interactive global database of standardized MIS 5 relative sea-level indicators and associated geochronological analyses made available to the earth science community for use in continuing and future studies of climatic change, sea-level oscillations, neotectonics, and ecological development.

A statistical framework for integrating non-Gaussian and limiting proxy distributions into geological reconstructions of relative sea level

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Robust, proxy-based reconstructions of relative sea-level (RSL) change are critical to discerning the processes that drive variability in RSL; however, these reconstructions rely on the ability of statistical models of RSL to accurately constrain the relationships between the proxies and sea level that are often poorly described by traditional methods assuming Gaussian distributions. We develop a new statistical framework to estimate past sea-level change based on modern depth distributions of individual coral taxa. The new statistical framework is hierarchical and comprises data, process, and parameter levels. The data level describes each observed proxy's elevation and geochronological uncertainty from field and laboratory measurements and uses modern depth distributions of individual coral taxa to infer the likelihood of RSL, given the observed proxy elevations. The process level uses the full spatio-temporal covariance to model the RSL field over time and space. The parameter level dictates prior expectations regarding the correlation structure of RSL. Using Markov Chain Monte Carlo (MCMC) sampling, we approximate the posterior distributions of these parameters and RSL, conditioned on the observed data. The model is most sensitive to the temporal distribution of the data and data uncertainties. We demonstrate that our new framework for using nonparametric likelihoods, based on empirical distributions in multi-proxy models, has the potential to provide robust estimates of RSL during past interglacial periods, incorporate previously underutilized proxies from far-field locations, and constrain physical models of the dominant sea-level processes. This new framework has broader applications; it can be extended to virtually any type of proxy for sea level over a variety of temporal and spatial scales.

Investigation of the LIG sea-level highstand with massive ensembles

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Paleoclimatic sea-level analysis is based upon the evaluation of sparse indirect observational data, the sea-level indicators, and models for sea-level fluctuations, with a wide range of complexity. Individual records of paleo sea level depend not only upon the change in global ice volume, but also on the crustal deformation and gravity changes that are significant both near the glaciers and around the world. Understanding of these processes for the past is essential for interpreting the observations and generating better estimates of future changes.

We use massive ensemble approaches to analyse sea-level changes during the last interglacial (LIG). Employing a Bayesian statistical analysis, we compare the sea-level indicators to model-generated sea-level estimates. As a result we gain insight into the development of the ice sheets, the influence of the Earth deformation and the evolution of higher-than-present-day sea level during that period.

This contribution gives an overview of our sea-level analysis during the LIG. We focus on the highstand of sea level during the LIG and the duration of higher than modern sea level. The analysis helps to answer questions of the effect of the uncertainties in the indicators, both in height as well as in time, on features of the estimated global-average sea level. In particular, we address how well the data resolve sea-level oscillations during the LIG.

Reconstructions of Northwest Greenland Temperature and Hydrology during Past Interglacials

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Greenland's climate during Quaternary warm periods is an important influence on sea level via changes in the mass balance of the Greenland Ice Sheet. The climatic information from reconstructions of past warm periods provides essential information for data-model comparisons, and important tests for models that project future sea level rise. However, there are few quantitative temperature estimates for past warm periods, like the early Holocene and Last Interglacial (LIG), from Greenland. Furthermore, there is little empiric evidence that documents regional changes in precipitation during these interglacials, which could affect accumulation over the ice sheet. Here we discuss findings from a rare sedimentary archive from northern Greenland that preserves both the early Holocene and the LIG. Insect (midge) assemblages used to quantify summer air temperature demonstrate pronounced warming during both the early Holocene and the LIG. These warm estimates align with previously disparate estimates from the Agassiz Ice Cap for the early Holocene and the

NEEM ice core for the LIG. Together, these records reveal a pattern of exceptionally strong warming over northern Greenland with insolation-driven Arctic warming. This warming likely contributed to enhanced thinning of the northwest margin of the Greenland Ice Sheet near Camp Century in the early Holocene. In contrast, strong warming in the LIG is difficult to consolidate with inferred ice sheet extent and modeled ice sheet evolution. A mismatch between observations and models suggests something is missing in our understanding of Greenland during the LIG. We propose one possible way to accommodate both observations is an increase in precipitation in Greenland during the LIG. We also present evidence from compound-specific hydrogen isotope ratios for distinct differences in the hydroclimate regime of northern Greenland during the late Holocene, the early Holocene, and the LIG. We discuss preliminary findings from a Greenland modern calibration dataset that demonstrates sedimentary leaf waxes are a reliable proxy for regional precipitation in Greenlandic watersheds. We discuss changes in local precipitation in comparison to changes in local temperature through the Holocene and LIG as reflected in lake sediments in northwest Greenland.

Determining the last interglacial ice sheet configuration using glacial isostatic adjustment modelling

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The last interglacial (MIS 5e) was a period characterized by sea level that was up to 6-9 m above present day level, due in part to the partial collapse of the Greenland and West Antarctic Ice Sheets. Assessing the pattern of sea level change for this period is complicated due to the uncertainties in the relative contributions of these two ice sheets. In addition, past sea level is the integrated history of water load changes and associated glacial isostatic adjustment before and after the period of interest. We present a the initial results of a global ice sheet reconstruction that seeks to untangle the last interglacial ice sheet configuration. The ice sheets are reconstructed by using the program ICESHEET, which uses ice sheet margin reconstructions and estimates of basal shear stress to produce realistic ice sheet configurations. We calibrate this model by modelling glacial-isostatic adjustment with relative sea level indicators. We also investigate the role of different Earth rheology models on the global pattern of sea level change during this period. We make an assessment of how much uncertainty in the last interglacial sea level is due to the ice sheet configuration during the last glacial cycle.

Gravitational, and regional dynamic sea level controls on the amplitude of an observed late MIS 5e meltwater pulse from Western Australia

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A detailed dGPS ground and airborne geophysical (Lidar) survey of last interglacial reefs and coastal barrier deposits was undertaken along the Western Australia's Pilbara, Cape Range and Quobba coasts, spanning a coastline length of ~750 km. Common to all surveyed Last Interglacial (LIG) sites was geomorphological, sedimentological, and geophysical evidence for a rise in sea level driven by a meltwater pulse late in the interglacial. The elevation difference between the pre and post meltwater pulse shorelines ranged between 2.5 m to as high as 5 m at some exposed higher energy coastal sites. While the surveyed coastal areas are known to be affected by neotectonism, it should be noted that the goal of the study was not to establish absolute eustatic sea level values but to simply quantify the change in sea level between early and late MIS 5e; a period short enough whereby shorelines elevations are unlikely to be affected by longer term dynamic or neotectonics processes.

While the amplitude of the sea level rise is captured in the fossil shorelines this does not represent the true eustatic value as there are a number of contributing factors, particularly relevant to the Western Australian coast that can result in a local/regional departure from the true eustatic value.

The first contributing factor that can result in a departure of local sea level rise from eustatic is the effect of water

migration away from a collapsing ice sheets due to the diminished gravitational attraction. For sites along the Western Australian (WA) Coast a collapse of the West Antarctica Ice Sheet can result in water levels up to 25% higher than the eustatic value, however an East Antarctic Ice Sheet collapse would see a sea level rise equivalent to 85% of the total (i.e., less than) eustatic value.

Sea level along the WA coast is also sensitive to changes in Pacific Decadal Oscillation (PDO), El Niño Southern Oscillation (ENSO), and Indian Ocean Dipole (IOD). A positive SOI and/or negative PDO can increase SST (ocean steric effect) across northern Australia, which can result in enhanced poleward Leeuwin Current flow along the WA. An example of this occurred during a very strong La Nina event, which peaked during the 2011 austral summer and autumn, where WA experienced sustained positive sea level anomalies of between 25 and 50 cm during this period. Variations in long-term (multidecadal to centennial) wave climate can also contribute to fluctuations of local relative sea level through changes in wave setup and swash characteristics that can add or remove several decimetres of water level from the local MSL.

All above-mentioned factors have the combined effect of adding positive sea level contribution on top of true eustatic sea level rise, resulting in a probable over estimation of the magnitude of late MIS 5e sea level rise. Here we report on a regional sea level budget for the West Australian coast during the last interglacial, taking into account gravitational and regional dynamic sea level controls in order to better constrain the true magnitude of eustatic sea level rise during the latter half of MIS 5e.