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Workshop

PALSEA

Using ecological and chronological data to improve proxy-based paleo sea level reconstructions

Organizers: N. Barlow, R. Edwards, J. Austermann, A. Rovere, J. Shakun, N. Khan

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Workshop rationale

The first meeting of the new phase (2019-2021) of the PAGES and INQUA working group PALeo constraints on SEA level rise (PALSEA) will focus on refining proxy-based reconstructions of past sea level. Sea-level rise due to polar ice sheet decay in a warming world is one of the most important, and most uncertain aspects associated with climate change. Because the instrumental record is short and changes to date have been modest, observations from the recent past provide at best a limited vantage point from which to gauge the future. The geologic record, in contrast, features major, and sometimes rapid, changes in ice sheets and sea level that remain to be fully explored and explained. Recent methodological improvements bear the potential to reduce uncertainties in local sea-level reconstructions, which will be crucial for reconciling sea level-based estimates of past ice sheet volumes.

Scientific program

General information

Presentations will be 15 mins + 5 mins for questions (with the exception of invited speakers who have 25 mins + 5 mins for questions)

Posters will follow the same format as for INQUA: portrait and no bigger than A0 (0.84 x 1.19 m). Please also bring along one slide (and upload it by lunchtime on Day 2) to form part of the speed poster presentation.

Sunday July 21st

8.30 - 9.00 Registration of participants

9:00 Workshop organizers: Welcome

Session 1. Ecological and environmental interpretation of proxy-based datasets

9:15 Chris Perry (Invited talk). Coral-based records of past and present sea level and environmental change: challenges, limitations and opportunities

9:45 Michael Bentley. The challenges of developing a comprehensive Antarctic relative sea level database

10:05 Alastair Clement. Leveraging coastal geomorphology to constrain and refine reconstructions of Holocene sea-level change in New Zealand

10:25 Michael O'Leary. Submerged landscape geomorphology in reconstructing sea level and wave climate over the last glacial cycle

10:45 Coffee break

11:10 Robin Edwards. Building foraminiferal transfer functions for tide level: Is there still a need to get our boots dirty?

11:30 Erica L. Ashe. Improving estimates of relative sea level through the use of nonparametric empirical distributions of proxy indicators

11:50 Graham Rush. A regional foraminifera-based transfer function for Holocene sea-level reconstructions around the North Sea and the importance of assessing both accuracy and precision

12:10 Discussion

12:30 Lunch

14:00 Sarah Woodroffe (Invited talk). Lessons in reconstructing late Holocene relative sea level from the high and low latitudes

14:30 Orijemie Emuobosa Akpo. Relative Sea-level Changes from Benin Region, southern Nigeria

14:50 Miklos Kazmer.

15:10 Torbjorn Tornqvist. Time-depth dependency of sediment compaction in coastal strata and its implications for sea-level reconstruction

15:30 Coffee break

15:55 Senthil Kumar Sadasivam. Bacteria based paleo sea-level reconstruction

16:15 Martina Conti. Organic geochemical markers of sea-level changes

16:35 Robert L. Barnett. Ecological Constraints on Sea-Level Indicators

16:55 Discussion

17:30 End of day

Monday July 22nd

9:00 Workshop organizers: General outline for the day

Session 2. Cutting-edge chronological attribution techniques

09:15 Christina Obert (Invited talk). U-series dating of fossil reef corals

09:45 Michael R. Sandstrom. An assessment of Sr isotope stratigraphy dating of late Miocene to mid-Pleistocene sea level highstands

10:05 Barbara Mauz. Improving the quality of optical ages for sea-level reconstruction

10:25 Lucy Wheeler. Bringing amino acid geochronology of sea-level records up to date: developing an intra-crystalline approach for foraminifera

10:45 Coffee break

11:10 Marc Hijma. Sea-level research in Greater Rotterdam, The Netherlands

11:30 Kim Cohen. Bayesian-calibration decisions for the basal-peat SLR data series of the Rhine-Meuse Delta

11:50 April Dalton. Chronostratigraphic records offer much-needed constraint on the Laurentide Ice Sheet prior to the last glacial maximum

12:10 Discussion

12:30 Lunch

14:00 Andrew Parnell. Improving chronological models for estimating sea level rise

14:30 Nicole Khan. Producing records of relative sea-level change from mangrove sedimentary archives

14:50 Benjamin Horton. Defining the beginning of the Anthropocene with proxy sea-level records

15:10 Discussion

15:30 Coffee break

15:55 Arrangements for Day 3 (Alessio Rovere and Nicole Khan)

16:00 Speed poster presentations (1-slide per person), followed by poster session

18:00 End

19:30 Conference dinner

Poster presentations

Amila Sandaruwan Ratnayake. Tropical Ecological Changes in Relation to Holocene Sea-Level Changes

Dorit Sivan. Roman times Mediterranean sea levels as a key question for the last 2ka trends

Ed Garrett. Holocene relative sea-level change in Chile

Edward Gasson. Towards improved paleo sea level estimates to constrain ice sheet models during past warm intervals

Evan J. Gowan. Last interglacial sea level along the Patagonian coast

Fiona Turner. Reconstructing Antarctica: Bayesian techniques to learn more about past ice sheet shapes.

Jacqueline Austermann. The effect of lateral viscosity variations on sea level during the last interglacial

Jayaraju Nadimikeri. Paleoecosystem of Pulicat Lake , East coast of India

Marc Hijma. First results of the 2017-2018 Early Holocene Sea-level Research Cruises on the North Sea

Mariel Samanta Luengo. Paleoenvironmental evolution and vegetation changes during the Holocene at the NE coastal plain of Buenos Aires, Argentina.

Natasha Barlow. Using seismic datasets to reconstruct palaeo sea-level change recorded in submerged landscapes

Rebecca Cleveland Stout. Leveraging preservation bias in Last Interglacial coral sea-level records to refine global ice volumes over the ice age

Roland Gehrels. Multi-decadal relative sea-level changes from salt-marsh indicators and tide gauges

Sophie Williams. Searching for fingerprints of early 20th century ice melt in Australian salt marshes

Timothy Shaw. Constraining Common Era relative sea-levels in Southeast Asia using mangrove environments

Tuesday July 23rd

9:00 Workshop organizers: Welcome

Session 1. Introduction and progress updates on each group and its objectives

9:10 Nicole Khan. The HOLSEA project

9:30 Alessio Rovere. The WARMCOASTS project

9:50 Jacky Austermann. Integrating sea level data with models of glacial isostatic adjustment - current approaches and challenges

10:10 Erica L. Ashe. Incorporating physical process into spatio-temporal statistical models

10:30 Coffee Break

Session 2. Breakout groups (11:00-3:30, including lunch from 12:30 to 2:00)

HOLSEA breakout group

Andrew Parnell	Amila Sandaruwan Ratnayake
Alastair Clement	Ed Garrett
Benjamin Horton	Erica L. Ashe
Dorit Sivan	Fiona Turner
Marc Hijma	Graham Rush
Robin Edwards	Jayaraju
Mike Bentley	Senthil Kumar Sadasivam
Miklos Kazmer	Mariel Samanta Luengo
Roland Gehrels	Sarah Woodroffe
Torbjorn Tornqvist	Nicole Khan
Sophie Williams	Orijemie Emuobosa Akpo
Timothy Shaw	Robert L. Barnett

Objective 1. Define open questions regarding Holocene sea levels and where more data or methodological advances are needed to answer these questions

Objective 2. Discuss future of the group: 2019 is the final year of INQUA funding – what's next?

- Reapply under HOLSEA (or modified name) with new or same leadership
- Expand the scope to include other time periods or more information on indicators (e.g., microfossils)

WARMCOASTS breakout group

Edward Gasson	Michael O'Leary
Jacqueline Austermann	Martina Conti
Christina Obert	Rebecca Cleveland Stout
Barbara Mauz	Natasha Barlow
Kim Cohen	Alessio Rovere
Evan J. Gowan	Jeremy Shakun
Lucy Wheeler	Deirdre Ryan
Michael R. Sandstrom	Patrick Boyden
April S Dalton	Sarah Eggleston

Objective 1. Discuss the World Atlas of Last Interglacial Shorelines and present the database template, with instructions on how to use it.

Objective 2. Define focus regions where data in literature is missing/scarce/hard to find and brainstorm on potential database contributors to invite to the Special Issue in preparation.

3:30-3:45 Coffee Break

Group Discussion (both groups combined) (3:45-4:30)

Objective 1. Summarize breakout group discussions

Objective 2. Gauge feedback from community on the direction we are taking with these database initiatives

Objective 3. Outline future avenues and research directions

Objective 4. Outline the possibility of a joint website (e.g. a Wiki) where sea level information can be described and stored long-term.

Objective 5. Visualization and analysis of sea level data, collection of ideas

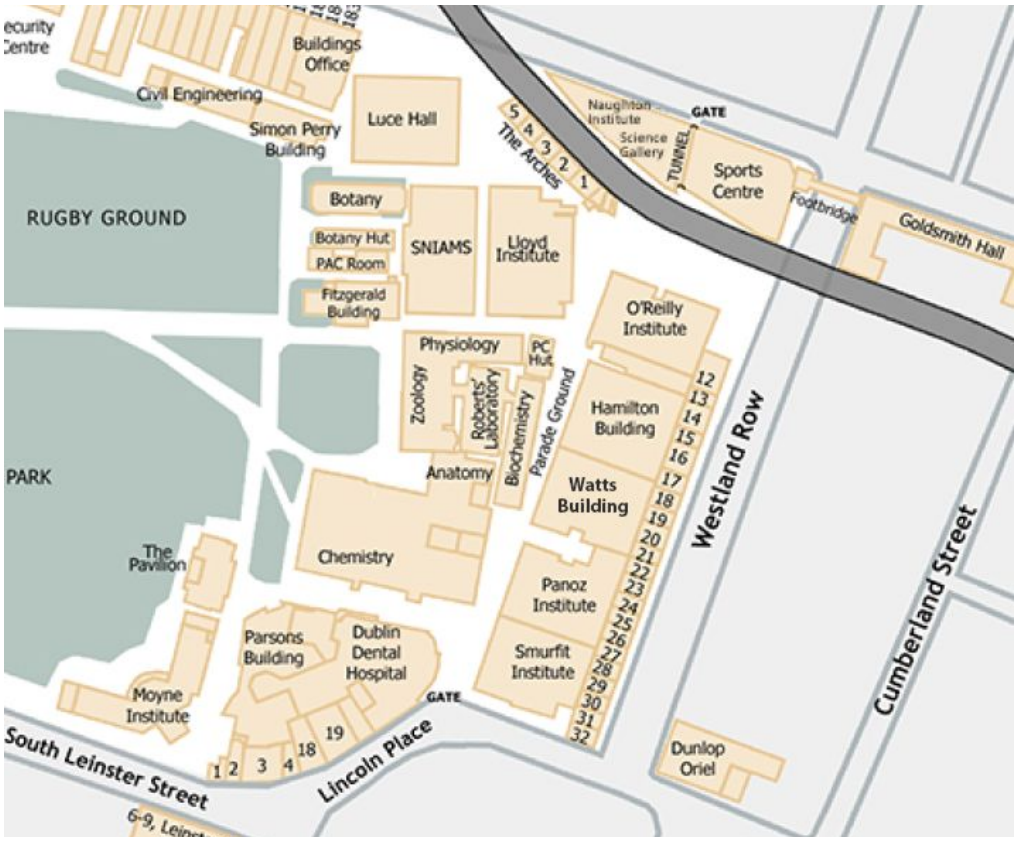
List of participants

Name	Affiliation
Alastair Clement	Massey University, New Zealand
Alessio Rovere	University of Bremen, Germany
Amila Sandaruwan Ratnayake	Uva Wellassa University, Sri Lanka
Andrew Parnell	Maynooth University, Ireland
April S Dalton	Durham University, UK
Barbara Mauz	University of Salzburg, Austria
Benjamin Horton	Nanyang Technological University, Singapore Rutgers University, USA
Chris Perry	University of Exeter, UK
Christina Obert	University of Cologne, Germany
Deirdre Ryan	University of Bremen, Germany
Dorit Sivan	University of Haifa, Israel
Ed Garrett	Durham University, UK
Edward Gasson	University of Bristol, UK
Erica L. Ashe	Rutgers University, USA
Evan J. Gowan	Alfred Wegener Institute, Germany
Fiona Turner	University of Sheffield, UK
Graham Rush	University of York, UK
Jacqueline Austermann	Lamont Doherty Earth Observatory of Columbia University, USA
Jayaraju Nadimikeri	Yogi Vemana University, India
Jeremy Shakun	Boston College, USA
Kim Cohen	Utrecht University, Netherlands
Lucy Wheeler	University of York, UK
Marc Hijma	Deltares, Netherlands
Mariel Samanta Luengo	CEIDE-UNLP, Argentina

Martina Conti	University of York, UK
Michael O'Leary	The University of Western Australia, Australia
Michael R. Sandstrom	Lamont Doherty Earth Observatory of Columbia University, USA
Mike Bentley	Durham University, UK
Miklos Kazmer	Eotvos University, Hungary
Natasha Barlow	University of Leeds, UK
Nicole Khan	University of Hong Kong, Hong Kong
Orijemie Emuobosa Akpo	University of Ibadan, Nigeria
Patrick Boyden	University of Bremen, Germany
Rebecca Cleveland Stout	Harvard University, USA
Robert L. Barnett	University of Quebec at Rimouski, Canada University of Exeter, UK
Robin Edwards	Trinity College Dublin, Ireland
Roland Gehrels	University of York, UK
Sarah Eggleston	PAGES, Switzerland
Sarah Woodroffe	Durham University, UK
Senthil Kumar Sadasivam	National College (Autonomous), India
Sophie Williams	University of York, UK
Timothy Shaw	Nanyang Technological University, Singapore
Torbjorn Tornqvist	Tulane University, USA

Venue information

The meeting is being held in the **Maxwell Lecture Theatre** which is located in the **Hamilton Building** at Trinity College Dublin (see map below). Entry to the Hamilton Building is via the Parade Ground. From 1100 on Day 3, the WARMCOAST's breakout group will be based in the **Seminar Room A** located on the ground floor of the **Museum Building.** For further information on the venues please see: https://www.tcd.ie/visitors/events/venues/



Conference dinner

The conference dinner on Monday 22nd July is at the **Stack A Restaurant, Urban Brewing**, Custom House Quay at 1930; which is a 10 minute walk north of Trinity College. There is a bar, Vault C, should people wish to meet prior to dinner. Your registration fee includes one glass of wine, draught beer or non-alcoholic drink per person with dinner. Please pay for any additional drinks at the bar.

Session 1.
Ecological and environmental interpretation of proxy-based datasets

Coral-based records of past and present sea level and environmental change: challenges, limitations and opportunities

Chris Perry*

*University of Exeter

Reconstructing past and recent changes in sea level is a major challenge in tropical settings. This is, however, an important issue not only for understanding how sea-level has and may change in far-field locations, but also because it provides us with a framework within which to understand (and therefore predict) how tropical coastal and marine landforms, such as coral reefs and reef islands, may respond to near-future sea-level change. Records for the past few decades can of course be obtained using satellite altimetry data (and the few long-term reliable tide gauge records), and can be compared against current best-estimates of recent reef growth as a function of contemporary ecology. However, records from any periods earlier than this, where corals and other marine proxy provide the tools for interpreting such change, are more challenging. In some cases, and especially in settings where the general trend since the mid-late Holocene has been steady sea-level rise, our understanding is based on core records from which coral species assemblages are then used to interpret palaeo-environments/ecology and thus palaeo-bathymetry.

This necessitates assumptions about species depth distributions. Whilst these records can provide high quality palaeoecological data, for sea level reconstructions the inherent variability in species depth distributions, and questions about whether corals have been deposited in-situ or not, can create significant challenges for depth resolution estimates. Taphonomic indicators do exist that could help such interpretations but these have not been widely developed. In other settings where the sea level trend since the mid- to late Holocene has been stable or slightly falling, microatolls have offered tremendous opportunities for high resolution sea-level research. However, even in regions with good microatoll records there remain major challenges, not least of which is the development of consistent and time continuous records. Major time gaps are often evident, the reasons for this not always being clear. The divergent published records of the post mid-Holocene sea level trend in northern Australia provides an interesting insight into these challenges. Whilst it has clearly been feasible to generate sea level reconstructions from many coral reef regions, most have considerable uncertainty associated with them or major questions remaining (especially

around intra-regional variablity). Improving the resolution of these may require significant work to: 1) better document or synthesise species distributions in different reefal settings (e.g., with respect to wave energy exposure) so as to improve interpretations from core records (although we should acknowledge that many areas lack good (or any) core coverage); 2) develop and test the use of taphonomic indicators to improve depth and palaeo-interpretations; and 3) integrate records from complimentary toll such as corals, microfossils, oyster beds etc. These may provide opportunities for the sea level research community to develop and enhance tropical sea-level reconstructions.

The challenges of developing a comprehensive Antarctic relative sea level database

Mike Bentley*, Dom Hodgson, Alex Simms, Elie Verleyen, Pippa Whitehouse, David Small

**Durham University*

Understanding past sea level change in Antarctica is important for providing constraints on models of glacio-isostatic adjustment, and in particular providing datasets against which uplift predictions can be tested. The Antarctic coastline is unusual in that only 3-5% of the coast is ice-free and so the range of sites available for relative sea level (RSL) records is highly limited. Moreover, most of the coastline is affected by a high energy wave regime and seasonal ice action (sea ice or scouring icebergs) that can destroy the potential for fine-grained sedimentation along the coast. These factors mean that attempts to determine RSL change in Antarctica have been limited compared to other continents elsewhere, and have used a range of sea level indicators, some of which are unique to Antarctica. Understanding the (quantitative) indicative meaning of these indicators, can be challenging and uncertainties can be commensurately larger. These uncertainties can be further compounded because the vast majority of sites in Antarctica have no nearby surveying datum and instead rely on surveying to local indicators of sea level. In this talk we explore the indicative meaning of a range of sea level indicators sampled for radiocarbon dating, including penguin bones, marine shells, seal skin, whalebone, driftwood, seaweed, isolation basins, and beach cobbles sampled for OSL dating. We also explore some of the difficulties of incorporating quantitative elevational information into databases. We conclude with an interpretive framework that should allow us to add ~1000 Antarctic RSL datapoints to databases.

Leveraging coastal geomorphology to constrain and refine reconstructions of Holocene sea-level change in New Zealand

Alastair Clement*, Pippa Whitehouse

*Massey University

Meltwater loading on the continental shelf is hypothesised to be a significant driver of variability in Holocene sea-level (SL) changes around the New Zealand coast. The Northland peninsula, at the northern end of New Zealand's North Island, is a key laboratory for examining the impact of meltwater loading on land deformation and SL variability around New Zealand during the Holocene: the coastline is convoluted, with a variable-width continental shelf; the peninsula was tectonically stable during the Holocene, and was ice-free during the last glaciation; and the peninsula has been predicted to experience spatially-variable amounts of hydro-isostatic subsidence during the Holocene, from ~1 m in the south increasing to ~12 m in the north. Ongoing work seeks to obtain new palaeo SL reconstructions to validate glacial isostatic adjustment (GIA) model predictions of land deformation and SL variability across the peninsula.

Proxy reconstructions of Holocene SL changes in New Zealand are almost exclusively constructed using fossil molluscs preserved in coastal sedimentary sequences; several reconstructions have been made using salt-marsh foraminifera, though these span only the past c. 500 years BP. Molluscs have been favoured as there are species with a well-defined ecological relationship with tide level, and the sedimentary sequences in which molluscs are preserved span the Holocene. However, in some settings the vertical errors associated with mollusc sea-level index points have been large.

In pursuing new reconstructions of Holocene SL changes from Northland, we are leveraging coastal geomorphology to provide natural constraints for our palaeo SL index points derived from fossil molluscs. One location we are targeting due to its unique geomorphology is the Hokianga Harbour, a drowned river valley estuary that extends inland approximately half the width of the Northland peninsula. The partially-infilled upper reaches of the harbour therefore lie on the midline of the peninsula. The antecedent geomorphology of the harbour therefore physically constrains the timing and nature of the infilling initiated in the upper harbour in the mid-to-late Holocene, and thereby places constraints the SL signal preserved in the upper reaches. This has the potential to reduce uncertainty in the resulting SL

reconstruction, allowing us to better elucidate the role of land deformation in SL variability around New Zealand.

Submerged landscape geomorphology in reconstructing sea level and wave climate over the last glacial cycle

Michael O'Leary*, Ian Goodwin, Victorien Paumard

**The University of Western Australia*

Australia's western continental margin represents an area of approximately 1,239,690 km2 spread over 25 degrees of latitude. The shelf is starved of fluvial derived terrigenous sediments with carbonates sands dominating the coastal and nearshore through to the shelf edge environments. A result of this unique sedimentology has been the post depositional induration and preservation of carbonate dominated coastal landforms on the shelf through successive regressive and transgressive sea level cycles.

While in the past the nature and location of these landforms have been enigmatic, recent advances in high resolution 3D seismic data processing (PaleoScanTM) and the release of industry and government multibeam and bathymetric LiDAR datasets covering hundreds of thousands of square kilometres of continental shelf, have revealed in unparalleled detail, the behaviour of sea level, wave climate and coastal response from the termination of MIS 5e through to the last glacial maximum.

Two of the most well-developed submerged sand barrier shorelines typically occur as couplets and are consistently located at depths of -16 and -22 m, and possibly represent MIS5a and 5c shorelines. A very extensive and geomorphically mature coastal sand barriers and lagoons are located at depths of -75 to -80 m and represent an extended interval of stable sea level at this elevation. Other less mature features including beach ridges, sand spits, estuarine tidal channels are observed at multiple depths and likely represent brief sea level still stands followed by a sea level regression. Interestingly reef terraces or coral build ups are not observed on the sea floor suggesting cooler SST during the last glacial cycle possibly through a weakened Leeuwin Current.

Building foraminiferal transfer functions for tide level: Is there still a need to get our boots dirty?

Robin Edwards*, Niamh Cahill, Andrew Kemp, Andrew Parnell

**Trinity College Dublin*

Saltmarsh foraminifera are widely employed as sea-level indicators because they form high abundance, low diversity assemblages with affinities for particular tidal elevations which make them well suited to quantitative analysis. Species-elevation relationships are established by the measurement of modern vertical distributions (modern analogues) which are then used to infer palaeomarsh-surface elevation from fossil foraminiferal assemblages. A key assumption of foraminifera-based reconstructions is that the relationships among individual species and tidal elevation have remained constant through time: an assumption that cannot be directly tested. Instead, to gauge the stability of species-environment relationships, it is common practice to substitute space for time and argue that a species which exhibits a characteristic elevation preference across a wide range of sites is less prone to the distorting influences of 'secondary variables' than a taxon with site-specific vertical distributions.

Nearly half a century of research has produced a rich dataset of surface foraminiferal distributions from sites spanning the length of the North American Atlantic coast. We employ these data to evaluate how training set composition impacts foraminiferal reconstructions, using both frequentist and Bayesian-based transfer functions for tide level. We address the extent to which species response curves vary in space; the susceptibility of relative sea-level reconstructions to these variations; and their potential significance for 'fingerprinting' approaches which utilise spatial patterns to infer drivers of change. We conclude with recommendations for future work, including whether or not the time has come to stop collecting new surface data and work instead with a standardised, universal training set.

Improving estimates of relative sea level through the use of nonparametric empirical distributions of proxy indicators

Erica L. Ashe*, Nicole S. Khan, Lauren E. Toth, Robert E. Kopp

**Rutgers University*

Formal statistical treatments are needed to account for the spatially and temporally sparse distribution of data and for geochronological and elevational uncertainties. Accurately reconstructing relative sea level (RSL) relies on the ability of statistical models to realistically constrain the relationship between individual proxies and RSL. These relationships can be complex, and are often poorly-described by traditional methods that assume Gaussian likelihood distributions.

Several RSL proxies have modern depth distributions that are clearly non-Gaussian, including various coral taxa. Many proxy data are assumed to form within a Gaussian distribution, but this is assumption is often untested. We use distribution-fitting techniques to analyze two example proxies, mangroves and corals, based on databases (from south Florida and the greater Caribbean, respectively) of their modern elevations/depths. Results show that mangrove elevational distributions are approximately normal in relation to sea level. For each coral taxon, however, normal distributions are a poor approximation of the modern depths in relation to sea level. We, therefore, present techniques for estimating RSL using coral proxies with empirical, nonparametric distributions.

We also present a Bayesian hierarchical statistical model that incorporates these modern distributions as likelihoods. We validate the performance of this nonparametric model by applying it to synthetic data (which emulates real data based on a synthetic "true" spatio-temporal sea-level field) and perform sensitivity analyses on various precisions and amounts of synthetic data to determine the data requirements for reconstructing different sea-level scenarios. We show that average error and log-likelihoods of the new model are lower than previously published models, validating the enhanced performance of our new statistical framework. The sensitivity tests reveal that accurately reconstructing large accelerations in RSL rates of change, such as those that may have characterized melt-water pulses (rates up to ~ 40 m/kyr), requires ~ 10

high precision (90% likelihood within ~6 m) data points/kyr. Precisely and accurately reconstructing smaller amplitudes (~15 m/kyr) in rates of RSL change, such as those characterized by the Holocene, requires fewer than 6 data points/kyr with less precision. As expected, smaller uncertainties (in both ages and vertical uncertainty) improve the accuracy of predictions and enable more precise predictions of large changes in sea level, which is necessary for reconciling sea level-based estimates of past ice sheet volumes.

We then employ the nonparametric model for several applications from the Holocene and deglacial periods. We reanalyze a circum-Caribbean dataset, where we restrict the likelihoods of several distributions based on taphonomic indicators of depth environment or geomorphic features. Results include the reconstruction of the Caribbean sea-level field over the Holocene, which are separated into local, regional, and common processes.

We also apply the model to the Barbados deglacial dataset to produce a probabilistic assessment of melt-water pulses recorded by the data and enable a discussion of the processes that affect sea level over this period.

A regional foraminifera-based transfer function for Holocene sea-level reconstructions around the North Sea and the importance of assessing both accuracy and precision.

Graham Rush*, Roland Gehrels

**University of York*

The vertical relationship between foraminifera and sea level in intertidal environments has long been recognised and applied to reconstruct past sea levels using fossil foraminifera as proxies. Late Holocene sea-level reconstructions from salt-marsh foraminifera have been established in many temperate coastal regions with high vertical precision, often quoted as sub-decimetre. The majority of studies use modern samples, collectively known as a training set, from a proximal site to develop local transfer functions that are then applied to fossil cores. This method relies on the explicit assumption that the species assemblages in the modern environment are an accurate analogue for fossil foraminifera in the core. In the absence of "good" analogues in local training sets, and therefore non-conformity of environmental conditions, a regional dataset developed from multiple sites may be more appropriate. This is particularly relevant for sea-level reconstructions from middle and early Holocene salt-marsh foraminifera, for which the likelihood that environmental conditions have remained constant may be small.

We developed a North Sea foraminifera-based transfer function using both existing and new data from ten sites in the UK and continental Europe. We established a suitable standardised water level index that is used to produce a suite of regional regression models. The various models are tested against early Holocene fossil records from two sites to test for functionality in terms of accuracy and precision. The resultant models will be made available and applied to produce an early Holocene relative sea-level reconstruction for the Ythan Estuary in northeast Scotland.

Lessons in reconstructing late Holocene relative sea level from the high and low latitudes

Sarah Woodroffe*

*Durham University

Relative sea-level (RSL) reconstructions with decimetre or less vertical errors and sub-century horizontal errors are becoming commonplace from temperate intertidal sediments, which are predominantly aimed at trying to understand the history of ice-equivalent sea level over the past decades to millennia. These reconstructions often use statistical models such as transfer functions and more recently Bayesian techniques that incorporate other prior understanding from different proxies to further improve accuracy and precision. Using multiple dating methods and marker horizons also allows development of sophisticated age-depth models that allow researchers to investigate changes in the rate of RSL changes over recent decades and centuries.

Employing these methods in environments other than temperate salt marshes can be challenging. During this talk I will discuss my experience of working in Arctic saltmarshes with the aim to reconstruct changes in the Greenland ice sheet over recent centuries, in particular since the Little Ice Age. These environments are hard to extract high precision RSL data from, because of issues with low sedimentation rates, patchy microfossil preservation and a lack of dating marker horizons to aid the development of age/depth models. Equally I have been involved in studies investigating late Holocene RSL changes in mangrove-dominated coastlines on northern Australia and the Seychelles. These environments have different, but no less significant challenges in terms of microfossil preservation, bioturbation and issues with obtaining in situ material for radiocarbon dating. This talk will focus on my recent RSL research in the Arctic (Greenland) and low latitude (Seychelles) environments to highlight ongoing issues with developing high-resolution RSL data in these sedimentary environments.

Relative Sea-level Changes from Benin Region, southern Nigeria

Orijemie Emuobosa Akpo*

**University of Ibadan, Nigeria*

The latest Holocene history of Relative Sea Levels (RSL) of two localities in the Benin region of southern Nigeria was reconstructed. The reconstruction was based on a Rhizophora/Avicennia (R/A) ratio model obtained from two sediment cores I (8m) and II (1.5m) drilled in the Mangrove Swamp Forests (MSFs) of the Benin region; Rhizophora naturally inhabits shorelines and tidal areas while Avicennia prefers inshore areas. Therefore, an abundance of Rhizophora over Avicennia is indicative of high marine influence and vice versa. Four periods of significant sea level changes were inferred to have occurred during the last 1, 300 yrs BP. The first, a natural phenomenon, occurred at 1,100 yrs BP, while the other three occurred in the last ca. 500 yrs BP; these were accompanied with evidence of human intervention within the mangrove swamp forest and in the adjoining high rain forest during the later periods. The paper further explores the impact of the reconstructed sea levels on the economic history of the area with special attention on the significance of sea trade relations between pre-colonial Benin and Portugal, as well as the rest of Europe up until the 19th century AD.

Fixed biological sea level indicators in Holocene and Last Interglacial tropics

Miklos Kazmer*

**Eotvos University, Budapest, Hungary*

"Fixed biological indicators are organisms that live fixed to hard substrates and their living range… is located… at sea level" (Rovere et al., 2015, Handbook SL Research). The technique of using immobile organisms to recognize sea-level change was developed by Laborel (1994 JCoastRes 10) mostly for the Mediterranean, a microtidal sea in the warm temperate climate zone. There vermetid gastropods, coralline algae, corals, Lithophaga bivalves, oysters, barnacles live close to each other, at or just below sea level. The Laborel scheme is based on bioconstruction, on organisms cemented to rock shore. The scheme works pretty well not only in the Mediterranean but also in the tropical Atlantic (Laborel 1996 QuatInt 31). While it is used by practically everyone, shore profiles measured and documented in detail do not abound.

The rest of the tropics is understudied in this respect. In Southeast Asia tidal range is often 3 m high. Organism zones expanded along an elevation interval ten times higher than in the Mediterranean allow their clear separation and let us study their intercalation and overlap. Seawater temperature is about 30 degrees year round. Chemical processes run faster and organisms grow larger, uninterrupted by seasonal changes, unlike in the temperate zone. Traces of biological erosion are spectacular here; these are easily included in the scheme of sea level markers.

Here a composite scheme of sea-level markers is provided for the tropics (Indian and Pacific oceans) based on bioconstructing and bioeroding organisms. Numerous profiles measured in detail reveal the systematic arrangement of individual zones. The biological background (competition, predation) and ecological parameters (temperature, desiccation, illumination) is added to reveal the significance and reliability of each zonal element as sea level marker.

The requirements of fixed biological indicators as listed by Laborel (1996) unnecessarily exclude bioerosion features: most of them fulfil his criteria. The only disadvantage is the scarcity of body parts in trace fossils, making them less suitable for radiochronology (but linings of Lithophaga borings can be readily measured). Examples are provided to

prove their usefulness in identifying subsidence and uplift, and in assessing whether displacement was slow or instantaneous.

Fossilization potential of borers is significantly higher than that of encrusters. Skeleton of encrusters easily fall prey to grazing and boring organisms. Echinoid boreholes, up to 20 cm deep decorate carbonate coasts of Thailand up to several metres height, indicating significant coastal uplift.

Southeast Asia mostly has barnacle-limpet-chiton-Lithophaga-Echinometra urchin zonation. India has extensive corallinacean algal crusts. Arabian shores display worm bioherms in the intertidal zone. Microatolls of Indonesia are faithful recorders of coastal uplift and subsidence on an annual scale."

Time-depth dependency of sediment compaction in coastal strata and its implications for sea-level reconstruction

Molly Keogh, Torbjörn Törnqvist*, Alexander Kolker, Gilles Erkens

**Tulane University*

Sea-level indicators collected from unconsolidated deposits are often affected by sediment compaction and a variety of studies have shown that vertical displacement on the order of several meters due to this process is possible in Holocene coastal strata. Sea-level data synthesized from previously published work often exhibit considerable scatter outside of quantified errors and some of this may be due to undetected compaction issues. Recent attempts to better understand this problem have occurred on one hand through empirical studies that compare compaction-free to compaction-prone samples of similar age, in order to quantify magnitudes (and rates) of vertical displacement. On the other hand, geotechnical modeling has been applied within the context of sea-level studies by quantifying post-depositional lowering of marsh strata. Collectively, these studies have shown that coastal successions vary widely. Examples range from relatively pristine and highly organic marshes on the US Atlantic Coast that exhibit minimal compaction effects, versus Holocene wetland strata from the Mississippi Delta that have undergone vertical displacement of 5 m or more. These contrasts are likely related, at least in part, to the mineral content and thickness of overburden strata, hydrologic conditions, and the resulting rate of increase of effective stress with depth.

Here we examine a dataset from coastal Louisiana that was assembled to study the time-depth dependency of sediment compaction in coastal/deltaic deposits â€“ facies that are frequently used in sea-level studies. Specifically, we focus on changes with depth (and, hence, age) of dry bulk density, accounting for organic-matter content. A key element of this dataset is the sediment characterization of the uppermost 24 cm, available from almost 300 sites across coastal Louisiana, representing essentially unconsolidated wetland facies. We compare this dataset with relatively organic-rich wetland facies from sediment cores, buried up to ~12 m deep. Our initial findings show that the overwhelming majority of bulk density increase, volume loss, and vertical

displacement due to sediment compaction in this area occurs within the uppermost 2 m or less, which corresponds temporally to no more than a few centuries. These new findings have the potential to benefit sea-level reconstructions in various ways, including (1) providing a better foundation for selecting sampling sites; and (2) enabling a more rigorous interpretation of published sea-level data, provided that they contain an adequate amount of stratigraphic information.

Bacteria based paleo sea-level reconstruction

Senthil Kumar Sadasivam*, Bhavatharini Shanmuganathan, Shan P. Thomas, Sivakumar Krishnan, Kartika Goswami, Maha Dev, Manoj Kumar Jaiswal, Anbarasu Kumaresan

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Bacteria based sea-level reconstruction has been attempted and it is the first Geobiotechnological study of integrated approach providing more comprehensive understanding of bacteria based paleo sea-level reconstruction. Five sediment cores to a depth of about 25m were collected from the study area-Cauvery delta, Tamil Nadu, South East Coast of India. OSL dating revealed that the deepest sediments of the all the five cores belonged to Late Pleistocene. In Vettaikaraniruppu (VKI) core, foraminifers were observed at the depths of 21.0m & from 10.9m to 5.6m and the sediments at the depths have been dated to 122.10±39.00 & 9.27±1.22 kaBP which coincide with Last Interglacial Transgression (LIGT) and Mid Holocene Transgression (MHT) respectively. In Thalainayar (TNR) core, foraminifers were observed from 16.0m to 14.5m and from 7.5m to 7.0m. In Korukkai (KUI) core, foraminifera were observed at 17.0m (121.49±20.49 kaBP) which coincide with Last interglacial transgression, from 15.0 to 14.5m and from 9.0m to 8.5m. The study is not simply about biodiversity and not simply an add-on to conventional stratigraphic studies.

The study had attempted with careful planning, of field and laboratory work right from the choice of sampling location (Paleo-Beach Ridges). Beach ridge serve to be an ideal location for unveiling bacterial diversity for studies related to paleo sea-level reconstruction. The reliability of bacterial signals extracted from the sediments had been carefully assessed. Extensive high throughput techniques had been used for actively guiding and developing the paleo sea-level reconstruction studies based on bacteria. 16S rDNA sequencing on Illumina NextSeq 500 was effective for characterizing diverse group of bacteria and is the most advanced technique available for describing the composition of bacterial communities from the sediments. DNA yield was low in VKI-5 (7.2m), VKI-8 (13.6m) and KUI-11 (14.5m) and these results were in consonance with the sedimentological profile as the clayey sediments have high affinity towards DNA. Inspite of low DNA yield, VKI-5 possessed highest bacterial diversity. Alpha diversity analysis of the bacterial communities also revealed highest bacterial diversity in VKI-5 (7.2m, 6.04 ± 1.25ka BP) and KUI-16 (24.2m, 145.51 ± 27.92 ka BP) among their

respective core samples. VKI-5 sample showed highest marine bacterial proxies which was in consonance with the marine transgression that occurred during 9-6ka and also coincided with foraminiferal profile. The sediments formed during the marine transgression period of 9 kaBP and 6 kaBP are observed from 10.9m depth to 5.6m depth respectively in VKI core located ~2.6Km inland.

This transgression was also reported from other parts of the World. Bacterial indicators correlated well with global and regional marine transgression and regression and coincide well with robust geomorphological, chronological framework, sedimentological, and micropaleontological analysis. The pattern and ratio of abundance to rare marine bacterial species exhibited at different depths of VKI with respect to marine transgression and regression respectively illustrated the prospects of employing bacterial proxies for tracing paleo-sea level reconstruction. Bacteria based paleo sea-level reconstruction had been achieved in the present study and it coincided well with the sea-level changes depicted by the conventional geological proxies.

Organic geochemical markers of sea-level changes

Martina Conti*, Natasha Barlow, Martin Bates, Kirsty Penkman, Brendan Keely

**University of York*

Targeted analysis of organic materials in soils is useful for evaluating past environmental conditions, as specific fauna / flora are related to sea-level changes. However, this depends on the preservation of macro and microfossils in the sediment. Specific molecular fossil compounds (termed biological markers or biomarkers), preserved in the soil matrix, may also be directly linked to organisms and hence to the conditions in which they thrived. Variations in biomarker distributions have therefore become a powerful tool for understanding changes in palaeoclimate conditions. Understanding the main drivers for local past climate changes can inform predictions of future sea-level rise.

This work determines the utility of molecular fossil marker evidence for Quaternary sea-level changes in sediment deposits from the UK, alongside establishing detailed chronologies for the sediments by amino acid racemisation (AAR) dating of carbonate shells and foraminifera. The cores consisted of unconsolidated immature sediments from the mid-late Pleistocene (< 500,000 years) that represented sea-level transgressions. The production of organic geochemistry biomarkers (such as chlorophyll pigments and lipids) change as a response to palaeoenvironmental conditions, providing a useful marker for sea-level changes. Fluctuations in the pigment and n-alkane distribution reflect changes in primary producer activity, while the GDGT-based index of branched and isoprenoid tetraether lipids (BIT) differentiates between terrigenous and marine organic matter inputs. Lipids were analysed by GC-FID and HPLC-MS while analysis of chlorophyll pigments was carried out using a new UHPLC-DAD method. The AAR chronology provides temporal constraints to the transgressions, enabling the reconstruction of Pleistocene sea-level changes beyond the capabilities of 14C dating.

The results from biomarker analyses show excellent time-resolved agreement with the lithological and ecological interpretation, but enabled a more sensitive response of different primary producers to changing conditions to be observed. Linking the pigment, lipid and chronological records, the impact of climate change on the primary producer communities and preservation of molecular signatures can therefore be

assessed over transgressive phases of sea-level change. This coupled approach - using biogeochemical markers within temporally constrained deposits - enables exploration of a far wider set of sediments for understanding the past.

Ecological Constraints on Sea-Level Indicators

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Precise (palaeo) sea-level data rely on narrow indicative meanings that constrain the vertical distributions of proxy indicators. High-precision Late Holocene data are often derived from elevation-dependent relationships between sea level and modern analogues, including the distributions of intertidal microorganisms across wetland surfaces. These relationships are frequently demonstrated to be robust at local to regional scales, and are therefore considered reasonable approximations for past ecological conditions over recent centuries and millennia. However, for modern day analogues to be applied as indicators of Late Quaternary (e.g., Last Interglacial) sea-level changes, when ecological conditions may have been significantly different from present, these proxy – sea-level relationships must be robust across larger scales if the rule of uniformitarianism is to be assumed. Local modern analogue datasets (e.g., distributions of wetland microorganisms) exist for all continents except Antarctica and are often collocated with measured ecological variables (e.g., salinity, pH, grain size, nutrients, carbon). However, these data are yet to be collated and curated, and collection protocols of new datasets of this kind are yet to be standardised and optimised following a community-wide approach. This contribution aims to develop a framework for the collation, curation and collection of these data, built around community-driven motivations. The resulting database will be used to explore relationships between sea-level indicators (e.g., foraminifera, diatoms, testate amoebae) and ecological variables (e.g., sedimentology, carbon content, geochemistry) across extra-regional and global scales. This database will be an important and valuable tool for: i) developing verified sea-level indicators that are robust across time and space; ii) contributing new data and (ecological) perspectives to discussions on rates and budgets of blue carbon, and; iii) constraining widespread ecological changes driven in recent centuries by sea level and climatic changes.

Session 2.

Cutting-edge chronological attribution techniques

U-series dating of fossil reef corals

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Institute of Geology and Mineralogy, University of Cologne

Fossil reef corals provide an important archive for sea-level and seasonally resolved climate reconstructions across the (sub-)tropical oceans, and are well suited for 230Th/U dating. While Th incorporation into the coral skeleton is excluded due to its very low solubility in seawater, U is incorporated and subsequently decays to 230Th. The activity ratio of 230Th to U can be measured and used to calculate the time that has passed since coral growth. However, this method is based on two conditions: no 230Th is initially incorporated and activity ratios are only changed by radioactive decay, i.e., the coral behaves as a closed system.

The closed-system condition is often violated by U-series open-system behaviour affecting the activity ratios of the coral carbonate. Calculated 230Th/U ages can thus be inaccurate, despite seasonally resolved temperature proxies such as Sr/Ca and oxygen isotopes can still show clear annual cycles unaffected by these subtle diagenetic processes. Within the last decades, several criteria have been established in order to identify open-system behaviour, but as the underlying mechanisms are still not fully understood, these criteria are often not sufficient to identify all altered ages. One of the most reliable ways to identify altered ages is the combination of 230Th/U dating with 231Pa/U dating.

We applied both dating methods combined with 226Ra/230Th isotope analyses to five last interglacial corals from Aqaba (Jordan) in the desert-surrounded northern Red Sea. These corals have been studied before using the 230Th/U method and showed extremely high initial (234U/238U) ratios indicating substantial open-system behaviour. Our new results confirm the history of diagenetic alteration and, in combination with quantitative modelling, provide further information on the nature and timing of the open-system processes.

The modelling results suggest that conventional 231Pa/230Th ages provide the best estimate for the true age of four of the five corals ranging from 109.1 to 114.1 ka. This implies a late Last Interglacial time of deposition. For the fifth coral, we consider the

conventional 230Th/U age of one subsample (117.3 ka) as the most reliable age estimate, based on a concordia diagram for all subsamples.

Two of the five corals were probably affected by two separate phases of U addition with different (234U/238U) ratios. The trends observed for two other corals can be explained by U addition followed by U loss. The fifth coral shows signs of both U gain and loss at the same time in the more recent past. The timing of the diagenetic processes is remarkably similar for the five corals and can be constrained to approximately 103.1 - 113.1 ka and 12 - 14 ka, respectively.

The timing of the modelled open-system processes suggests that the early event of U addition was associated with interaction with 234U-enriched seawater or saline groundwater. The later open-system event can be described as U redistribution within the coral reef since some corals apparently lost U while others gained U. The timing of the second event is broadly consistent with the Bølling-Allerød interstadial, which was probably characterised by enhanced wetness in this typically hyper-arid region.

An assessment of Sr isotope stratigraphy dating of late Miocene to mid-Pleistocene sea level highstands

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**Lamont Doherty Earth Observatory of Columbia University*

Precise dating of biogenic marine carbonate from paleoshorelines is essential for establishing sea level and ice volume history, long-term vertical displacement rates, and correlation between fossil terraces worldwide. However, placing chronological constraints on shorelines beyond the limit of U-series radiometric dating (~600 kyr), or at high latitude sites lacking coral, is often challenging. Strontium isotope stratigraphy (SIS), based on temporally changing 87Sr/86Sr ratios in the ocean, is a relative dating technique useful for constraining ages on unaltered shallow water carbonates preserved on land. The SIS method is not without its limitations, one concern centers on the requirement that a sample retain a perfectly preserved signature of the seawater Sr ratio incorporated during formation. This assumption of perfect preservation is problematic in dating paleoshorelines, as near-shore carbonate fossils often undergo digenetic alteration (weathering and remineralization) that can cause apparent SIS ages to deviate from the true age of formation.

We assess the robustness of SIS dating techniques by measuring Sr isotopes on sequentially leached Pleistocene to Miocene bivalves (n=19) and corals (n=15) collected from fossil shorelines globally. Well-preserved material would theoretically contain only one Sr isotopic reservoir that represented the original 87Sr/86Sr seawater composition when the carbonate precipitated. In this case, we would expect that all sample leaches have the same isotopic value. On the other hand, diagenetically altered material often contains two or more Sr reservoirs, incorporating unequally distributed mixtures of the original seawater Sr and contaminating Sr of variable concentration and isotopic composition (e.g. ground water, surrounding sediment). This can lead to large variation and trends in the 87Sr/86Sr ratio between successive leaches, as different reservoirs of Sr are released with every sequential dissolution. Our progressive leaching method enables more accurate screening of samples for diagenetic alteration, while simultaneously providing information on minimum or maximum age constraints, and

can reduce age errors. We systematically evaluate these new methods of SIS dating/screening along with more traditional techniques (XRD, SEM, elemental analysis, etc.) and find a close correlation between the two, leading us to propose new practices for measuring Sr on shallow water carbonates. Employing these methods allows for more robust screening and more reliable dating of shallow water fossil bivalves and coral from the Miocene to Mid-Pleistocene.

Improving the quality of optical ages for sea-level reconstruction

Barbara Mauz*, Detlev Degering, Paul Nolan, Albrecht Degering, Zhixiong Shen

**University of Salzburg (Austria)*

In an ideal world multiple sea-level index points are generated across the carbonate platform and, thereby, coral-based index points are constrained independently by non-coral index points. Multiple index points along an isochron would allow to robustly infer a change of sea level and independent dating would reduce the vertical error associated with the living range of the coral. Therefore, the question is: do coral-based and sediment-based proxies deliver the same result for the same site? The answer should be "yes" (or "no") but, instead, the answer is often "unclear". This is because the coral-based data points have a large vertical and a small horizontal uncertainty while the sediment-based data points have a small vertical and a large horizontal uncertainty. Here we address the latter by reducing the uncertainty of optical ages of sediment-based proxies so that the comparison becomes more meaningful.

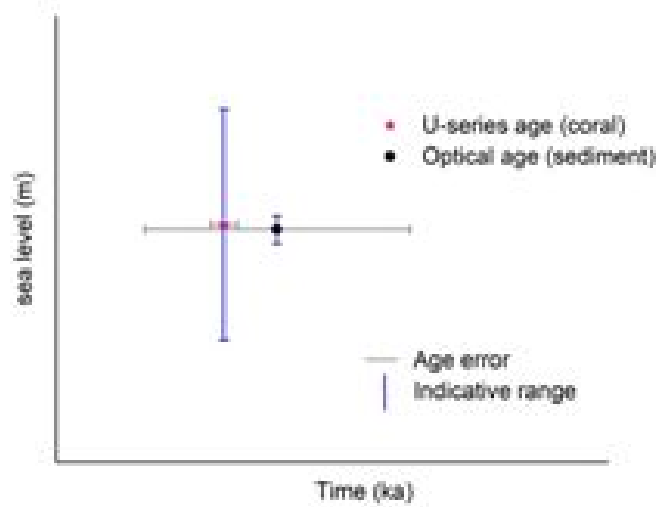

Figure 1. Illustration of uncertainties associated with two different proxies originating from the same site.

The large uncertainty of optical ages is caused by a number of post-depositional processes, one of which is isotopic fractionation of the elements resulting in a state of disequilibrium between the parent nuclide and its daughters in the Uranium chain. Our approach to the issue is three-fold: first detecting and quantifying the status of disequilibrium using gamma-spectrometry, second, identifying unreliable age data using a Bayesian statistical model and, third, determining the age using double differential equations for scenarios of constant and proportional exchange of U-234. First results show significant improvement of optical age accuracy and limited improvement of age precision.

In our presentation we will briefly outline the methodological approach. The focus will be on the comparison between corrected and uncorrected age data and resulting potential and limitations of the novel approach.

Bringing amino acid geochronology of sea-level records up to date: developing an intra-crystalline approach for foraminifera

Lucy Wheeler*, Kirsty Penkman, Roland Gehrels, Natasha Barlow

**University of York*

Amino acid racemisation dating (AAR) is one of a range of techniques used to date Quaternary deposits. Recently significant improvements in AAR have been made by isolating an "intra-crystalline" fraction of proteins from certain biominerals (e.g. mollusc shells, corals, enamel), which effectively acts as a closed system and therefore removes external influences on racemisation rate, as well as the contamination and leaching of native biomineral proteins [1]. This approach has been used to constrain the ages of interglacial sea-level deposits using freshwater snail opercula [2], but where opercula are absent (e.g. marine sediments), this limits the technique's application. Therefore we are extending the intra-crystalline approach to species of foraminifera which are widely used in palaeosea-level reconstruction.

Although foraminifera have been a target for AAR since the earliest days of the technique [3], comparatively little is known about the behaviour of biomineral proteins in foraminifera and therefore their suitability for AAR. In this research, bleaching experiments have been carried out to test whether an intra-crystalline fraction of proteins can be isolated from two benthic species of foraminifera, Ammonia spp. and Haynesina germanica. The adherence of each species' intra-crystalline protein fraction to closed-system behaviour and the patterns of racemisation have been determined using high-temperature decomposition experiments. Future work will perform these tests on a wider range of species of foraminifera and assess the reliability of the intra-crystalline approach for dating Pleistocene sea-level deposits.

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Sea-level research in Greater Rotterdam, The Netherlands

Marc. P. Hijma*, Kim M. Cohen

**Deltares*

The Netherlands has a long tradition of sea-level research from which vast amounts of data accumulated over the last 60 years. The results, however, are scattered across large numbers of papers and reports, were obtained using different sampling and dating techniques, have been in part revised, and as a whole had not been uniformly scrutinized on quality and usability today.

For the Rhine-Meuse delta and transgressed palaeovalley below 'Greater Rotterdam' (RMD), we have recently re-assessed the sea-level reconstruction data. Following documented protocols, index points tied to radiocarbon dates from peat beds were selected (catalogued), then documented and screened individually in a database, and then further screened in ensemble on quantified age-depth position and inshore palaeotidal setting. The RMD database holds 50 sea-level index points (SLIPs) and 56 upper limiting data points. The SLIPs cover an age-range of 8.8-3.0 ka, beginning at -21 m O.D. in the RMD near offshore. For upper limiting data points, the coverage reaches further offshore tracing the Rhine palaeovalley, back to 11 ka BP and down to -34 m O.D. (Fig. 1)

Between 8.0 and 4.5 ka, relative sea-level rise gradually decelerated from 0.9 to 0.2 m/cy. Between 9.0 and 8.0 ka, rates of rise were much higher. They averaged 1 m/cy, and were briefly higher (~2m/cy) during a superimposed "sea-level jump". For this jump, the RMD resolves a magnitude of 1.7±0.6m for the first phase (starting 8.45 ka), and a few more decimetres in a second phase (8.3-8.25 ka). This corresponds to globally-averaged jump components of 2.5±0.9m (1sigma) and 0.1-0.4m respectively, caused by drainage of Lake Agassiz-Ojibway also known from the 8.2-ka cold event.

For the pre-9 ka BP period, for which data is to be sampled offshore, SLIPs are rare and not currently available from the Rhine palaeovalley. More to the north (Oyster Grounds and Doggerbank regions), a few SLIPs exist, that have considerable uncertainties with respect to their sampled elevation, their indicative meaning and their age. Resampling for SLIPs, aiming to densify the vertical series from subregions offshore is an ongoing

effort, with two cruises with the vessel Pelagia (NIOZ, Royal Netherlands Institute for Sea Research) completed in 2017 and 2018.

In this paper we focus on the new results for Greater Rotterdam (including record of the pre-8.2 sea-level jump; as documented in Hijma & Cohen, 2019). In an accompanying poster we will show the first results of our Pelagia-cruises.

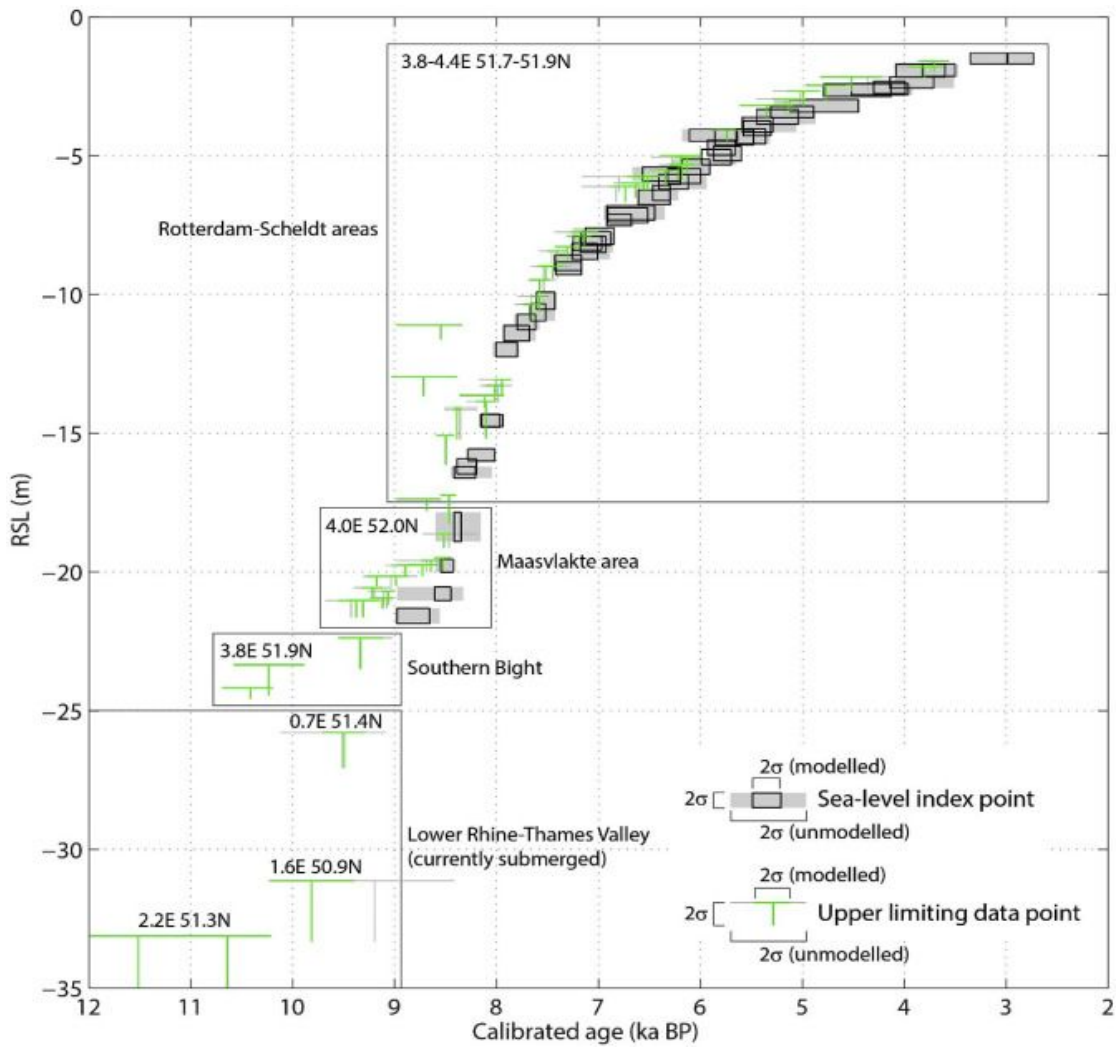

Figure 1. Age-depth plot of SLIPs and upper limiting data points in the RMD database (Hijma & Cohen 2019, their fig. 5)

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Hijma, M.P., Cohen, K.M. 2019. Holocene sea-level database for the Rhine-Meuse Delta, The Netherlands: implications for the pre-8.2 ka sea-level jump. Quaternary Science Reviews, 214, 68-86.

Bayesian-calibration decisions for the basal-peat SLR data series of the Rhine-Meuse Delta

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Recent SLR databasing efforts coordinated through PALSEA, require stepwise processing and administration of regional sets of data points. Database fields that store dating information on individual samples are filled early on in database filling workflow. Then follow further steps, focusing on quantifying vertical uncertainties and indicative meaning as well as temporal uncertainty, all considering the *properties of the individual samples*.

Where sampling has been dense and replicating enough, the latter steps need also to consider further the *position of samples in sequences*. Doing so is important because it offers extra means to identify some of the collected data points to be more indicative, relevant and vertically and temporally constrained than others. The Rhine-Meuse Delta because of its history of research, is a study area where this is particularly apparent. We have reviewed past procedures to weed and highlight data points and converted, modified and improved these in line with PALSEA quality control recommendations and database templates (Hijma, this meeting; Hijma & Cohen 2019, QSR PALSEA SI).

Our handling of the SLR data of the Rhine-Meuse data, towards the end of the workflow has included a step of Bayesian calibration of sequences of part 'upper limiting', part 'sea-level index point' basal peat dated. Per site, we have sequentially ordered the data in OxCal's CQL-script format (Bronk-Ramsey, 1998) to generate Bayesian modeled calibrated age ranges for each sample (Figure 1). This workshop contribution is on the a-priori choices made for earlier and younger parts of the sea level curve, and how this has impacted the temporal accuracy fields of completed database.

For the period 8.0-4.0 ka, the Bayesian calibration of the Rhine-Meuse database entries has been kept separated for the four inland dune sites (four CQL scripts) that host the majority of the data points for this time frame (transgression aftermath) and portrayed as a conservative choice. For this period we can discuss room for remaining improvement. In contrast, for the period 9.0-8.0 ka, during which rates of SLR was markedly higher and the data set is spatially distributed (ongoing transgression), the

Bayesian calibration used a single CQL script and had grouped subsets of dates that were separated by transgressive surface contacts (still reasonably conservative, but less so than post 8.0 ka). For this period, we can present the results of alternative subgrouping (less probable), and show the Bayesian blurring effect that results when ignoring sedimentary evidence for chronological boundaries that would result if a post-8.0 rule book would have been applied to the pre-8.0 part of the dataset.

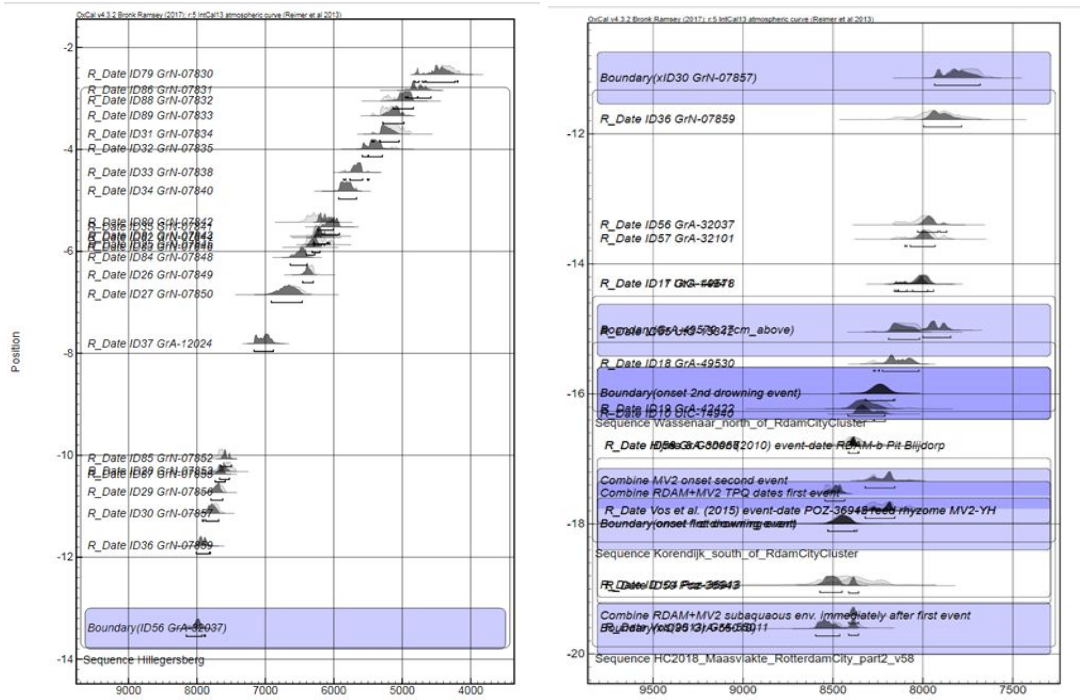

Figure 1. OxCal age-depth plot of CQL-calibrated series of SLIPs and upper limiting dates (RMD dataset; Hijma & Cohen 2019). Left: conservative approach to data from site R'dam Hillegersberg over SLR deceleration interval. Right: more opportunistic approach to data from R'dam Maasvlakte and CityCentre over SLR acceleration-deceleration interval.

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Chronostratigraphic records offer much-needed constraint on the Laurentide Ice Sheet prior to the last glacial maximum

April Dalton*, Chris Stokes

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Sea level estimates through the last glacial cycle (~110 ka to ~24 ka) are subject to substantial uncertainties, which hinder the development and refinement of numerical models of ice sheets, sea level and broader Earth systems. A key reason for this uncertainty is the evolution of the Laurentide Ice Sheet (LIS; the largest contributor to global sea level change during the Late Pleistocene), which is poorly constrained through this interval. Although numerical models have been developed to show the hypothesized distribution of this ice sheet, few geological constraints are available to verify the outputs of these models. Recently, however, there have been significant surges of geological data from the glaciated region, largely due to improved chronological techniques that have allowed dating of sites beyond the ~45 ka limit of radiocarbon dating. Critically, some of these data imply that the configuration of the LIS differed from that predicted by numerical models (e.g. a significant ice reduction at ~42 ka, with global mean sea level potentially 10s of meters higher than previously believed for that interval; Dalton et al. 2019, Geology). Clearly, significant insights on past ice sheets and sea level change can be gained by extending this empirical work to cover the entire last glacial cycle. Here, we assemble and analyse available geological data from the ~110 ka to ~24 ka interval (>850 geochronological data points) to better constrain the inception and dynamics of the LIS along with the pattern of ice build-up toward the last glacial maximum. Although spatial and temporal gaps exist in this dataset, preservation of geological sites is possible in low-lying regions such as the St. Lawrence Lowlands and Hudson Bay Lowlands. These key areas have networks of stratigraphic records spanning beyond 100 ka, dated using radiocarbon, U-Th, and optically stimulated luminescence techniques. Using these data, along with other geological constraints (e.g. records of striations and lineations), we aim to produce an empirically derived “best estimate” ice margin product that spans the last glacial cycle. We compare results of this work to numerical estimates of ice extent and sea level records. This

product will be made available to the scientific community for the calibration of a new iteration of numerical models (ice sheet and sea level) for the last glacial cycle.

Improving chronological models for estimating sea level rise

Parnell, A.

Maynooth University

A huge amount of effort is often spent on levelling the proxies of former sea level and transferring them (using weight averaging, Bayesian methods or similar) into estimates of past sea level. The chronological precision of these proxies often receive relatively scant attention and thus it becomes almost impossible to accurately estimate important components of sea level such as rate and acceleration. In this talk I'll give some examples of potential research avenues where we might be able to improve past sea level estimates by using more information in building the chronology.

Producing records of relative sea-level change from mangrove sedimentary archives

Nicole Khan, Benjamin Horton

University of Hong Kong

In tropical locations, mangroves occur at the interface between terrestrial and marine environments and preserve vital archives of climatic, environmental and relative sea-level (RSL) change. These tropical locations span a gradient across the intermediate- and far-field of polar ice sheets, and may provide important constraints on sea-level equivalent changes and its sources since the Last Glacial Maximum. While numerous high-resolution (decimeter vertical and decadal age resolution) RSL records have been obtained from temperate salt-marsh environments, these records are non-existent in tropical mangroves. High rates of decomposition and bioturbation may limit preservation of mangrove micro- and macrofossils and introduce complications in interpreting the indicative meaning and developing precise chronologies of RSL change.

Here, we provide a review of recent methodological developments used to interpret and date mangrove archives, drawing from case studies in Florida, USA, Puerto Rico, and Bermuda. We assess controls on the vertical distribution and resolution of mangrove proxies, and offer suggestions to improve their precision when microfossils (e.g., foraminifera) are absent or poorly preserved. In addition, we examine the distribution of ages of different mangrove peat components (leaf and wood macrofossils, bulk peat, fine roots) and assess the impact on the interpretation of RSL and its rates based on chronologies obtained from different components from these cores. Based on this analysis, we outline best practices for obtaining accurate chronologies from mangrove sedimentary archives. Finally, we demonstrate the successful application of these methodological advancements to produce high-resolution records of RSL change over the mid to late Holocene in Florida.

Defining the beginning of the Anthropocene with proxy sea-level records

Jennifer Walker, Benjamin Horton*, Don Barber, Nicole Khan, Tim Shaw, Robert Kopp

**Rutgers University and Earth Observatory of Singapore*

The Anthropocene implies that humanity has driven such substantial change on Earth that this time period should be formally differentiated from the Holocene. Defining the accurate beginning of the Anthropocene provides a quantitative estimate of the start of substantial human impact on the natural world. Providing a pre-industrial baseline is crucial to define target climate thresholds for the future. However, a substantial range of suggested dates for the beginning of the Anthropocene persists depending on the environmental evidence and the dating methods used and their associated errors. Although sea-level rise is one of the most significant impacts of human-induced climate change, sea level has never been used to define the onset of the Anthropocene.

We use a global database of instrumental and proxy sea-level records from the past millennia with high-resolution chronologies to examine the precise timing and spatial variability of the beginning of accelerated rates of sea-level rise due to human influence. The proxy records are from over 30 regions around the world using proxies such as microfossils, coral microatolls, archeological evidence, and sediment geochemistry. We produce a new relative sea-level record in northern New Jersey to use as a case study to provide an example of how these records are produced and to examine shifts in rates of sea-level rise. A spatio-temporal hierarchical model analyzes the new northern New Jersey record with the global database of sea-level records to determine when sea-level change shifted from background rates of rise to accelerated rates of rise from anthropogenic influence.

Poster session

First results of the 2017-2018 Early Holocene Sea-level Research Cruises on the North Sea

Marc Hijma*, Kim Cohen, Freek Busschers, Paolo Stocchi, Natasha Barlow

**Deltares*

Onshore The Netherlands a reliable sea-level record until 8.8 ka BP (-21 m O.D). has been obtained. To extend this record to the Late Glacial it is necessary to go offshore. In the Dutch part of the North Sea a few upper limiting datapoints and sea-level index points exist, but they have considerable uncertainties with respect to their sampled elevation, their indicative meaning and their age. Resampling for SLIPs, aiming to densify the vertical series from subregions offshore is an ongoing effort, with two cruises with the vessel Pelagia (NIOZ, Royal Netherlands Institute for Sea Research) completed in 2017 and 2018. These sampled peat beds between -60 and -25 m O.D. (completed) to obtain sea-level index points (in preparation, first results coming in).

Data analysis will consist of 14C-dating, pollen and diatom counts, macrofossil determination, XRF-scanning, loss-on-ignition and subsequent analysis using the HolSea-database protocol. With the resulting SLIPs and upper limiting datapoints we will reconstruct sea-level changes in the North Sea basin and calibrate new GIA-models for this region.

This poster will present and discuss the first results of this research. The research is a collaboration of Deltares with the Geological Survey of The Netherlands, Utrecht University, NIOZ, Leeds University and the Dutch Culteral Heritage Agency.

Towards improved paleo sea level estimates to constrain ice sheet models during past warm intervals

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Through the efforts of the PALSEA research group, there is a greater understanding of sources of uncertainty on sea level estimates during past warm intervals such as the last interglacial and the mid-Pliocene. This has arguably led to an increase in the range of sea level estimates, in particular for the mid-Pliocene. At the same time these intervals are increasingly being used to constrain ice sheet models. Here we discuss the limitations of using these sea level estimates and ways that these data can be used to improve understanding of past ice sheet behavior.

The effect of lateral viscosity variations on sea level during the last interglacial

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LDEO, Columbia University

Sea level during the last interglacial (LIG) period is significantly affected by glacial isostatic adjustment (GIA). Uncertainties in GIA models persist and hamper a robust estimate of ice sheet stability during the LIG, a time period that often serves as a testing ground for future ice sheet models. Uncertainties in the GIA correction arises due to our incomplete knowledge of the ice sheet history prior to and during the LIG, as well as a poor understanding of the Earth's internal viscoelastic structure. All GIA models for the LIG so far assume that Earth's internal structure is radially symmetric, which is at odds with results from seismic tomography, mineral physics, and geodynamics. Here we explore for the first time how lateral variations in viscosity affect last interglacial sea level. We use a newly constructed global 3D viscosity model that self-consistently maps 3D lithospheric and asthenospheric properties using seismic tomography and anelasticity parameterisations. The Earth model is paired with an ice sheet reconstruction that is constrained during MIS 6 by the Tahitian coral record and benthic oxygen isotope variations spanning the last 150 kyr.

These calculations are computationally expensive and therefore don't allow for a full exploration of the parameter space. However, results provide an estimate and general understanding of the potential effect that lateral viscosity variations might have on locally reconstructed sea level during the LIG. We present global GIA maps as well as predictions at selected locations from sites of particular interest including the Seychelles, the Caribbean, and Western Australia. We investigate to what extent 3D GIA could explain discrepancies in existing sea level records from different sites.

Paleoecosystem of Pulicat Lake, East coast of India

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**Yogi Vemana University*

The Pulicat lake is the second largest brackish water basin in India .Paleoclimate studies in the Pulicat Lake were not began until now. The overall purpose of this work is to characterize the paleoecosystem documented owing to the Climate change on the Lake and its implications to the Paleoclimate. Much of the character of terrestrial climate in the study area is governed by the position and duration of centers of atmospheric circulation over the Bay of Bengal. Paleolimnological and paleoclimate records of the other parts of the world, dated by radiocarbon dating, can be linked to study the interaction of these climate systems and their effects on terrestrial ecosystems. Pulicat lake is especially relevant in this regard, because of its close proximity with the Bay of Bengal . A total of 10 sediment cores were collected, 5 cores are of 8.5 meters depth, 2 cores are 10.5 meters and reaming 3 are of 12.5 meters depth. The core was slab bed properly and cut into two halves. One half was wrapped in tin paper and preserved for future studies. Core logging was carried out on the second half, to record lithology, grain size, sedimentary, physical and bioturbation features. The core was photographed using digital camera. Subsequently, core was subsampled at every 30cm and processed for analysing paleoecosystem using foraminifers as proxies and other micropaleontological remains by adopting standard techniques. The molluskan shells found at 12m and 1m depth intervals were subjected for C14 isotope dating. This paper attempts to underline the paleolimnology of Pulicat lake and its biodiversity foraminiferal proxies as documents in the sediment cores.

Using seismic datasets to reconstruct palaeo sea-level change recorded in submerged landscapes

Natasha Barlow*, Victor Cartelle

**University of Leeds*

Global temperatures during the Last Interglacial were ~1°C warmer than pre-industrial values and 3-5°C warmer at polar latitudes, during which time global mean sea level was 6-9 m above present, far above that experienced in human memory. Though the drivers of warming during the Last Interglacial are different to those of today, it is the amplified warming at polar latitudes, the primary locations of the terrestrial ice masses likely to contribute to long term sea-level rise, which makes the Last Interglacial an interesting analogue for improving understanding of future climate and sea-level change and associated landscape response. However our understanding of Last Interglacial sea level change is primarily limited to tropical and sub-tropical latitudes and it is important to understand the response of temperate estuarine settings to rising sea level.

A new European Research Council project focuses on specifically targeting palaeo shorelines sequences buried within the southern North Sea, preserved beyond the limit of the Last Glacial Maximum ice sheets, to reconstruct the rate and nature of transgression of the basin during the Last Interglacial. There is a broad understanding of the Last Interglacial sedimentary sequences of the southern North Sea, but not the flooding of the former terrestrial landscape. Geophysical data has been used for a long time in 'deep time' offshore Geology, but recent advances in higher resolution data collection makes it possible to identify shallow late-Quaternary stratigraphic units. A wealth of new offshore geophysical and borehole data has become available as a result of significant investment into energy sources in the North Sea region and is providing a driver for Holocene-focused research, establishing a methodological framework that can be applied to older sequences.

The offshore sedimentary archives offer significant advantages over the geomorphologically restricted onshore records, with the ability to trace the transgression in 3-dimensions over a much greater area. Furthermore, the offshore

record should capture the earliest flooding of the Last Interglacial North Sea basin, when the far-field data suggests ice sheet melt was at it maximum, during the peak in global warmth during the Last Interglacial. This has the potential to allow us to 'fingerprint' the source of melt (Greenland and/or Antarctica) during the interglacial sea-level highstand.

Leveraging preservation bias in Last Interglacial coral sea-level records to refine global ice volumes over the ice age

Rebecca Cleveland-Stout*, Tamara Pico, Jacqueline Austermann, Peter Huybers, Jerry Mitrovica

**Harvard University*

Accurately reconstructing sea level during the Last Interglacial (~125 ka) will improve our understanding of how ice sheets have reacted to warm temperatures in the past, and this insight can aid in refining estimates of future sea level rise in a warming world. Past sea levels have been reconstructed using biologic and geologic shoreline features, such as fossil coral reefs, marine terraces, and erosional notches. Amongst these sea level indicators, fossil coral reefs are the most widely used, as their chronology can often be tightly constrained using U-Th dating. Today's record of existing sea-level markers are a result of systematic preservation biases, which to-date have not been directly considered in reconstructions of Last Interglacial global mean sea level. Tectonic uplift, sea level change, accretion rates, and erosion rates dictate whether a coral reef forms and its subsequent probability of preservation, resulting in preferential preservation of proxies reflecting relative sea level highstands.

We explore the observed distribution of Last Interglacial coral reef sea-level markers using a statistical model that accounts for the growth and destruction of coral reefs over the last glacial cycle. We force this model with sea-level predictions from a large ensemble of glacial isostatic adjustment simulations sampling a range of possible ice volume change scenarios across the last ice age, and identify spatial signatures in model-produced coral distributions, to show how regional sea level patterns produce distinct records of coral reef preservation. We show that predicted elevation distributions of preserved corals in the Bahamas and western Australia are strongly imprinted by local sea level histories. We find that this modeling yields an improved understanding of indicative meaning, which is essential in constraining global mean sea-level values across the Last Interglacial and the subsequent glacial cycle, because only a certain subset of ice histories predict a present-day distribution of sea-level markers consistent with the observed dataset of Last Interglacial coral reef records. This reveals the potential to leverage the observed elevation distribution of Last Interglacial

corals to constrain past relative sea level, and thereby global ice volumes, across the last glacial cycle.

Holocene relative sea-level change in Chile

Ed Garrett*, Daniel Melnick, Tina Dura, Marco Cisternas, Lisa Ely, Rob Wesson, Julius Jara-Muñoz, Pippa Whitehouse

**Durham University*

We present a comprehensive relative sea-level (RSL) database for north, central, and south-central Chile (18.5°S – 43.6°S) using a consistent, systematic, and internationally-comparable approach. Despite its latitudinal extent, the Chilean coastline has not previously received rigorous or systematic attention and details of the RSL history remain largely unremarked. To address this knowledge gap, we re-evaluate the context and age of previously published sea-level indicators, providing 80 index points and 84 marine or terrestrial limiting points that span the period from 11,000 years ago to the present day. We also describe two new limiting points from two sites in the Maule and Bío Bío regions. Our database incorporates a range of different types of sea-level indicator, including tidal marsh sediments, beach ridges, marine deposits and freshwater sediments, dated through radiocarbon and luminescence approaches. We compare the spatiotemporal distribution of sea-level indicators with a suite of glacial isostatic adjustment models and place first-order constraints on the influence of tectonic processes along the coastline. By compiling and comparing the RSL history for 11 different regions, we summarise current knowledge of Chilean RSL, highlight directions for future sea-level research, and provide a resource to assist attempts to understand the distribution of archaeological, palaeoclimatic, and palaeoseismic evidence in the coastal zone.

Paleoenvironmental evolution and vegetation changes during the Holocene at the NE coastal plain of Buenos Aires, Argentina

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**CEIDE-UNLP, CONICET ARGENTINA*

This study integrates paleontological (pollen, non- pollen palynomorphs, shells) proxy data from the central zone of Bahia Samborombón, with radiocarbon dating from sedimentary organic matter and shell material to reconstruct the saltmarsh vegetation history and environmental changes at millennial to centennial time scale. There were selected 2 sedimentary sequences PM1 (35°58'14.8"S/57°24'49.72"O) y PM2 (35°36'8.23"S/57°15'32.52"O). The PM2 analysis shows the paleoenvironmental evolution in response to the sea-level increase during the Mid-Holocene. During the interval ~7000-6670 cal yr BP, halophytic communities prevailed in a middle-high marsh in an environment of extensive tidal plains and open sea, which was located at ~10 km from the present coastline. Between ~6670 and 6500 cal yr BP the middle-high marsh vegetation was replaced by low marsh vegetation communities; which is related with the sea-level rise during this period and evidenced by the gradual increase of the dinocysts *Operculodinium* spp. y *Spiniferites* spp. during the transgression phase. From 6500 to 6400 cal yr BP, continues the predominance of marsh vegetation in coexistence with freshwater vegetation under increasing marine influence. From ~6400 cal yr BP, the palynological record is scarce; nevertheless autochthon mollusk assemblages of *Tagelus plebeius* indicate a stabilized period of the sea-level. During the last 3000 cal yrs BP, the multi-proxy analysis of PM1 showed the paleoenvironmental evolution from a subtidal-intertidal environment under significant tidal influence, to a supratidal environment with brackish-freshwater influence related to the sea-level decrease during this time. During the period ~2700-1660 cal yr BP, halophytic vegetation from a marsh developed in the vicinity of a subtidal-intertidal depositional environment at ~5.7 km from the present coastline. Within this period, at ~2050 cal yr. BP a gradual and partial aerial exposition occurred in relation to a lower tidal influence due to the sea-level steady fall; along with the development of middle-high marsh vegetation, similar to the

present vegetation of this transitional zone, evidenced by the presence of *Limonium brasiliense* and the decrease of dinocysts abundance. Between 1660 and 950 cal yr. BP a stable mature saltmarsh established in environments that change from those of intertidal conditions to supratidal conditions with shallow water bodies developed as reflected by gradual increase of *Azolla* filiculoides and Ricciaceae. This change of environments is linked to the coastal progradation. The last period, from ~950 cal yr BP to the present, the predominance of marsh vegetation continues although accompanied by freshwater vegetation developed in small water bodies with rare or null tidal influence. The climatic signal was possible to infer once the marine influence left to be superimposed related to the sea level fall; which was characterized by a greater precipitation regime as suggested by the high increase of the freshwater components.

Searching for fingerprints of early 20th century ice melt in Australian salt marshes

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Sea-level rise during the 20th century was faster than during any other century in the last 3000 years. Proxy evidence from salt marshes suggests that the magnitude of the sea-level acceleration from the 19th into the 20th century was greater in the Southern Hemisphere in comparison to the Northern. The cause of this sea-level acceleration remains unknown. Anthropogenic forcing was still weak; therefore, the rise must have been driven by natural processes. One potential source may have been melting of Arctic glaciers and the Greenland ice sheet (GrIS) during the Arctic Warm Period of the 1920s and 1930s. This melt produced a sea-level fingerprint, including high relative sea-level rise in far-field areas like South Africa, South America and the Pacific. In this study, we search for the fingerprint of ice melt in the salt marshes of southeastern Australia to test the hypothesis that Arctic and Greenland ice melt was responsible for the rapid rise in sea level in the early 20th century. Using microfossils, specifically benthic foraminifera preserved in sediment cores, changes in sea level will be reconstructed over the last ca. 500 years at cm-scale resolution at three sites in southeastern Australia including Bruny Island (Tasmania), Tarra River (Victoria) and Wapengo Lake (New South Wales). Core chronology will be established via a variety of dating tools including ITRAX-XRF, stable lead isotopes (206Pb/207Pb, 206Pb/208Pb, radionuclides (137Cs and 210Pb), and AMS-bomb spike 14C. Reconstructions will be compared to the sea-level fingerprint of historical changes in Arctic ice mass.

Constraining Common Era relative sea-levels in Southeast Asia using mangrove environments

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Proxy relative sea-level (RSL) reconstructions using geological, biological and archaeological indicators in understanding global Common Era sea levels (Kopp et al., 2016) revealed a response of sea levels to natural climate warming and cooling variability (e.g. the Medieval Climate Anomaly and Little Ice Age). Furthermore, these RSL reconstructions also revealed an acceleration in global sea level beginning in the 19th century that was coincident with anthropogenic warming. The spatial distribution of proxy RSL reconstructions, however, is uneven, resulting in significant gaps in our understanding of Common Era sea levels. In Southeast Asia, there are currently no proxy RSL reconstructions that accurately constrain this period, and many tide-gauge records are temporally restricted to the past ~50 years and/or hampered by vertical land motions. Here, we explore the potential of tropical mangrove environments in Southeast Asia to derive new Common Era RSL data.

Nearly one third of the world's mangroves are found in Southeast Asia, yet they remain an unexplored, potentially important RSL archive. Reconstructions of RSL from their temperate latitude equivalent salt marshes have been central to our understanding of Common Era sea levels. Salt marsh foraminiferal distributions have been widely used to reconstruct RSL due to their strong relationship with tidal levels. We adopt similar approaches to reconstruct RSL, using our understanding of contemporary mangrove environments and foraminiferal distributions to constrain the vertical position (and uncertainty) of past RSL from fossil counterparts enumerated in chronologically (e.g. radiocarbon) constrained sediment cores. Our new RSL reconstructions will be used to assess magnitudes and rates of RSL change during the Common Era in Southeast Asia and detect any significant inflection in modern RSL rate. Furthermore, new RSL reconstructions will provide important constraints that may be used to reduce geological uncertainty in future sea-level projections across the Southeast Asia region.

Roman times Mediterranean sea levels as a key question for the last 2ka trends

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In the Mediterranean, two different relative sea level (RSL) reconstructions exist for the last 2ka: a) a continuous rising curve with low Roman levels rising to the medieval and then present levels, b) a fluctuating curve around present levels with Roman levels already at near current mean sea level (MSL), falling in the medieval period, then rising again to present ones.

The observations used in the Mediterranean include archaeological, biological, and sedimentological indications, with quantified uncertainties for each proxy. In the east (mainly Israel and Greece) and central Mediterranean (Italy and Tunisia- Libya), a great deal of the data is obtained from archaeological indications. While using archaeological remains as past RSL indication, the measured architectural remain and its relationship to mean sea level (MSL) at time of construction and use (known as the functional height) must be evaluated. Various types of archaeological remains have different functional heights and related uncertainties. Fish tanks are considered one of the most reliable archaeological indicators, but even in this case, different interpretations of their functional height results in different RSL, even for the same fish tanks as in the case of those in west Italy from 2ka BP, where the RSL interpreted by different researchers fall between -1.25 m vs. -0.5 m. Harbor installations are in most cases less reliable as RSL indicators. For coastal water wells in Israel, the translation to RSL is based on the offset between present water table and sea level, which increases the uncertainty. Archaeological data must be interpreted cautiously, since other RSL proxies like beachrocks (which in many cases are still not well dated) and sedimentological or paleontological strata sometimes offer different conclusions.

Study of Mediterranean sea level changes for the last 2 ka should focus on two important eras: Medieval levels in the second millennium CE and Roman levels in the first millennium CE. In the Mediterranean only a few studies focused on the last millennium, but all data indicate medieval levels lower than present. In the case of the Israeli coast, continuous, large amount of archaeological data combined with biological

indicators show an RSL of ~ -0.5m (with estimated lows up to ~0.8 m) between the 12th to 13th centuries CE. In Greece, where glacial isostatic adjustment (GIA) and tectonic factors also have to be considered, medieval RSL estimates range between -0.4 m to -0.8 m ± 0.15 in Methoni (SW Peloponnese) between 1300 and 1500 CE. On Paros Island results are even lower, with an estimate of -1.2±0.26m at 1300 CE rising to -0.7±0.26m by 1500 CE. Estimates of -0.3m RSL has been evaluated for the 12th to 15th century in Bari, east Italy as well. Current, on-going research we carry out using submerged medieval saltpans in the east Adriatic coast also indicates lower than present medieval levels. In the west Mediterranean, the data for this period is scarce, and either dating or elevations are less reliable due to tectonic activity, compaction, etc.

But the main question remains: what was the eustatic (or "ice volume equivalent") sea level at 2 ka BP? In the stable areas of the Mediterranean, the records indicate near present levels: in Israel, it is estimated at ± 0.1m within present levels; in Tunisia and Libya the results indicate -0.2±0.5m; in Frejus on the southeast coast of France, fixed biological remains on Early Roman fish tanks indicate RSL of 0.40 ± 0.1 m, and previous indications in the close vicinity indicate -0.22± 0.1m to -0.26 ± 0.1 m, which are all in agreement with results from the ancient harbor of Marseille. Therefore, it seems that in the frame of the uncertainties (vertical and chronological), the eustatic sea level around 2ka BP was somewhere between -0.3 m and present sea level, with uncertainties up to ±0.3 m.

Once we accept that Mediterranean eustatic sea levels in Roman times where close to present levels, we can treat the relatively large and continuous Israeli record as representing the last 2 ka since this reconstruction is based on different proxies from a relatively small and tectonically stable coast with little GIA input during this time period.

On-going research we carried out on saltpans along the Dalmatian coast is expected not only to add additional RSL data for the medieval and Roman periods in Croatia, but to introduce a new, reliable proxy from the last 2 ka for use in other parts of the Mediterranean.

Multi-decadal relative sea-level changes from salt-marsh indicators and tide gauges

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**University of York*

Historical coastal relative sea-level (RSL) data are derived from two main sources: tide-gauge observations and proxy data. The two types of data sets differ in terms of temporal resolution, vertical accuracy and precision. Comparing and integrating the two data sets is important to investigate recent sea-level changes on multi-decadal and centennial timescales, but, due to differences between datasets, this is a challenging task. This study is the first attempt to create a fully integrated data set of individual RSL time series for the last ~300 years, using tide-gauge and salt-marsh data. Our working hypothesis is that both proxy and tide gauges are complementary sources of RSL information that measure the same signal, although with different accuracies, temporal sampling and time spans. Our aim is to maximise the sea-level information measured by co-located tide gauges and salt marshes and use it to quantify long-term RSL changes and rates since 1700.

We used a set of 16 proxy salt-marsh records distributed in three regions: northeast North America, Europe and Southwest Pacific (Australia and New Zealand). Global coverage is not possible given the limited geographic distribution of proxy sea-level data. In each of our three target regions, two long tide-gauge records have been used as complementary RSL observations.

We explore, describe and quantify multi-decadal to centennial RSL changes using a single and statistically consistent time series for each site. We computed non-linear RSL trends at each site, including locations with merged records but also proxy-only and tide gauge-only time series, where available, for completeness. RSL changes since 1700 in northeast North America vary between 0.4 and 0.8 m. These changes are not steady in time: RSL rise since 1900 in this region is on average 52% of the total RSL rise in the last 3 centuries (ranging between ~40% and 60%). In Europe, the merged series in Iceland and southern UK indicate a RSL change since 1700 of 0.49 m and 0.34 m, respectively; the corresponding RSL rise since 1900 represents 38% and 54% of this total amount, respectively. In the southwest Pacific region, only the proxy record in Pounawea (NZ)

starts in the 18th century and provides a RSL change of 0.41 m, most of which (72%) results from the rapid rise observed during the 20th century.

All records located in North America and Europe display the highest rates of RSL rise during the second half of the 20th century. Some sites in northeast North America also show large rates in the 18th century; the southernmost stations, in contrast, show a steadier increase in the rates of change. The European stations have overall smaller rates of RSL change, with maximum values below 2 mm/yr after 1950. The RSL rates in the proxy records in Australia and New Zealand reflect local multidecadal variability with rates reaching 2 to 4 mm/yr. In both cases, these rates from proxies are much larger than those in the tide-gauge records for the overlapping periods, although these tide gauges are located hundreds of kilometres away.

Last interglacial sea level along the Patagonian coast

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As part of the World Atlas of Last Interglacial Shorelines (WALIS), we critically review existing chronologically constrained last interglacial sea level indicators along the coast of Patagonia in Argentina, South America. Since Charles Darwin's voyages on the Beagle in the 1830s, the staircase-like shoreline platforms along the Patagonian coast have been used as evidence that it has been subject to uplift. Paleo-sea level indicators, ranging between about 7 and 24 m have been attributed to the Last Interglacial on the basis of electron spin resonance and U/Th dating on mollusc shells, and shows remarkable continuity along the entire coast. If the age of these indicators are accurate, then it would indicate that there is a significant uplift rate during the past 120,000 years, since these values exceed the generally accepted peak globally averaged sea level for the last interglacial. However, the Patagonian coast is close enough to the Antarctic and Patagonian ice sheets that there could be a signal from glacial-isostatic adjustment (GIA). This might be an alternative explanation for these higher than average paleo-sea level values. We test the magnitude of the effect of GIA on the coast of Patagonia using a simple ice reconstruction spanning the past two glacial cycles, using a variety of Earth models.

Reconstructing Antarctica: Bayesian techniques to learn more about past ice sheet shapes

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Understanding the way ice sheets are affected by warming is vital for accurate projections of climate change. A better understanding of the past size and shape of the Antarctic ice sheet would allow us to improve our predictions of how it may change in the future; this is of particular relevance in predicting future global sea level changes. This research uses a combination of Bayesian analysis, previous ice sheet reconstructions and proxy data to create a model of the Antarctic ice sheet at the Last Glacial Maximum (LGM). We do this by finding the relationship between the ice sheet shape and water isotope values.

A prior model is developed describing the variation between a set of reconstructions of the ice sheet at the LGM. Ice sheet shapes output by this model, determined by a consultation with experts, are run through the general circulation model HadCM3, providing us with paired data sets of ice sheet shapes and water isotope estimates. The relationship between ice sheet shape and water isotopes is explored using a Gaussian Process emulator of HadCM3. We then attempt to find an ice sheet shape that creates isotopic values matching as closely as possible to observations collected from ice cores, and therefore create a more accurate estimate of the ice sheet at the LGM. This allows us to quantify the uncertainty in the shape and incorporate expert beliefs about the Antarctic ice sheet.

Tropical Ecological Changes in Relation to Holocene Sea-Level Changes

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Tropical mangroves are a major terrestrial carbon sink during the Holocene. The current study is focused to investigate geochemical characteristics and formation mechanism of tropical mangrove peatlands. In this study, nine core samples were collected in Sri Lanka for the representative lagoon, coastal lake, and terrestrial land for the understanding accumulation of carbon in a changing climate. Geochemical characteristics of sediments were determined using proximate, CHNS elemental, gas chromatography-mass spectrometry, X-ray diffraction, Fourier-transform infrared spectroscopy (FTIR), atomic absorption spectroscopy analyses. Chronology was determined using accelerated mass spectrometry (AMS) 14C data for shells, wood, and bulk organic matter. Stratigraphic observations and geochemical results suggest deposition of two sedimentary facies of lower sedimentary succession (i.e., from ca. 7.5 ky B.P. to 2.5 ky B.P.) and upper sedimentary succession (from ca. 2.5 ky B.P. to the Recent) which has linked to the Holocene sea-level changes in regional scale. The lower sedimentary succession can indicate deposition of marine-terrestrial organic matter under oxygen-poor to anoxic conditions. In addition, this period is marked by enhancement of tropical peat formation with respect to mid-Holocene sea-level highstands. The upper sedimentary succession is characterized by an accumulation of terrestrial organic matter/peat in the nutrient-rich coastal aquatic systems. The mid-Holocene regression at ca. 2.5 ky B.P. mainly changed geomorphology of the southwest coast of Sri Lanka from bay/river-mouth to a semi-enclosed brackish estuary setting. Molecular geochemical studies reveal that a gradual climatic transition from wetter to dryer since the middle Holocene based on n-C29/n-Call and n-C37/n-Call alkane proxies. A ternary diagram of n-C27, n-C29, and n-C31 alkanes reveal that mangrove dominant sediments are enriched in n-C31 with the significant amount of n-C29. Mangrove and herbaceous plants (grasses and/or floating plants) can thus be preferentially dispersed in tropical brackish sediments which have linked to the Holocene sea-level changes in regional scale. The late Holocene detailed paleoclimatic investigations based on calculated humification index using FTIR peak intensities

suggests the sapric humus condition in the upper sedimentary succession (Humification Index-H1) due to plant remain, easily identifiable with no amorphous material.