Relative sea level rise since Roman times and implications for flooding scenario at Lipari island (Aeolian Islands, Italy)

[1]Anzidei M., [2]Bosman A., [1]Carluccio R., [1]Carmisciano C., [3]Casalbore D., [1]Chiappini M., [2]Chiocci F. L., [1]D'Ajello Caracciolo F., [1]Esposito A., [4]Fabris M., [1]Muccini F., [1]Nicolosi I., [1]Pietrantonio G., [1]Sepe V., [5]Tusa S.

[1] Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy
[2] Università di Roma La Sapienza, Dip. Scienze della Terra, Rome, Italy
[3] IGAG-CNR, Rome, Italy
[4] Università di Padova, Dipartimento di Ingegneria Civile, Edile e Ambientale, Padova, Italy
[5] Soprintendenza del Mare della Regione Sicilia, Palermo, Italy

The island of Lipari belongs to the active volcanic arc of the Aeolian archipelago, located in the Southern Tyrrhenian sea (Italy). Ancient populations settled this region since prehistory but only during roman times were built coastal installations in these islands. In this study we show and discuss data on the relative sea level change inferred from a~200x60 m of size submerged pier of Roman age, dated at 2000±100 years BP, located along the coast of Marina Lunga, that correspond to the location of the modern harbor of Lipari. This structure is a valuable indicator of relative sea level changes and vertical land movements, being presently located at~9.6±0.2 m below sea level. We studied this area through underwater archaeological investigations, ultra-high resolution multibeam bathymetry and aerial photogrammetric surveys. The latter also performed by UAV surveys. Finally, detailed digital terrain and marine models integrated in the same reference system and at resolution better than 0.2 m, were produced.

The current submergence of Lipari can be explained by the cumulative effect of the relative sea level changes caused by the regional glacio-hydro-isostatic signal, active since the end of the last glacial maximum, and volcano-tectonic land subsidence. From our investigations, a mean subsidence rate exceeding~6±0.3 mm/yr^{-1} is estimated, with a volcano-tectonic contribution of~ 5±0.3 mm/yr^{-1} for the last 2 ka BP, as inferred from the comparison against the latest sea level prediction for the Southern Tyrrhenian Sea. Based on *i)* Digital Terrain and Marine Models, *ii)* current rates of land subsidence estimated from 15 years of GPS data, *iii)* elevations of the submerged roman pier and flooded buildings built during the last three centuries, and *iv)* future projections of sea level rise, a flooding scenario is provided for the year 2100. Relative sea level rise at Lipari is causing a diffuse submersion of the current coastline and the expected flooding of the land will bring large impacts on the environment and coastal installations. It must therefore be regarded as an important factor of hazard for the local population living near the shore.

EARTH RHEOLOGY IN THE BARENTS SEA INFERRED FROM GLACIAL ISOSTATIC ADJUSTMENT MODELLING AND COMPARISON TO RELATIVE SEA-LEVEL DATA

Auriac, A[1], Whitehouse, PL[1], Bentley, M[1], Patton, H[2], Hubbard, A[2] and Lloyd, JM[1]

[1] *Department of Geography, Durham University, South Road, Durham, UK*
[2] *CAGE - Center for Arctic Gas Hydrate Environment and Climate, Department of Geology, UiT, Arctic University of Tromsø, Norway*

The Barents Sea, bordered by Norway to the south, Svalbard to the north and Novaya Zemlya to the east, was covered by ice during the last glacial cycle. The extent and thickness of the marine-based ice sheet as well as timing of glaciation / deglaciation are, however, difficult to constrain partly due to the few terrestrial areas available. There are various models for the ice load history in this region, but large discrepancies remain between them depending on the dataset used as constraint (e.g. sea-level data, temperature record or geomorphology data). Our aim here is to compare four of the ice load scenarios covering the last glacial cycle and solve for the Earth structure in the area.

To achieve this, we solve for the sea-level equation and obtain predictions of the present-day rate of crustal deformation in the area and sea-level variations during the last deglaciation. We use a wide range of Earth models, where we vary the lithosphere thickness and the upper and lower mantle viscosities. The first three ice load scenarios are published models from M. Siegert, J.-O. Näslund and ICE-5G model from W. R. Peltier. The last scenario is currently being developed at the University of Tromsø, Norway. The modelled sea-level predictions are compared to a database of published relative sea-level curves from key locations around the Barents Sea. Using chi square, we infer the best Earth structure and ice history for the area. We also compare the predicted rate of surface deformation from our best model with GPS observations from stations located on the land surrounding the Barents Sea. The GPS provides a constraint on the present-day evolution of deformation in the area and is complementary to the relative sea-level data, which constrain the long-term deformation.

First results show that the published ice load scenarios are not accurate enough to reproduce the sea level curves around the Barents Sea, regardless of the Earth model tried. However, the last model, currently being developed, provides a much better fit to the relative sea level data.

THE IMPACT OF DYNAMIC TOPOGRAPHY ON MID-PLIOCENE ICE VOLUME ESTIMATES

Austermann[1], J, Mitrovica[1], JX, Pollard[2], D, Moucha[3], R, Forte AM[4], Rovere[5], A, DeConto[6], RM

(1) Harvard University, Cambridge, MA, United States
(2) Pennsylvania State University, University Park, PA, United States
(3) Syracuse University, Syracuse, NY, United States
(4) Université du Québec à Montréal, Montréal, Québec, Canada
(5) MARUM - University of Bremen, Bremen, Germany
(6) University of Massachusetts, Amherst, MA, United States

Past changes in global mean sea level (GMSL) are a sensitive indicator of climate variability. Reconstructions of GMSL during the Pleistocene ice age have been largely based on correcting local sea level records for glacial isostatic adjustment (GIA). Here, we are concerned with an estimate of GMSL during an earlier phase of ice age, the mid-Pliocene warm Period (MPWP, ~3 Ma). The MPWP was characterized by temperatures 2-3°C higher than present, and it therefore serves as an important case study for assessing ice sheet stability under warmer conditions. The ice volume deficit during this period is a matter of significant debate, with estimates ranging from 0-40 m GMSL equivalent. On the timescale of the MPWP one faces the complication that local sea level records adopted in these estimates need to be corrected not only for GIA but also for mantle flow induced dynamic topography (DT).

There are three well documented paleo shorelines that date to the MPWP; these are located along the U.S. east coast, and the southern coasts of Australia and South Africa. Previous predictions of GIA- and DT-corrected elevations from these three different sites have not yielded a consistent estimate of GMSL for this period. To revisit this issue, we've performed a suite of new DT calculations that include two improvements from previous modeling efforts: First, we incorporate a revised, gravitationally self-consistent treatment of sea level changes driven by DT that accurately accounts for the displaced water load. Second, we use a new numerical model of mantle convection to test the sensitivity of our sea level and shoreline reconstructions to a wide range of model inputs, including, in particular, lateral variations in mantle viscosity.

A second, independent approach to constraining MPWP ice volumes is based on ice sheet modeling driven by climate forcing consistent with our current understanding of conditions during the MPWP. These estimates require, as input, the bedrock elevation of the modeled ice sheet. Previous efforts of this type account for changes in the bedrock elevation due to GIA but generally neglect other processes that perturb the bedrock elevation. Here we reexamine Antarctic ice sheet stability during the MPWP using a bedrock elevation reconstruction that incorporates DT changes. In particular, we couple the same models of DT changes described above with a three-dimensional ice sheet model for the Antarctic. Our DT modeling indicates post-MPWP uplift in the area of the Transantarctic Mountains and the adjacent Wilkes basin, which implies a lower elevation of the basin in the Pliocene than previously considered. This uplift is consistent with evidence from the geological record, and leads to a more significant retreat of the grounding line within the basin during the MPWP, and hence higher predictions of Antarctic melt, compared to model runs that do not include the impact of DT.

LAST INTERGLACIAL EQUILIBRIUM, TRANSIENT AND SENSITIVITY EXPERIMENTS, GOING THROUGH THE EXISTING WEALTH OF CLIMATE MODEL OUTPUT.

Bakker, P

College of Earth, Ocean and Atmospheric Sciences, Oregon State University, USA

Over the last years a large number of climate modeling experiments have been performed that focused on the evolution of the Last Interglacial climate. Climate models of differing complexity and resolution have been used to perform equilibrium simulation for different time slices and transient simulations covering the whole interglacial. Furthermore, a suite of sensitivity experiments have been performed to test the importance of various *i*) forcings, orbital vs greenhouse-gas concentrations, *ii*) feedbacks, for instance changes in vegetation, *iii*) initial conditions, like the strength of the Atlantic meridional overturning circulation at the start of the interglacial, and *iv*) boundary conditions, with the most important being the evolution of the height and extend of the major ice sheets during the Last Interglacial and the impact of changes in the different ice sheets on the freshwater fluxes into the ocean. This wealth of Last Interglacial climate simulations has been used extensively over the past years to address a range of questions. However, no attempt has been made thus far to combine all the different Last Interglacial climate experiments.

In the work presented here the Last Interglacial equilibrium and transient model results of the multi model inter-comparison studies by Lunt et al. (2013) and Bakker et al. (2013) will be combined with sensitivity experiments performed with the LOVECLIM climate model (Loutre et al., 2014) with a focus on large scale temperature changes. This allows one to provide a best estimate of Last Interglacial temperature evolution, to quantify the difference between equilibrium and transient simulations and compare these result with the impact of uncertainties related to missing feedbacks, initial conditions and boundary conditions. This analysis can help to focus future research efforts in this field: Should we aim for higher resolution equilibrium experiments? Provide better constraints on changes in the cryosphere? Take into account the impact of the preceding deglaciation? Use GCMs coupled to ice-sheet models to interactively include feedbacks related to changes in the Antarctic and Greenland Ice Sheets? Perform more ensemble members for a given experimental setup? Or simply try to do all of the above despite limited computational capacity?

The evolution of sea level, the cryosphere and climate through the Last Interglacial are intimately coupled and as such close collaboration between the different communities is necessary to advance our understanding of the Last Interglacial and determine its value in the light of future climate change.

TESTING HYPOTHESES OF THE LAST GLACIAL MAXIMUM ICE CAP OVER SOUTH GEORGIA, SUB-ANTARTIC, USING GLACIO-ISOSTATIC ADJUSTMENT MODELLING OF RAISED MARINE FEATURES

Barlow, NLM[1], Bentley, MJ[1], Evans, DJA[1], Spada, G[2] and Brader, MD[1]

*1. Department of Geography, Durham University, Lower Mountjoy, South Road, Durham, DH1 3LE, UK (*n.l.m.barlow@durham.ac.uk)*
2. Università degli Studi di Urbino "Carlo Bo", Via Santa Chiara 27, I - 61029 Urbino (PU), Italy

There are at least two alternate hypotheses as to the size of the ice cap over South Georgia during the Last Glacial Maximum. The first of these suggests that the ice cap was extensive, with ice grounded well out on the continental shelf around South Georgia including in various cross-shelf troughs. This view of ice cap extent has been developed largely from marine geological and geophysical data. A second, contrasting hypothesis, is that the ice cap was much more restricted and that the ice margin remained in the inner fjords along the north coast of the island. The restricted hypothesis is based largely on terrestrial evidence of geomorphology supported by cosmogenic surface exposure dating and radiocarbon dating of lake sediments.

Here we use glacio-isostatic adjustment (GIA) modelling constrained by raised marine features (beaches, rock platforms etc) to test between these two widely contrasting hypotheses. Because raised marine features record the GIA following deglaciation they can be sensitive to former ice sheet extent and thickness, and thus have the potential to distinguish between the extensive and restricted ice cap hypotheses. We report new data on raised marine features from a range of sites along the north coast of South Georgia, and integrate these with previously published reports of raised marine features to develop a relative sea level database. We use a GIA model to explore several ice cap extent scenarios where each scenario provides predicted relative sea level histories that can be tested against the database. We discuss the utility of such modelling for distinguishing between the two ice cap hypotheses.

A RELATIVE SEA-LEVEL DATABASE FOR ANTARCTICA

Bentley, MJ[1], Whitehouse, P[1], Hodgson, D[2]

[1] *Department of Geography, Durham University, South Rd, Durham, DH1 3LE, UK*
[2] *British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK*

Antarctic relative sea-level (RSL) data have become increasingly useful for understanding past sea-level change around the continent, and for constraining models of glacial isostatic adjustment (GIA). Here we compile the available data from a wide variety of sources. Most of the data can be classified into one of three main geomorphic indicator types: raised beaches, erosional features, or isolation basins. These features have been dated in a variety of ways including radiocarbon dating of marine organic remains such as seal bone and skin, penguin bones, shells, sediment, seaweed and driftwood, as well as Optically Stimulated Luminescence dating of beach cobbles, and Electron Spin Resonance dating of shells. We also include a compilation of marine limits, many of which have not been dated and so need to be utilised with particular caution but which can still be potentially useful for constraining models.

The data are mostly geographically restricted to the Ross Sea, northern Antarctic Peninsula and sites around the East Antarctic margin. Almost all beaches date from the Holocene, with only a few reported instances of features dated prior to the last Glacial Maximum. There is a clear need for more RSL data against which GIA models can be compared, and we identify the regions and time periods that would be particularly valuable targets for future work. Finally, we discuss the questions that the collection of such data might help address.

INTERPRETING HOLOCENE SEA-LEVEL RECONSTRUCTIONS FROM THE TROPICAL PACIFIC

Botella A (1), Hallmann N (2), Pothin V (2), Milne GA (1), Camoin G (2), Vella C (2), Eisenhauer A (3), Samankassou E (4)

(1) Dept of Earth and Environmental Sci., University of Ottawa
(2) CEREGE, Aix-Marseille Univ
(3) GEOMAR, Helmholtz Centre for Ocean Research Kiel
(4) Dept of Earth and Environmental Sci., Univ. of Geneva

This study examines mid-to-late Holocene changes in relative sea level (RSL) reconstructed using coral reef records from French Polynesia – specifically, four atolls from the Tuamotu Archipelago (Fakarava, Manihi, Rangiroa, Tikehau) and four high islands (Bora Bora, Mangareva, Maupiti, Raivavae) from the Society, Gambier and Austral Archipelagos. We focus mainly on the RSL reconstructions based on microatolls, which are relatively precise low-tide recorders, with an aim to estimate changes in global ice volume during the period spanned by the data.

Using two published ice models and a suite of several hundred Earth models, we seek to determine an optimal parameter set that fits the observations. To improve model parameter determination, we also take into account a similar published dataset from the nearby Christmas Island (Woodroffe et al., 2012). This inversion produces a best estimate of the local Glacial Isostatic Adjustment (GIA) signal. We also consider the influence of volcanic loading for the high islands. By removing these two low-frequency signals from the reconstructed sea-level curves, we obtain an approximation of ice volume and thermosteric contributions to sea-level changes. We then compare this residual signal and its uncertainty to recent estimates of ice-volume changes for the mid-to-late Holocene and climate models output. In particular, we consider whether the observations are consistent with relatively low rates of ice-volume changes (multi-century averaged rates of a few tenths of a mm/yr) during the past few millennia.

This analysis provides an estimate of RSL changes due to natural processes and thus important context for interpreting sea level changes in the Anthropocene.

POSTGLACIAL RELATIVE SEA-LEVEL CHANGE AND THE DEGLACIATION OF NORTHWEST ICELAND

Brader,MD[1*], Lloyd, JM[1], Bentley, MJ[1], Barlow, NLM[1], Newton, AJ[2], Patton, H[3], Spada, G[4] and Hubbard, A[3,5]

*1. Department of Geography, Durham University, Lower Mountjoy, South Road, Durham, DH1 3LE, UK (*m.d.brader@durham.ac.uk)*

2. Institute of Geography, School of Geosciences, University of Edinburgh, Drummond Street, Edinburgh, EH8 9XP, UK

3. CAGE - Centre for Arctic Gas Hydrate, Environment and Climate, Department of Geology, UiT The Arctic University of Norway, Tromsø, Norway

4. Università degli Studi di Urbino "Carlo Bo", Via Santa Chiara 27, I - 61029 Urbino (PU), Italy

5. Geography & Earth Sciences, Aberystwyth University, Llandinam Building, Penglais Campus, Aberystwyth, SY23 3DB, UK

In comparison to the UK and Fennoscandia, relatively little research has been undertaken to establish postglacial relative sea-level (RSL) changes in Iceland, particularly in the northwest. This project employs new and existing RSL data to resolve the current debates surrounding the extent of the Last Glacial Maximum (LGM) Icelandic ice sheet (IIS). An accurate understanding of the LGM IIS is important, as two contrasting maximum and minimum ice loading scenarios would have very different implications for global thermohaline circulation and climate. Previous studies of glacial geomorphology and sedimentology have failed to unequivocally differentiate between these two scenarios. However, reconstruction of past sea level has the potential to address this issue, particularly when undertaken in locations which are likely to yield contrasting RSL histories under the two LGM glaciation scenarios. Northwest Iceland has this potential, as well as proving sensitive to current ice and Earth models for Iceland. In order to facilitate this analysis, a series of new sea-level index points have been generated for northwest Iceland, through the investigation of isolation basin and coastal lowland sediment samples along two perpendicular transects of research. Diatom, tephrochronological and radiocarbon analyses have allowed the generation of a series of new sea-level index points for the region. In addition, mapping of the marine limit has provided an insight into the pattern and timing of deglaciation. The resulting RSL records demonstrate contrasting patterns of postglacial RSL in the region. Along with new RSL data, this study provides a critical test of three new ice models for Iceland, alongside a suite of rheological profiles, through glacio-isostatic adjustment (GIA) modelling. The GIA model outputs have been tested against the field evidence to determine the most likely LGM ice loading scenario. Through this analysis, there is clear evidence from both field data and modelling outputs to support the maximum glaciation hypothesis.

ROLE OF SEDIMENT COMPACTION AS A DRIVER OF RELATIVE SEA-LEVEL CHANGE RECONSTRUCTED FROM SALT-MARSH SEDIMENT

Brain, MJ[1], Kemp, AC[2], Hawkes, AD[3], Cahill, N[4], Horton, BP[5,6], Donnelly, JP[7], and Vane CH[8]

1. *Durham University, UK*
2. *Tufts University, USA*
3. *University of North Carolina, Wilmington, USA*
4. *University College Dublin, Ireland*
5. *Rutgers University, USA*
6. *Earth Observatory of Singapore, Singapore*
7. *Woods Hole Oceanographic Institution, USA*
8. *British Geological Survey, UK*

Sequences of salt-marsh sediment on the Atlantic coast of North America are valuable archives of relative sea-level changes that occurred during the last ~2000 years. Salt-marsh sediment is usually recovered as a core that is later sectioned to provide vertically-ordered samples for reconstructing tidal elevation using a sea-level indicator such as foraminifera. A limitation of this approach is that thickening of the sequence as sediment accumulates may cause compaction of underlying material and post-depositional lowering of samples, resulting in an overestimation of the magnitude and rate of relative sea-level rise. Therefore, the contribution of compaction must be quantified and removed from sea-level reconstructions to permit fair comparison among records and to ensure that the sensitivity of sea level to forcing factors is not misinterpreted or overstated.

We investigate sediment compaction using two approaches and draw upon examples from Connecticut and North Carolina, USA:

(1) In Connecticut, a relative sea-level reconstruction produced from incompressible basal salt-marsh sediment exposed in a trench is compared to a paired reconstruction using a sediment core from the same location. Differences between the records are attributed to sediment compaction.
(2) We develop and apply a geotechnical model to estimate post-depositional lowering in cores of salt-marsh sediment and to subsequently quantify the effect of compaction on reconstructed sea-level trends. The model is calibrated using local surface sediment samples and applied to cores from North Carolina and Connecticut.

Our results demonstrate that sediment compaction in relatively shallow and recent sequences of salt-marsh peat does not materially distort reconstructed sea-level trends. Importantly, application of this approach to additional records requires an expanded modern dataset for model calibration to account for the variable geotechnical properties of salt-marsh peat that formed in different climate regions, ecological zones, and geomorphic settings.

NORDIC SEAS OCEAN-ICE SHEET INTERACTIONS AND GLOBAL SEA LEVEL BETWEEN 50 AND 150 KA

Brendryen, J (1,2), Haflidason, H (1,2), Sejrup, HP (1) Hannisdal B (1,2,3), Grasmo, KJ (1) Edwards, RL (4), Cheng H (4), Kelly, MJ (4), Lu Y (4).

(1) University of Bergen, Department of Earth Science, (2) Bjerknes Centre for Climate Research, (3) Centre for Geobiology, (4) University of Minnesota Twin Cities

We present a high resolution and multi-proxy record of ocean-ice sheet interactions from the Nordic Seas from between 50 and 150 ka BP. This period spans a full glacial cycle from the MIS-6 glacial maximum, Termination II, Last lnterglacial and the glacial inception in MIS-5 and 4.

The record incorporates proxies for near surface and intermediate water circulation, temperature and hydrology as well as the activity of the Fennoscandian Ice Sheet. The records are obtained from a sediment archive strategically located on the Norwegian Margin close to both the inflow of warm Atlantic Water to the Nordic Seas and to the marine-based margin of the Fennoscandian Ice Sheet.

We place the records on a precise radiometric chronology based on correlations to U/Th dated speleothem records from China and the Alps. This enables a comparison of the records to U/Th dated sea-level records from corals and speleothems as well as from benthic and Red Sea $\delta^{18}O$ records. The data indicate a very close connection between ocean–ice sheet interactions in the Nordic Seas and abrupt millennial-scale changes in sea-level. We will discuss potential mechanisms and forcing factors behind this coupled system.

A NEW LAST INTERGLACIAL TEMPERATURE DATA SYNTHESIS AS AN IMPROVED BENCHMARK FOR CLIMATE MODELING

E Capron[1], EJ Stone[2], A Govin[3,4], V Masson-Delmotte[4], S Mulitza[3], B Otto-Bliesner[5], TL Rasmussen[6], LC Sime[1], C Waelbroeck[4], EW Wolff[7].

[1] British Antarctic Survey, High Cross, Madingley Road, CB3 0ET Cambridge, UK
[2] BRIDGE, School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, UK
[3] MARUM/Center for Marine Environmental Sciences, University of Bremen, Leobener Strasse, 28359 Bremen, Germany
[4] Institut Pierre-Simon Laplace/Laboratoire des Sciences du Climat et de l'Environnement, UMR 8212, CEA-CNRS-UVSQ, 91191 Gif-sur-Yvette, France
[5] Climate and Global Dynamics Division, National Center for Atmospheric Research (NCAR), Boulder, CO 80305, USA
[6] CAGE-Centre for Arctic Gas Hydrate, Environment and Climate, UiT, the Arctic University of Norway, Tromsø, Norway
[7] Department of Earth Sciences, University of Cambridge, CB2 3EQ Cambridge, UK

The Last Interglacial (LIG, 129-116 thousand of years BP, ka) offers an opportunity to assess the effect of warmer-than-present-day polar climate on climate-sensitive parts of the Earth system, most notably polar ice sheets and sea level. However, mainly because aligning different palaeoclimatic archives and from different parts of the world is not trivial, a spatio-temporal picture of LIG temperature changes is difficult to obtain.

Here, we provide the first compilation of high-latitude temperature changes across the LIG associated with a coherent temporal framework built between 47 ice core and marine sediment records. We also compile four data-based time slices with temperature anomalies (compared to present-day conditions) at 115, 120, 125 and 130 ka, They provide improved benchmarks to perform climate model-data comparison exercises.

In particular, the 130 ka data-based time slice highlights non-synchronous maximum temperature changes between the two hemispheres with the Southern Ocean and Antarctica records showing an early warming compared to North Atlantic records. We perform a comparison of this 130 ka data-based time slice with the surface temperatures simulated by two General Circulation Models (GCM; CCSM3 and HadCM3) as part of the PMIP3 2012 General Meeting. We highlight that the two GCMs predict warmer-than-present-day conditions earlier than documented in the North Atlantic, while neither model is able to produce the reconstructed early Southern Ocean and Antarctic warming. It strongly suggests that important processes were missing in the set-up of those model experiments.

By including realistic freshwater forcing in HadCM3 to account for the early melting of the Northern Hemisphere ice sheets, we are now able to simulate the asynchronous pattern observed between the two hemispheres in the 130 ka data-based time slice. Our new 130 ka simulations also suggest that the Antarctic surface temperatures are better reproduced when accounting, in addition to a realistic freshwater forcing, for the disintegration of the West Antarctic Ice sheet.

USING COSMOGENIC NUCLIDE INHERITANCE TO TEST ICE-SHEET MODEL BED-THERMAL PROPERTIES ON GREENLAND

[1]Carlson, AE, [1]Sinclair, G, [2]DeConto, RM

[1]College of Earth, Ocean, and Atmospheric Sciences, Oregon State University
[2]Geosciences, University of Massachusetts – Amherst

While cosmogenic nuclide surface exposure ages have been used to document past ice-sheet retreat that can be compared against ice-sheet model simulations, they also could provide information on past ice-sheet thermal regimes and erosivity. Here we use a new Greenland wide database of cosmogenic nuclide exposure ages (n=527) to document the fraction of samples in a given portion of Greenland (n=14) that contain inheritance. Inherited nuclides producing an apparent exposure age older than the last glacial maximum indicate incomplete erosion of the bedrock or boulder surface during last glacial maximum cover, reflecting periodic to even permanent cover by cold-based non-erosive ice. We find high fractions of inheritance in regions that usually lack extensive fjord systems or at high elevations – near Thule, northeast Greenland, south of Nuuk, and near Sisimiut. In these regions, bedrock samples are more likely to show inheritance than boulder samples. This general correlation between frequent inheritance with poorly developed fjords and high elevation suggests these areas have generally been regions of cold-based ice for multiple glacial cycles. Two exceptions to this pattern are near Upernavik and Scoresby Sund, which both have high fractions of inherited nuclides. Interestingly, there is no statistical difference in the fraction of inherited nuclides between bedrock or boulder samples in these two regions. We compare this pattern to new high-resolution (5-10 km) Greenland ice-sheet model simulations of the last glacial maximum that include interaction with ocean temperatures. The ice-sheet model simulates ice advancing to the continental shelf break all around Greenland, consistent with recent observations. Warm based, fast ice flow occurs in major fjords, consistent with minimal nuclide inheritance in Disko Bugt, Paamiut, southernmost Greenland, and along its southeast coast. We find frozen bed conditions and minimal basal motion occurring near the aforementioned regions of significant inheritance. The model also simulates frozen beds and minimal ice motion on either side of the Upernavik and Scoresby Sund fjords likely due to relatively thin ice cover where the cosmogenic data also suggest cold-based conditions. We surmise that cosmogenic exposure data can also prove valuable for testing ice-sheet models basal regimes, a test that has so far been under utilized.

LAST INTERGLACIAL TRANSGRESSION RATES AND HIGH STAND DURATION IN THE NEAR-FIELD EEMIAN NORTH SEA

Cohen, K.M.[1,2,3], Peeters, J.[1,2,3], Sier, M.J.[1], Busschers, F.S.[3], Hijma, M.P.[2]

[1]Utrecht University, Fac. Geosciences, [2]Deltares Research Institute, [3]TNO Geological Survey of the Netherlands -- Utrecht, The Netherlands

The sea-level history of the Eemian transgression and high stand in the Southern North Sea (The Netherlands), first described by Zagwijn (1983), features in many Last Interglacial sea-level and GIA studies. The reconstruction is based on sedimentary contacts in coastal deposits (transgressed tidal-mud buried peat beds, regressed peat-covered tidal flat tops). The location of the area and the rates of transgression that are experienced indicates a relation with deglaciation history of the nearby Scandinavian Ice Sheet, notably its southwestern sector.

The relative dating of the sequence of Eemian index-points comes from pollen palynology and is well-established. This sea-level history spans some 1000-2000 years of last rapid transgression (relative sea level rise of some 30 meters), some 6000-5000 years of high stand (sea level stays within a few meters) and then ends with a sea-level fall, in tandem with climatic deterioration. These durations follow from the correlation of the pollen zones to varved sequences in the NW Germany (classic sites Bispingen and Quakenbrück, newer sites in the Eifel: ELSA, Sirocko et al. 2005). The highstand duration in the Scandinavian near field is about half as short as the far field + intermediate field high-stand as established with U/Th dating of fossil reefs in the tropical seas of all oceans (e.g. Medina-Elizalde 2013).

The absolute timing assigned to the Eemian transgression and high-stand, varies greatly between studies. Some authors correlate the shape of regional sea-level curve to the global benthic $\delta^{18}O$ signal and have recording of transgression start as early as 130-128 ka and sea-level fall begin at 123-121 ka (e.g. Kopp et al. 2009). Other authors correlate onset of temperate conditions as testified by pollen, equating sites off Iberia (going back to Sánchez-Goñi et al. 1999) and in the Mediterranean to those at the latitude of the North Sea, arriving at a recording onset of *c.*124 ka and high stand ending *c.*117 ka. Further authors would have it start and stop a few 1000 years later than that, implying that temperate conditions in the North Sea set on later than in Southern Europe, lagging to a stronger degree than into the Holocene. New data and analysis (Sier et al. *in review*) from the central Netherlands will be presented and supports a relatively late onset (*c.*121 ka). Lines of reasoning include palaeomagnetic correlations (onset Blake event), the NEEM record and EDML1 time scale, the ELSA record.

To further evaluate these findings, checking if the Eemian near-field postglacial GIA could lag the $\delta^{18}O$ signal too, we connect to Scandinavia (e.g. Bauch & Erlenkeuser 2008). The earlier the Eemian near-field transgression starts, the earlier into the Last Interglacial had this ice sheet lost most of its mass (or GIA response between the two glaciations would be very different, which is unlikely). The later the transgression starts, the longer some ice-mass survived. This has implications for roles attributed to other ice-sheets. A comparison of the (ocean marine) deglaciation history of Scandinavia for Termination II and Termination I, and the rates of postglacial sea-level rise recorded in the Eemian and Holocene will be presented.

DATA MANAGEMENT TELECONNECTIONS OF ARCTIC OSCILLARTION, SOUTHERN OSCILLATION AND OCCEAN SURGES : AN OVERVIEW IN WEST AFRICA COASTAL AREAS

[1] Ediang O. A. (Ph.D),[2] Ediang A. A. (Ph.D)

[1] Nigerian Meteorological Agency Marine Division,
[2] *The Nigerian Maritime Administration and Safety Agency, 6 Burmal Road, Apapa, Lagos,Nigeria.*
Ediang2000@yahoo.com

In recent years ocean technology has leaped to the aid of scientists by providing them with cost-effective tools that can take measurements of essential biogeochemical variables autonomously, i.e. sensors on autonomous platforms. These autonomous measurements are complementary to efforts carried out by traditional ship-based sampling, with the aim of improving data coverage worldwide. Yet, despite these options becoming more readily available, there is still a gap between the technology (investigators and technicians that deploy these technologies) and the end-user.

Climates studies over West Africa especially in Nigeria, have in the past been based mainly on empirical/statistical techniques. These techniques consider concept of persistence, trends and cycles, which assume that future conditions can be extracted from past ones. These methods do not accurately understand the process that produce climate, and therefore find it difficult to predict the effects or changes in the process.

The attempt in this study is however to highlights and extend examine what are the principal patterns of various on in ocean properties and monsoon observed in both data and modeling simulations forced with realistic external forcing? Also, what are the most likely underlying mechanism?

The attempt also looked in this paper is however to high light the features of the teleconnections of Arctic oscillation, Southern oscillation and Ocean surges in the Nigeria coast (West Africa).

The paper also deals with data assimilating of traditional and remote data in distributed oceanic model.

THE BARBADOS SEA LEVEL RECORD

Fairbanks, RG[1, 2]; Mortlock, RA[1]; Abdul, NA[1]; Wright, JD[1]; Cao, L[3]; Mey, J [4,5]

1. Earth and Planetary Sciences, Rutgers University, Piscataway, NJ, United States.
2. Columbia University, New York, NY.
3. Morehouse School of Medicine, Atlanta, GA.
4. City University of New York and Kingsborough Community College, New York, NY
5. Lamont-Doherty Earth Observatory, Palisades, NY.

The Barbados Sea Level Record is the most detailed, precise, and accurate relative sea level record available. Geophysical model computations indicate that Barbados relative sea level history is remarkably close to the global average sea level making it unique among sea level reconstructions. New drill cores, more than 100 new radiometric dates, and 1000 km of Multibeam mapping greatly enhances the Barbados Sea Level Record. Extensive Multibeam around the entire island covers approximately 2650 km^2 of the sea bottom and integrates the offshore reef topography and Barbados Sea Level Record with the unparalleled onshore core collection, digital elevation maps, and Pleistocene Sea Level Record spanning the past one million years.

The reef crest coral, *Acropora palmata*, remains the stalwart indicator of sea level for many reasons that are validated by our redundant sea level records and redundant dating via Th/U and Pa/U analyses. Microanalysis and densitometry studies better explain why *Acropora palmata* is so well preserved in the Pleistocene reef records and therefore why it is the species of choice for sea level reconstructions and radiometric dating.

The Barbados *Acropora palmata* Sea Level Record has a sampling resolution of better than 100 years throughout much of the last deglaciation showing unprecedented detail in overlapping drill cores. The Melt Water Pulses (MWP1A and MWP1B) are well resolved and the intervening interval that includes the Younger Dryas reveals sea level changes in new detail that are consistent with the terrestrial records of ice margins. MWP1A spans the time interval 14,800 to 13,900 years before present (YBP) when sea level rise reached 28 mm per year. MWP 1B spans the time interval 11,500 to 11,100 YBP when sea level rise peaked at 40 mm per year. These Melt Water Pulses are likely the delayed ice sheet response to the dramatic shifts from zonal to meridional ocean and atmospheric circulation in the North Atlantic as deglaciation progressed.

More than 100 paired Th/U and radiocarbon ages place the Barbados Sea Level Record unambiguously on the radiocarbon time scale for direct comparisons with the terrestrial records of ice margin changes and $\delta^{18}O$ records in benthic foraminifera. The precision and accuracy of The Barbados Sea Level Record is on a par with the precision and accuracy of Milankovitch's radiation calculations for 65^{o} north spanning the same time interval allowing us to demonstrate the simple and direct correspondence between the interval of maximum summer radiation over the ice sheets and the period of maximum sea level rise.

Progress and Challenges in Coupling Ice Sheets into the Community Earth System Model

Jeremy Fyke

I will present recent progress in coupling the Community Ice Sheet Model (CISM) into the Community Earth System Model. New developments that enable 2-way coupling include dynamic Community Atmosphere Model topography updating, routing of CISM-calculated ice sheet discharge to the CESM ocean model (the Parallel Ocean Project), utilization of new dynamic land unit capabilities in the Community Land Model, and the ability to incept ice sheets over bare land. In addition, a new higher-order ice model ('CISM2') has been implemented in the coupled architecture. Ongoing work involves stress-testing the new coupled configuration, carrying out preliminary scientific validations, and initiating new model developments (pending human resources!). These include, for example, explicit icebergs, multiple ice sheet instances, explicit firn, and atmospheric model tuning. I will close with a brief discussion of challenges that may arise when the coupled model is used to address cutting-edge paleoclimate questions.

MIOCENE ANTARCTIC ICE SHEET SIMULATIONS USING AN ASYNCHRONOUSLY COUPLED RCM

Gasson, E, DeConto, R, Pollard, D

Climate System Research Center, University of Massachusetts, Amherst, USA
Earth and Environmental Systems Institute, Pennsylvania State University, USA

Both direct and indirect evidence suggests that there was fluctuation of the Antarctic ice sheet over the past 34 million years. For example, sediment provenance studies suggest retreat into the Wilkes Subglacial Basin during the Pliocene and possibly earlier, in the Miocene. Indirect evidence, such as from the oxygen isotope record from benthic formanifera, suggests fluctuations in ice volume exceeding 50 m in sea level equivalence during the Miocene. Ice sheet models have struggled to achieve such large-scale retreat under the relatively modest atmospheric CO_2 concentrations suggested by proxy records.

Attempts to resolve this data-model conflict have recently focused on simulating retreat into the marine basins of Antarctica, with retreat into the Wilkes Subglacial Basin during the Pliocene simulated in two recent ice sheet modeling studies using different approaches. Although retreat into the subglacial basins may explain approximately 20 m of ice volume fluctuation from Antarctica, it is still lower than the magnitudes suggested by the oxygen isotope record for the Miocene.

Here we focus on improving simulation of the Antarctic ablation zone by using an asynchronously coupled RCM to provide climate forcing to an ice sheet model. We use a GCM with a Miocene paleo-geography to provide boundary forcing for the RCM, with atmospheric CO_2 at various concentrations. In previous simulations there was limited retreat of the ice sheet away from the continental margin, due to a strong hysteresis mechanism. In these asynchronous simulations there is increased retreat of the Antarctic ice sheet, with continental sectors retreating away from the continental margin. This results in a greater overall decrease in ice volume than for non-asynchronously coupled simulations.

MODELLING NORTHERN HEMISPHERE GLACIAL INCEPTION AND ITS RELATION TO GLOBAL SEA-LEVEL CHANGE

Authors1: George,SE
Authors2: Gregory,JM
Authors3: Smith,RS

NCAS-Climate, Department of Meteorology, University of Reading, UK

The cryosphere is an integral part of the global climate system. Ice-sheets, in particular, are very sensitive to changes in surface mass balance (SMB).Perturbations in SMB can lead to changes in the size and extent of ice-sheets, which, in turn, induce feedback effects in the general climate system. The present study models the growth of ice sheets following the last glacial inception, and investigates the relationship between land-ice accumulation and sea-level change.

This study is the first to couple an AOGCM (atmosphere-ocean general circulation model) with a thermomechanical ice-sheet model of full (northern) hemispheric extent. The ability to simulate long palaeoclimate timescales is enabled by the availability of FAMOUS: an AOGCM with low computational cost, but with physical parameterisation comparable to higher resolution models. FAMOUS is coupled to the BISICLES ice-sheet model employing GLINT for flux exchange (BISICLES running at a much higher resolution than FAMOUS).

Ice-sheet models have traditionally used positive degree day (PDD) schemes to parameterise SMB. However, such schemes have been shown to overestimate climate sensitivity, and do not explicitly consider energy balance or the separate influence of variables such as solar radiation and albedo change. An alternative method (used here) is to calculate energy and mass balances (including refreezing of meltwater) within the AOGCM and present the ice-sheet model with a full SMB field (rather than temperatures with which to calculate PDD). FAMOUS-BISICLES employs the JULES land surface model to simulate AOGCM sub-gridscale fractional tile surface types at a range of height levels. MOSES2.2 is used to model multi-layer snowpack on a tile-by-tile basis, which in turns produces the SMB fields for BISICLES.

The present study simulates conditions at the time of the last glacial inception regarding CO2 and orbital forcing, beginning with no Northern Hemisphere ice sheets except on Greenland. The rate of glacial inception, and ice-sheet development is compared with palaeo records of sea-level change during the initial growth of Northern Hemisphere ice-sheets. Best estimates of Antarctic ice-mass variability are used to adjust the palaeo sea-level records to be Northern Hemisphere specific.

IMPACT OF ICE SHEET MELT WATER FLUXES ON THE CLIMATE EVOLUTION AT THE ONSET OF THE LAST INTERGLACIAL

Goelzer, H[1], Huybrechts, P[1], Loutre, MF[2], Fichefet T[2]

[1] *Earth System Sciences & Departement Geografie, Vrije Universiteit Brussel, Brussels, Belgium.*

[2] *Université catholique de Louvain, Earth and Life Institute, Georges Lemaître Centre for Earth and Climate Research (TECLIM), Louvain-la-Neuve, Belgium.*

Abstract. The focus of this study is the impact of ice sheet changes and associated freshwater fluxes on the climate evolution at the onset of the Last Interglacial, where large climate perturbations occurred as the ice sheets retreated from their glacial configuration. For that purpose we have simulated the period from 135 to 115 kyr BP with the Earth System model of Intermediate Complexity LOVECLIM version 1.3, which includes realistic representations of the Northern Hemisphere and Antarctic ice sheets and their freshwater fluxes. Variations in meltwater fluxes from the Northern Hemisphere ice sheets lead to North Atlantic temperature changes and modifications of the strength of the Meridional Overturning circulation (MOC). By means of the interhemispheric see-saw effect, MOC variations also give rise to temperature changes in the Southern hemisphere, which are modulated by the direct impact of Antarctic meltwater fluxes into the Southern Ocean (SO). During the retreat of the Antarctic ice sheet, associated freshwater fluxes into the SO lead to a millennial time scale oceanic cold event with expanded sea-ice cover as evidenced in ocean sediment cores. Consequently, increased stratification and reduced sea-air heat exchange lead to a build-up of anomalous mid-depth ocean warming, which is discussed as potential feedback on the ice sheet evolution.

RELATIVE SEA-LEVEL CHANGES IN FLORIDA DURING THE LAST 8000 YEARS

Hawkes, AD[1], Kemp, AC[2], Donnelly, JP[3], Horton, BP[4,5], Peltier, WR[6], Cahill, N[7]

1. *University of North Carolina Wilmington, USA*
2. *Tufts University, USA*
3. *Woods Hole Oceanographic Institution, USA*
4. *Rutgers University, USA*
5. *Earth Observatory of Singapore, Singapore*
6. *University of Toronto, Canada*
7. *University College Dublin, Ireland*

Holocene relative sea-level (RSL) reconstructions provide data for testing Earth-Ice models and the influence of rotational feedback, constraining the spatio-temporal pattern of deglaciation and describing the geometry of the Laurentide Ice Sheet's collapsing forebulge. Sea-level reconstruction from the southeast Atlantic coast of North America may also provide a regional constraint on ice-equivalent meltwater input and gravitational fingerprinting. But a paucity of reconstructions in Georgia and Florida prohibit characterizing the above parameters and validating new Earth-Ice models.

We reconstruct RSL during the last 8000 years in northeast Florida from basal salt marsh sediments that are free from compaction. The elevation of RSL was reconstructed from fossil assemblages of foraminifera preserved in core material using an indicative range technique. The use of foraminifera as a sea-level indicator is underpinned by understanding the relationship between the foraminifera and sea level. The timing of sediment deposition was estimated using radiocarbon dating of identifiable plant macrofossils. We produced 32 sea-level index points that constrain the position of RSL in time and space and together describe trends in regional Holocene RSL. Here we show that RSL rose by 5.7 m in the last ~8000 years with no evidence of a mid-Holocene highstand. RSL rises rapidly in the early Holocene at ~1.3 mm/yr (0.6-2.0 mm/yr) from 8000 to 6000 calibrated years BP followed by a decrease in rate to ~0.5 mm/yr (0.3-1.4 mm/yr) during the mid- to late-Holocene from 6000 calibrated years BP to present. The changing rate of RSL rise reflects the continuing collapse of the Laurentide forebulge and decreased meltwater input.

RECONSTRUCTING HOLOCENE GREENLAND ICE SHEET HISTORY IN AN ICE SHEET – EARTH SYSTEM MODEL FRAMEWORK

Helsen, MM[1], Van de Wal, RSW [1], Reerink, TJ [1], Bintanja R[2], Li, Q[3], Zhang, Q[3]

1: Institute for Marine and Atmospheric research Utrecht, Utrecht University, The Netherlands
2: Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands
3: Stockholm University, Stockholm, Sweden

The earth system model EC-Earth is a valuable tool to calculate effects of greenhouse gas (GHG) scenarios on various components of the climate system. Coupling a thermomechanical ice sheet model to EC-Earth offers the possibility to not only quantify effects of GHG scenarios on ice mass changes, but also to take into account the effects of geometrical changes of the ice sheet on the climate system.

Here we use a LGM simulation of EC-Earth to initialize a Greenland ice sheet model, as a starting point for a simulation of the evolution of the Greenland ice sheet through the Holocene. Geological evidence of ice sheet extent is used to constrain the size of the LGM ice sheet.

An energy balance approach is used to calculate the surface mass balance over the ice sheet, to translate atmospheric fields to a realistic climate forcing for the ice sheet within EC-Earth. First results will be shown of a coupled ice sheet – earth system modelling setup, in which we focus on the interaction of a retreating Greenland ice sheet and its atmospheric and oceanic environment during the transition from the glacial into the Holocene. We compare these results with offline (more schematic) calculations of the glacial – interglacial transition, obtained by scaling between LGM field and present-day fields as a function of northern hemispheric insolation.

FOSSIL CORALS AND SPELEOTHEMS AS MARKERS OF PAST SEA LEVELS: TOWARDS A CONSISTENT GLOBAL REPOSITORY

Hibbert FD[1], Rohling EJ[1,2], Chutcharavan PM[3], Dutton A[3], Zhao C[1], Williams F[1]

1. Ocean and Earth Science, National Oceanography Centre, University of Southampton, UK
2. Research School of Earth Sciences, The Australian National University, Canberra, Australia
3. Department of Geological Sciences, University of Florida, Gainesville, Florida, USA

Coral benchmarks and speleothem records are valuable markers of past sea level that can be dated with high analytical precision using U-Th geochronology. Corals provide a minimum estimate for the position of past sea level because they must remain submerged during growth, whereas speleothems provide upper limits for sea level because they only grow when caves are subaerially exposed. In this way, these two archives provide complementary information to bracket past sea level. Despite the fact that corals and speleothems remain a preeminent method for reconstruction and evaluating former sea levels during the Late Quaternary, there are considerable challenges in interpreting such data and in comparing data between individual studies and sites. These challenges include difficulty in constraining paleodepth of fossil corals that are also affected by taphonomy and limited context of heterogeneous reef structure for specimens collected from limited 2-D (section) or 1-D (drill-core) perspectives, diagenesis and open system behaviour of U and Th isotopes in coralline aragonite, local tectonic and isostatic influences, as well as inconsistencies and gaps in data reporting. As a first step towards tackling these heterogeneous issues, we provide an internally consistent database of published coral and speleothems U-Th data that have been used in sea level studies along with a database of modern coral depth distributions.

Our data compilation of U-series dated corals includes available geochemistry and field observations, and uses modern ecological depth habitat constraints to refine the paleodepth interpretation of fossil coral data. To support the growing awareness within the palaeoclimate community of the importance of coral habitat, we provide both global and regional depth habitat ranges for each species. As such we present an internally consistent global compilation of coral benchmarks (building on the compilations of Medina-Elizalde, 2012 and Dutton and Lambeck, 2012) containing >100 studies. We include a rigorous consideration of each error term associated with these records, such as: age, depth habitat, elevation measurement, and uplift correction. We apply commonly employed age screening methods ($\delta^{234}U_{initial}$ and detrital ^{232}Th concentrations). This includes consideration of stratigraphic integrity, replication (and any concordant age determinations) and validation of assumptions (e.g. uplift rates), where possible. We also present a new compilation of speleothem sea level markers (both U-series and radiocarbon dated). This presentation will show both datasets as currently compiled (>3,000 datapoints), and initial evaluations on a site-specific basis.

COMMON ERA SEA LEVEL DATABASE

Benjamin P. Horton[1] Niamh Cahill[2] Andrew C. Kemp[3] Roland Gehrels[4] Robert Kopp[5]

[1] Department of Marine and Coastal Sciences, Rutgers University, USA
[2] School of Mathematical Sciences, CASL, Earth Institute, University College Dublin
[3] Department of Earth and Ocean Sciences, Tufts University, USA
[4] Environment Department, University of York, UK
[5] Department of Earth & Planetary Sciences and Rutgers Energy Institute, Rutgers University, USA

Understanding of Common Era (CE) sea-level change is fragmentary compared to understanding of temperature variability, for which several global syntheses have been generated. This limitation prevents accurate assessment of the CE relationship between temperature and sea level, including the sea-level response to climate phases such as the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA).

We will construct a CE relative sea level (RSL) database using geological proxies. The reconstructions are from coasts that are tectonically stable and are based on four types of proxy archives (archaeological indicators, coral microatolls, salt marsh sediments and vermetid [mollusk] bioconstructions) that are best capable of capturing submeter-scale RSL changes. The database consists of reconstructions from Australasia (n = 2), Europe (n=5), Greenland (n = 3), North America (n = 6), the northern Gulf of Mexico (n = 3), the Mediterranean (n = 1), South Africa (n = 2), South America (n =2) and the South Pacific (n =3).

We perform Bayesian inference on the CE rates of RSL change. The model we propose places a Gaussian process prior on the rate of RSL change, which is then integrated, to obtain the mean of the distribution for the observed data, and set in an errors-in-variables framework to account for age uncertainty. The resulting model captures the continuous and dynamic evolution of sea-level change with full consideration of all sources of uncertainty. We will address the following research questions: (1) Did RSL vary during the MCA and LIA? and (2) Is the 20th century rate of sea-level rise greater than any other centennial trend during the last 2000 years?

REAPPRAISAL OF SEA-LEVEL LOWSTAND DURING THE LAST GLACIAL MAXIMUM OBSERVED IN THE BONAPARTE GULF, NORTHWESTERN AUSTRALIA

Ishiwa, T

Atmosphere and Ocean Research Institute, The University of Tokyo

During the Last Glacial Maximum (LGM) ice volume reached a relative maximum and global temperature was lower than today. Understanding continental ice volume change requires accurate reconstruction of relative sea level, but tectonic uplift and isostatic adjustment effects complicate many records. Using marine sediment cores from the Bonaparte Gulf in northwestern Australia, a so-called "far field" tectonically stable site, Yokoyama et al. (2000) reported that the LGM terminated abruptly at 19 ka with a rapid sea-level rise (19 ka event). Although their sea-level reconstruction constrained the age of the LGM termination, the timing of its inception remained less well constrained, partly because the number of their radiocarbon analyses was insufficient to constrain LGM duration. Here we return to the Bonaparte Gulf and present a new relative sea level that better constrains LGM duration with high-resolution radiocarbon dating of a recently recovered marine sediment core (water depth: 120 m, length: 583 cm). Radiocarbon dating of 23 molluscs and 26 bulk organic-matter samples, together with total organic carbon, total nitrogen, and stable carbon isotopes, provide a record of paleoenvironments in response to sea level changes. Our results indicate that the LGM sea-level minimum occurred at ~21 cal ka BP and the LGM duration was shorter than previous reported.

RAPID SEA-LEVEL RISE AND FALL AT THE END OF THE LAST INTERGLACIAL – BIOEROSION EVIDENCE FROM THAILAND

Kazmer, M

Department of Palaeontology, Eotvos University, Budapest, Hungary

There are bivalve boreholes positioned anomalously high above late interglacial marine notches along the Andaman Sea coast of Thailand. Intertidal macrobioeroders (chitons, bivalves, and sea urchins) leave distinct traces with high fossilization potential. The traces are arranged in zones according to the ecological needs of their producers. Chitons are on top (these live in the higher intertidal zone), holes of boring bivalves in the middle (these live in the lower intertidal zone), and boring sea urchins below (these live just below low tide level).
Their joint activity creates marine notches, extending vertically between high and low tide, and horizontally as far as 10 m into the rock.

There are two levels of notches in Phuket Bay: an actively forming, lower one, and a fossil, speleothem-filled upper one, 4-5 m above the active notch. Dimensions of the latter are similar to the lower notch. The last interglacial age is suggested by a single U/Th date measured on a stalagmite within the upper notch on Ko Pha Nak island: 19,000 +/- 1300 yr (Scheffers et al. 2012, Holocene, 22, 1169-1180). The enclosing notch most probably formed during the last interglacial highstand.

An anomalous set of boreholes are preserved in the upper notch. Bivalve boreholes cover the notch roof, where normally boring bivalves never live (desiccation during low tide would kill them). There are holes of sea urchins on the vertical back wall of the notch, a place where they never live, not resistant to desiccation and predation during low tide. The upper boundary of these boreholes are about 2.5-3 m above their regular vertical distribution. These fixed biological indicators are evidence for a period when last interglacial sea level was briefly higher than the roof of the intertidal marine notch.

This short-term excursion of sea level did not last long, as there was no significant alteration of notch shape by biological erosion. Rise of sea level was rapid (probably within a few decades), as it did not alter the outline of the marine notch in any remarkable manner. Fall of sea level was even faster, since the bioerosion features remained as they were, not obliterated by supratidal karstification processes. After the rise and subsequent fall of sea level there was no bioerosion within the notch at all; i.e. sea level fell below the notch.

Evidence for late interglacial overrun of sea level is known, among others, from Pleistocene coastal dunes of the Bahamas (Neumann & Hearty1996, Geology 24, 775-778) and coral reefs of Mexico (Blanchon 2009, Nature 458, 881-885). The locations in Phuket Bay, Thailand are better than either of them: holes bored into compact, Permian limestone preserve exquisite details of the evidence for rapid of sea level change at the end of the last interglacial.

HOLOCENE RELATIVE SEA-LEVEL CHANGES FROM NEAR-, INTERMEDIATE- AND FAR-FIELD LOCATIONS

Khan, NS[1], Horton, BP[1], Engelhart, SE[2]

1. *Sea Level Research, Department of Marine and Coastal Sciences, School of Environmental and Biological Sciences, Rutgers University, 71 Dudley Road, New Brunswick, NJ, 08901, USA*
2. *Sea Level Research, Department of Geosciences, University of Rhode Island, Woodward Hall, 9 East Alumni Avenue, Kingston, RI 02881, USA*

Holocene sea-level changes provide important background rates for 21st century sea-level rise and offer a regional context for these changes. Changes in relative sea level (RSL) result from the redistribution of mass due to the growth and decay of ice sheets that results in isostatic compensation of the underlying solid Earth, a process called glacial isostatic adjustment (GIA). Research groups have compiled local or regional databases of former sea levels to constrain models of GIA, although because of their restricted spatial extent, these databases are limited in their ability to validate multiple geophysical parameters. Here, we present a database of sea levels since the last glacial maximum for the Pacific and Atlantic coasts of North America (including Bermuda), the Caribbean and South America.

We describe the methodology used to reconstruct former sea levels, which follows the practices established by the International Geoscience Programme (IGCP). We produce sea-level index points, which define the unique position of RSL and consist of an X (age) and Y (the position of former RSL) estimate. A suite of index points developed from a locality or region depicts changes in RSL through time and estimates rates of change. The following four criteria must be known or estimated for a valid index point: (1) location of the sample; (2) the altitude of the sample (and the error associated with measuring that altitude); (3) the indicative meaning (the relationship between the sample and a tide level); and (4) the age of the dated sample calibrated to calendar years.

Over 2000 sea-level index points from near-, intermediate-, and far-field regions comprise this database. Formerly glaciated areas (near field) show variable RSL change; where data are present, highstands of RSL occur immediately following deglaciation and in the mid to late Holocene. Sites bordering formerly glaciated areas (intermediate field) display a continuous rise in RSL with a decreasing rate through time due to the collapse of the proglacial forebulge and the reduction in meltwater input during deglaciation. At increasing distances from the major centers of glaciation (far field), the ice-induced component of the signal diminishes in magnitude and the eustatic (or meltwater) signal becomes dominant. We estimate rates and sources of sea-level change during the Holocene and explore how predictions of RSL from GIA models have changed through the development of ice models and earth models.

SLIVISU, UPDATE OF THE VISUAL ANALYTICS SOFTWARE FOR INSPECTION OF SLI DATA AND DATA—MODEL INTERCOMPARISON

Klemann V[1], Unger A[1]

1. Department of Geodesy and remote Sensing, Helmholtz-Centre Potsdam, German Research Centre for Geosciences GFZ, Potsdam, Germany

Sea-level indicators (SLIs) are categorized as point samples which are sparsely distributed on the Earth's surface, are separated in time, are of variable quality and are showing different indicative meaning of relative sea level (RSL) with respective uncertainties for a specific location and geological epoch. The information of this data is usually presented in separated views: geographic maps showing the spatial content, sea-level diagrams showing its time–height dependence, and tables showing the additional meta-information.

For surveying such data, the visual-analytics software SLIVISU was developed at GFZ-Potsdam. The software gives direct access to properly formatted compilations of SLIs, and allows selection of data as detailed inspection of meta-information by interactive data views in the form of tables, maps and diagrams.

When comparing model simulations of RSL with SLI data, the respective fit or relevance to the observation has to be analyzed. Furthermore, a model simulation might contain one predicted sea-level height or is based on a whole ensemble of models due to a stochastic process or a parameter study. Analyzing such ensembles demands additional representations of the considered paramter space in context of the RSL prediction at the SLI.

To address this, SLIVISU contains additional parameter views, where a specific relation like an aggregated model fit to different subsets of SLIs is shown in representations like scatter plots, histograms, maps or tables. Specifically designed as an interactive visual-analytics tool, the different views of the observed and simulated data are interconnected, subsets of the respective data can be selected and the corresponding relations are aggregated on the fly. This allows an intuitive view on and additional insights into the model–data dependencies, where the link to the meta-information of the data is maintained. Insofar, we see this software as complementing the model-based analysis for reconstructing relative sea-level change.

SEA-LEVEL VARIABILITY OVER THE COMMON ERA

Kopp, R. E.[1], Kemp, A.C. [2], Bitterman, K. [3], Gehrels, R. [4], Horton, B.P. [1], Donnelly, J.P. [5], Hay, C.C. [1,6], Mitrovica, J.X. [6], Morrow, E.D. [1,6], and Rahmstorf, S[3].

(1) Rutgers University, (2) Tufts University, (3) Potsdam Institute for Climate Impact Research, (4) University of York, (5) Woods Hole Oceanographic Institution, (6) Harvard University

We present a new database of reconstructions of relative sea levels (RSLs) since 2 ka, synthesizing more than two dozen previously published studies. Coverage is densest in the North Atlantic region, but also includes the western Mediterranean, southern Africa, and the southern Pacific Ocean. The highest resolution records come from the eastern United States, where glacio-isostatic adjustment drives long-term RSL rise that salt marshes track to maintain their tidal elevation, creating sedimentary sequences of salt-marsh peat that are uniquely suited to reconstructing RSL changes.

We use a spatio-temporal empirical hierarchical model (EHM) to decompose RSL into long-term sea-level change (like glacio-isostatic adjustment), global sea-level change (e.g., due to changes in ocean heat content or land-ice volume), and regional sea-level variability (e.g., due to changes in ocean circulation and winds). The resulting global sea level (GSL) curve reveals GSL rise in the early Common Era, as well as GSL fall from ~800—1200 CE,. The historic period of GSL rise began in the 19th century, with GSL rise in the 20th century extremely likely faster than during any preceding century in the Common Era.

A HIGH ARCTIC HOLOCENE CLIMATE RECORD

Lecavalier BS[1], Fisher D[2], Milne G[2], Vinther B[3], Tarasov L[1], Huybrechts P[4], Lacelle D[5], Main B[5], Zheng J[6], Bourgeois J[6], Dyke A[7]

[1] *Department of Physics and Physical Oceanography, Memorial University, Canada*
[2] *Department of Earth Sciences, University of Ottawa, Canada*
[3] *Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Denmark*
[4] *Vrije Universiteit Brussel, Belgium*
[5] *Department of Geography, University of Ottawa, Canada*
[6] *Geological Survey of Canada, NRCan, Ottawa, Canada*
[7] *Department of Geography, Memorial University, Canada*

The Holocene Thermal Maximum in the Arctic occurred during the first half of the present interglacial and represents a period when air temperatures were warmer than present-day. The melt-layer and $\delta^{18}O$ records from Agassiz Ice Cap (Ellesmere Island, NU) are the most northerly continuous climate records that can quantify temperature changes throughout the Holocene and therefore play a pivotal role in our understanding of recent High Arctic climate change (Fisher et al., 1995). However, estimates of temperature changes from these two Agassiz records have yielded inconsistent results: the melt record indicates a well-defined peak in temperatures around 11 ka (Fisher et al., 2012), which is compatible with other proxy records from the region, whereas the $\delta^{18}O$ time-series (Vinther et al., 2009) indicates a smaller amplitude and broader temperature maximum between 10 to 6 ka. Here, we present revised $\delta^{18}O$ temperature reconstruction from the Agassiz Ice Cap that resolves this apparent discrepancy between the two records and update the $\delta^{18}O$ time-series to present-day, providing a more robust assessment of High Arctic Holocene temperature change. Our corrected $\delta^{18}O$ record exhibits an earlier and warmer peak temperature of 4.5 ^{o}C at ~10.5 ka (2σ uncertainty 3.4 – 5.3 ^{o}C) and includes temperatures up to 4^{o}C higher during the early Holocene (11.7 - 9 ka 2bk) compared to previous studies (Vinther et al., 2009). Additionally, the updated $\delta^{18}O$ time-series from a new shallow Agassiz ice core suggests that present-day air temperatures are at their warmest in the past 7.1–7.8 ka and rates of temperature change are at their highest since entering the present interglacial 11.7 ka. Finally, a warmer HTM in the High Arctic has implications for the evolution of the Greenland Ice Sheet. We present modelling results based on an extension of a recent model reconstruction of this ice sheet (Lecavalier et al., 2014) by implementing our revised Agassiz temperature forcing for northern Greenland. We find significantly enhanced thinning of this sector of the ice sheet compared to recent model reconstructions which is compatible with relatively sea level records and the Camp Century ice thinning curve (Lecavalier et al., 2014).

DEVELOPMENT TOWARDS A FULL BAYESIAN CALIBRATION OF A 3D GLACIAL SYSTEMS MODEL OF THE ANTARCTIC ICE SHEET OVER THE LAST GLACIAL CYCLE

Lecavalier BS[1]; Briggs R[2], Tarasov L[1]

[1]*Department of Physics and Physical Oceanography, Memorial University of Newfoundland, Canada*
[2]*Centre for Cold Ocean Resources Engineering (C-CORE), Canada*

How did the Antarctic Ice Sheet evolve over the last glacial cycle? How much do current uncertainties in the thermo-mechanical present-day state of the ice sheet affect projections of its future evolution? Without the associated quantification of uncertainties, answers to these questions have little value.

A developing technique for explicit uncertainty quantification of glacial systems is large-ensemble Bayesian calibration of models against large observational data-sets (Tarasov et al., 2012). The foundation for a Bayesian calibration of a 3D glacial systems model (GSM) for Antarctica has recently been completed (Briggs et al., 2014). Bayesian calibration thoroughly samples model uncertainties against fits to observational data through Markov Chain Monte Carlo methods using Bayesian artificial neural network emulators of the full GSM (Tarasov et al., 2012). For the first time, this methodology will generate a probability distribution for the Antarctic Ice Sheet deglaciation with explicit and well-defined confidence intervals.

Past work has shown the GSM to have likely inadequate range of grounding line migration in certain sectors as well as persistent ice thickness biases in topographically complex regions (Briggs et al., 2014). To advance towards full calibration, these deficiencies will be addressed through the following. First, basal drag representation will be improved. This will include improved sub-grid treatment of the thermo-mechanical impacts of high basal roughness, examination of the impact of inclusion of fully-coupled basal hydrology, and re-evaluation of uncertainties in basal drag parametric representation for regions that are presently marine. Second, an expanded climate forcing using statistical correction of simplified climate models will be added to better capture the uncertainty in past climate. Thirdly, the impact of past changes in ocean temperature on sub ice shelf melt will be explicitly incorporated. Finally, the calibration will also incorporate uncertainties in earth rheology in the context of isostatic adjustment.

We will outline the improvements currently being implemented, solicit further data constraints, and outline the remaining steps towards full calibration of the model. This research will improve our understanding of the present-day thermo-mechanical state of the AIS and its contemporary mass balance through the re-interpretation of geodetic data (Shepherd et al., 2012). By also running the calibrated GSM forward in time, a probability distribution for the future evolution of the AIS will be generated.

HOLOCENE DEGLACIATION OF ANTARCTICA: STEADY OR RAPID?

Mackintosh, A N, Jones, R S, Golledge, N
Antarctic Research Centre, Victoria University of Wellington, New Zealand

Norton, K
School of Geography, Environment and Earth Sciences
Victoria University of Wellington, New Zealand

Andrew.Mackintosh@vuw.ac.nz

Abstract

The East Antarctic Ice Sheet (EAIS) is the largest continental ice mass on Earth, and understanding its behaviour during the Holocene is important for evaluating its present-day and future response in a warming climate. We discuss EAIS retreat during this period, drawing on evidence from terrestrial cosmogenic nuclides, marine sediment and ice cores, as well as numerical modelling experiments. We show that during the Last Glacial Maximum, the EAIS thickened near its present-day grounding line and extended to the continental shelf margin, but thinned in the ice sheet interior. This ice sheet advance was associated with the formation of low-gradient ice streams that grounded at depths of >1 km below sea level on the inner continental shelf.

Terrestrial chronologies indicate that much of the retreat of the EAIS from this maximal extent appears to have occurred during the Holocene. Although this retreat was thought to have been largely steady and linear, evidence for rapid ice sheet thinning during the early to mid Holocene is now emerging from our new work at Mackay Glacier, and in recently published studies from the Antarctic Peninsula, and West Antarctic Ice Sheets. We argue that this rapid thinning occurred as a consequence of the marine ice sheet instability as the ice sheet retreated into the inner-shelf troughs that characterise the Antarctic marine margin.

THE RESPONSES OF ANTARCTIC ICE SHELVE'S BASAL MELTING TO CLIMATIC FORCING UNDER THE LGM AND A CO2 DOUBLING CLIMATE

Obase, T [1], Abe-Ouchi, A [1], Kusahara, K [2], Hasumi, H [1]

1 *Atmosphere and Ocean Research Institute, the University of Tokyo*
2 *Institute of Low Temperature Science, Hokkaido University*

Abstract:
Basal melting of Antarctic ice shelves is considered to be an important factor to the retreat of Antarctic ice sheet in the past or future, but little consensus exists on how the rate of basal melting changes against climatic forcing. We investigate Antarctic Ocean and basal melting of Antarctic ice shelves under the Last Glacial Maximum (LGM) and an equilibrium CO_2 doubling climate as well as present-day, using a circumpolar ocean model with ice shelf cavity component (Kusahara and Hasumi 2013). As the circumpolar ocean model requires atmospheric forcing at sea surface and oceanic forcing at lateral boundary of the model domain, we use outputs of a climate model (MIROC) simulations. To test the sensitivity to climate, we use present-day Antarctic ice sheet/shelf configuration in all experiments.

Although global radiative forcing of LGM and CO_2 doubling climate are similar, change in basal melting amount under the CO_2 doubling climate is more pronounced than the LGM. Change in background climate modifies basal melt rate of ice shelves through changes in water mass properties on continental shelves. Active sea ice production in the Antarctic Coast forms cold and dense water on continental shelves under a colder climate. Under a warmer climate, decreased sea ice production and dense water on continental shelves enable warm deep water in the Southern Ocean to intrude onto continental shelves and increase basal melting. This behavior of the water mass properties on continental shelves is not well represented in the climate model with a coarse resolution. A series of sensitivity experiment shows that atmospheric heat-derived forcing is the most important to sea ice production and basal melt rate. These results suggest that basal melt rate of ice shelves is not simply parameterized from deep ocean temperature in the Southern Ocean, and that it is required to consider water mass formation process in the Antarctic Coast.

CLIMATE VARIABILITY AND ICE-SHEET DYNAMICS DURING THE LAST THREE GLACIATIONS

Obrochta, SP[1], Crowley, TJ[2], Channell, JET[3], Hodell, DA[4], Baker, PA[5], Seki A[6], Yokoyama[6], Y

1. *Faculty of International Resource Science, Akita University, Japan*
2. *Deceased*
3. *Department of Geological Sciences, University of Florida, USA*
4. *Department of Earth Sciences, University of Cambridge, UK*
5. *Division of Earth and Ocean Sciences, Duke University, USA*
6. *Atmosphere and Ocean Research Institute, University of Tokyo, Japan*

A composite North Atlantic record from DSDP Site 609 and IODP Site U1308 spans the past 300,000 years and shows that variability within the penultimate glaciation differed substantially from that of the surrounding two glaciations. Hematite-stained grains exhibit similar repetitive down-core variations within the Marine Isotope Stage (MIS) 8 and 4–2 intervals, but little cyclic variability within the MIS 6 section. There is also no petrologic evidence, in terms of detrital carbonate-rich (Heinrich) layers, for surging of the Laurentide Ice Sheet through the Hudson Strait during MIS 6. Rather, very high background concentration of iceberg-rafted debris (IRD) indicates near continuous glacial meltwater input that likely increased thermohaline disruption sensitivity to relatively weak forcing events, such as expanded sea ice over deepwater formation sites. Altered (sub)tropical precipitation patterns and Antarctic warming during high orbital precession and low 65°N summer insolation appear related to high abundance of Icelandic glass shards and southward sea ice expansion. Differing European and North American ice sheet configurations, perhaps aided by larger variations in eccentricity leading to cooler summers, may have contributed to the relative stability of the Laurentide Ice Sheet in the Hudson Strait region during MIS 6.

THE DEVELOPMENT OF 3D ICE SHEET MODELLING (ICIES) INCLUDING VISCOELASTIC BEDROCK DEFORMATION: IMPLICATIONS FOR THE RELATIVE SEA-LEVELS IN GREENLAND

Okuno, J[1], Saito, F[2], Abe-Ouchi, A[3,2,1], Takahashi, K[2]

[1]*National Institute of Polar Research*
[2]*Japan Agency for Marine-Earth Science and Technology*
[3]*Atmosphere and Ocean Research Institute, The University of Tokyo*

It is very important to determine the temporal variation of meltwater volume and the spatial extent of ice sheets from the Last Glacial Maximum (LGM) for studying the Quaternary climate changes and for constraining viscosity structure of the mantle. Typical melting histories of ice sheets since LGM have been inferred on the basis of geographical and geological constraints combined with the Glacial Isostatic Adjustment (GIA) modelling. However, such reconstructions have ice thickness that is unconstrained in regions from which the required geophysical and geographical data are unavailable and furthermore insufficient constraint that might support them to be glaciologically self-consistent. On the other hand, dynamical ice-sheet modelling produces physically self-consistent ice sheets which further constrain the history and spatial variations of the load, but have difficulties due to their high sensitivity to the various climate forcing as well as from uncertainties associated with basal processes and ice calving. In this study, we try to incorporate the spherically symmetric, self-gravitating, viscoelastic earth deformation to the 3D thermo-mechanical ice sheet model (Ice Sheet for Integrated Earth system Studies: $I_C IES$ developed by Abe-Ouchi et al. 2013) in order to constrain the ice load history using the geographical and geological observations. In this presentation, we show the characteristics of the ice sheet geometry using the viscoelastic bedrock deformation, and we show the relative sea-level predictions in the coastal region of Greenland based on the ice loading history derived from $I_C IES$.

THE LAST INTERGLACIAL AS A TESTBED FOR COUPLED CLIMATE-ICE SHEET MODEL SIMULATIONS OF PAST ICE SHEET AND SEA LEVEL EVOLUTION

Otto-Bliesner, BL

Climate & Global Dynamics, National Center for Atmospheric Research, Boulder, CO USA

The stability of the polar ice sheets under anthropogenic warming and their potential contributions to sea level rise over coming centuries and millennia is of considerable concern. The paleoclimate record highlights the susceptibility of ice sheets and sea level to higher polar temperatures. Past warm climate states are ideal proving grounds for models that are to be used for sea level projections. Thus, from a policy perspective, realistic simulation of previous warm periods lends confidence to assessments of future changes.

The Last Interglacial (LIG, 129,000 to 116,000 years ago) has been prominently featured in the last two IPCC WG1 assessment reports, including statements in the Summary for Policymakers of the AR4 and AR5. With new coupled ice sheet/climate models at many modeling centers, we now have the opportunity to more fully assess the coupled climate/ice-sheet interactions for determining the much higher than present sea levels of the LIG, the evolution of sea level during the LIG, and the timings and contributions of the Greenland, West Antarctic, and East Antarctic ice sheets to the LIG sea level. To do so from a modeling perspective, we need to consider the transient evolution of the forcings, not only the insolation anomalies associated with the large eccentricity and phasing of precession and obliquity and the well-mixed greenhouse gases during the LIG but also the effects of meltwater from the retreating ice sheets of the penultimate glaciation. In this talk, I will discuss previous model results on the sensitivities of these three ice sheets to interglacial warming, current sensitivity simulations with the CESM-CISM, and the design of future simulations to simulate the transient evolution of sea level during the LIG.

EVALUATING GREENLAND ICE SHEET MODEL PERFORMANCE AND PALEO RECONSTRUCTIONS OVER THE LAST GLACIAL CYCLE

Robinson, A[1,2,3], Alvarez-Solas, J[1,2], and Montoya, M[1,2]

[1]*Complutense University of Madrid, Madrid, Spain*
[2]*Instituto de Geociencias, CSIC-UCM, Madrid, Spain*
[3]*Potsdam Institute for Climate Impact Research, Potsdam, Germany*

Estimating the past evolution of ice sheets is important for improving our understanding of their role in the Earth system and for quantifying their contribution to sea-level changes. Limited but significant paleo data and proxies are available to give insights into past changes that are valid, at least, on a local scale. Meanwhile, models can be used to provide a mechanistic picture of ice sheet changes. Combined data-model comparisons are therefore useful exercises that allow models to be confronted with real-world information and lead to better understanding of the mechanisms driving changes. In turn, models can potentially be used to validate the data by providing a physical explanation for observed phenomena.

Here we focus on the evolution of the Greenland ice sheet through the last glacial cycle to highlight common problems and potential opportunities for data-model comparisons. We will present examples of how present generation model results are inconsistent with estimates from paleo data, either in terms of the boundary forcing given to the model or the resulting characteristics of the ice sheet. We also propose a set of data-model comparisons as the starting point for developing a more standardized paleo model performance check. Incorporating such a test into modeling efforts could generate new insights in coupled climate – ice sheet modeling.

Last Interglacial sea level in the Mediterranean Sea: field data, tectonics and isostatic adjustment

Rovere A. (1,2) Stocchi P. (3), Antonioli F. (4), Ferranti L. (5), DeBoer, B.(3), Lorscheid T. (1)

1 MARUM, University of Bremen & Leibniz Center for Tropical Marine Ecology (ZMT), Leobener Str., 28359 Bremen, Germany

2 Lamont Doherty Earth Observatory, Columbia University, 61 Route 9w, Palisades 10964, USA

3 NIOZ, Department of Physical Oceanography, Texel, The Netherlands

4 ENEA, via Anguillarese 301, 00060, S. Maria di Galeria, Rome, Italy

5 DiSTAR - Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse Università di Napoli "Federico II", Largo S. Marcellino 10, 80138, Naples, Italy

The shoreline pertaining to the last Interglacial (MIS 5e) has been extensively used as a benchmark for constraining tectonic displacements, especially in active geodynamic setting such as the Mediterranean. Here, MIS 5e deposits have been studied since the 19^{th} century, with several hundreds of sites where markers of the MIS 5e shoreline have been recognized and mapped. The advantage of studying the Mediterranean is that, with its relatively low tidal ranges and low-intensity wave action (when compared to oceanic areas), the depositional ranges of sea level markers are usually narrower than elsewhere, and this translates into lower uncertainties in paleo sea-level reconstruction.

Usually, tectonic rates have been calculated from the observed elevation of the MIS 5e shoreline using the following relationship: *Tectonic rate (m/Kyr) = [Observed paleo RSL and associated error (m) - Eustatic sea level (7±3 m)] / (124±5 Kyr).* This equation contains intrinsically two main assumptions: the first is that the glacio-isostatic adjustment difference between MIS 5e and today is negligible and the second, more subtle, that the peak eustatic sea level does not change throughout the interglacial and is not regionally variable.

In this study we revise classical MIS 5e sites in the Mediterranean Sea in places where the local tectonic contribution is considered very mild, attributing to each RSL marker an indicative range and a reference water level based on the descriptions of the original authors and modern analogs. At some sites we performed fieldwork with high-accuracy GPS. We compare our results with different scenarios of predicted sea level obtained from a coupled GIA-ice sheet model. We show that vertical variations may have occurred at these sites without the need to invoke tectonic displacement and we argue that GIA and spatial variability of ESL cannot be neglected in MIS 5e studies in the Mediterranean sea.

DEVELOPMENT OF NUMERICAL ICE-SHEET MODEL IcIES AND ITS APPLICATION OF ANTARCTIC AND GREENLAND ICE SHEETS

Saito, F[1], Abe-Ouchi, A[2,1] and Takahashi, K[1]

1 Japan Agency for Marine-Earth Science and Technology
2 Atmosphere Ocean Research Institute, University of Tokyo

Ice sheet model for Integrated Earth-system Studies (IcIES) has been developed to simulate Greenland and Antarctic ice sheets as well as paleo-climate studies of past Northern Hemisphere ice sheets.

Now we have been restructuring and improving the model to implement the shallow-shelf approximation as well as a grounding-line flux parameterization (based on Schoof 2007) for better understanding of past/future evolution of ice sheets. In this study details of recent structure of the numerical model is described. Demonstration under ideal and realistic configuration including Greenland and Antarctic ice sheets are presented. Impact on the simulation by variation of technical details such as a convergence criteria in the matrix solver is described to show the influence of long-term simulations.

CORAL REEF RESPONSE TO ABRUPT SEA-LEVEL RISE IN HAWAII: IMPLICATIONS FOR UNDERSTANDING GLOBAL REEF RECORDS AND DEGLACIAL MELTWATER HISTORY

Sanborn, KL[1], Webster, JM[1], Yokoyama, Y[2], Eggins, SM[3], Braga, JC[4], Dutton, A[5], Clague, DA[6], Paduan, JB[6], Rooney, JJ[7,8], Hansen, JR[8], Wagner, D[8,9]

[1]Geocoastal Research Group, Department of Geosciences, University of Sydney, Sydney, NSW 2006, Australia, ksan2228@uni.sydney.edu.au; [2]Atmosphere and Ocean Research Institute, University of Tokyo, Tokyo 113-0033, Japan; [3]The Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia; [4]Department of Stratigraphy and Paleontology, University of Granada, Campus de Fuentenueva, 18002 Granada, Spain; [5]Department of Geological Sciences, University of Florida, Gainesville, FL 32611, United States of America; [6]Monterey Bay Aquarium Research Institute, Moss Landing, California 95039, United States of America; [7] Joint Institute for Marine and Atmospheric Research, University of Hawaii, Honolulu, Hawaii 96822, United States of America; [8]Association for Marine Exploration, Honolulu, Hawaii 96816, United States of America; [9]Papahānaumokuākea Marine National Monument, Honolulu, Hawaii 96818, United States of America.

Fossil reef records have been used as key evidence for studying glacio-eustatic sea-level change and quantitatively constraining last deglacial meltwater pulses (MWP). However, controversy still exists over the precise timing, magnitude and meltwater source of these abrupt sea-level rise events. Previous studies from drowned reef terraces in Barbados suggest MWP-1A occurred between 14.2-13.8 ka; however, these results are inconsistent with recent reef data from both Tahiti and Hawaii, which suggest it occurred at least 500 years earlier at ~14.7 ka. A field campaign was conducted in summer 2013 on Hawaii, in which human divers collected 30 samples off of the reef crests of four drowned terraces between -50 and -150 mbsl. The 32 new accelerator mass spectrometry radiocarbon (AMS-C14) and corresponding laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) ages have been combined with 35 existing ages to investigate the rate and amplitude of deglacial sea-level rise. The new ages and reinterpreted existing dates provide temporal constraints on the -150 m Hawaiian reef drowning

and backstepping in response to an abrupt rise in sea-level. The shallow-water coral-algal assemblages are encrusted by intermediate to deep coralline algal growth, which provides supportive evidence for the reefs having drowned. The lithologic data were integrated with dive observations and island-wide bathymetry and backscatter data, and show that the reef terraces are multi-generational features with complex growth and backstepping histories in response to reaching critical drowning depths. A robust suite of criteria has been established to reinterpret existing global reef records from Tahiti, Barbados, Vanuatu, Papua New Guinea, and the Great Barrier Reef, allowing for standardized paleoenvironmental interpretations of coral-algal assemblages and drowning signatures. Based on this global meta-analysis, improved constraints on MWP-1A will be discussed.

USING SURFACE EXPOSURE AGES TO TEST DEGLACIAL ICE SHEET MODELS: A GREENLAND TEST CASE

Sinclair, G.[1], Carlson, A.E.[1], Lecavalier, B.S.[2], Milne, G.A.[3], Mathias, A.[1], Buizert, C.[1], DeConto, R.M.[4]

[1]Oregon State University, USA [2]Memorial University, Canada, [3]University of Ottawa, Canada, [4]University of Massachusetts, Amherst, USA

Over the past two decades, the rapid expansion and improvement of surface exposure dating has enabled increasingly detailed and precise studies of past glacial behavior. For large ice sheets, exposure ages provide a unique opportunity to directly test ice-sheet deglacial models; unlike other dating methods, surface ages potentially give an accurate age of ice retreat from a location, instead of a relative or minimum-limiting age. In addition, most paleo-ice sheet models are calibrated with sea-level data, so ice-sheet margin dates represent a fully independent method for testing models. Here, we use the deglacial Greenland Ice Sheet as a case study to demonstrate how ^{10}Be surface exposure ages can be used to test ice sheet models. First, we present a database of the more than 500 published ^{10}Be ages from around the ice sheet margin, with all ages re-calculated consistently with the most up-to-date production rates and scaling schemes, so they can be compared with each other and other ice-margin dates.

Next, we outline a new method for using the ^{10}Be database for verifying ice sheet methods. Our approach averages ^{10}Be ages by model gridcell, to account for spatial limitations of the models. We compare the database with two recent deglacial ice sheet models: the Huy2 model (Simpson et al. 2009) and its successor the Huy3 model (Lecavalier et al. 2014). While overall the model and ^{10}Be ages match for the ice sheet, significant spatial variability observed in the ^{10}Be ages is absent from model simulations. In particular, ^{10}Be ages suggest the eastern and southern sectors of the ice sheet began to retreat onto land before the Younger Dryas, while the west Greenland Ice Sheet begins regional terrestrial retreat only after the Younger Dryas. In contrast, the models show more homogenous deglaciation immediately following the Younger Dryas. These discrepancies may be due to relatively low model spatial resolution or the absence of the direct effect of ocean warming on ice sheet retreat in ice-sheet models.

Finally, we outline several avenues for future model-data comparison using ice margin records. These include using information about ice-sheet erosivity contained in the ^{10}Be outliers that contain inherited nuclides to identify where cold-based ice may have been more prevalent over the last glacial cycle, and using minimum-limiting ^{14}C ages to test ice sheet models in areas where ^{10}Be ages are not available. As publication of more ice-margin ages and model simulations continues, the database and methodology presented here will enable rapid independent verification of ice sheet margins.

A STATISTICAL RE-ASSESSMENT OF MULTIPLE FAR-FIELD DEGLACIAL SEA-LEVEL RECORDS

Stanford, J.D.[1]; Hibbert, F.[2]; Williams, F.[2]; Beaulieu, C.[2]; Rohling, E.J.[3]; Tamisiea, M.[4]

[1] Dept. of Geography, Swansea University, SA2 8PP, UK; [2] National Oceanography Centre, Southampton; Dock Gate 4, Southampton, SO14 3ZH; [3] ANU College of Physical and Mathematical Sciences, Australian National University, Acton 0200, Canberra, Australia;[4] National Oceanography Centre, University of Liverpool, Joseph Proudman Building, 6 Brownlow Street, Liverpool, L3 5DA, UK

Large deglacial freshwater events, or meltwater pulses, offer test-beds for theoretical models of oceanic circulation, and hence climatic responses to them. Meltwater pulse (MWP)-1a is believed to have occurred post Northern Hemisphere deglacial inception, between 14.2 and 14.5 ka BP (thousands of years Before Present), and to have involved approximately 20 m of sea-level rise over a 500 yr period. Since MWP-1a first appeared in the literature, greater clarity has been gained on the multiple unknowns and uncertainties that now add considerable complexity to a precise dating of this event. These uncertainties cover, but are not restricted to, unknowns inherent to the proxies involved, such as uplift rates in non tectonically stable environments, the depth-habitat of fossilised coral species, the responses of corals under stress, reworking of submarine material, or the splicing of multiple core archives.

Constraint of the MWP-1a event, as well as the contested MWP-1b (at ~11.2 ka BP), is key to our understanding of the forcings and feedbacks of the AMOC system. Here we update the 2011, Stanford et al. Monte Carlo statistical assessment of the probability distribution of the uncertainties in multiple, far-field sea-level records. Our new and unique approach models uncertainties using a change-point analysis that identifies common inflexions in multiple sea-level records, and hence allows for extraction of statistically discernible meltwater pulses. We incorporate uncertainty arising from glacial isostatic adjustment by developing a 'possibility polygon' for each data point. For a given ice history, this polygon describes all potential glacial isostatic corrections within the dating error of the sample, and variation of the parameters used to describe a spherically symmetric visco-elastic earth model. This is only now made feasible due to (i) the addition of new records from Tahiti by Deschamp et al., and (ii) an enhanced understanding of the treatment of data.

FOUR RECORDED RELATIVE SEA-LEVEL HIGHSTANDS BEFORE THE MID-PLEISTOCENE TRANSITION

Stocchi P.[1], Antonioli F.[2], Montagna P. [3,4], Pepe F.[5], Lo Presti V. [2], Caruso A. [5], Renda P. [5], Frank N. [6], Douville E. [4], Pierre C. [7]

[1]NIOZ, Royal Netherlands Istitute for Sea Research, [2]ENEA, Casaccia, Roma, Italy , [3]ISMAR-CNR, Bologna, Italy, [4]LSCE, Gif-sur-Yvette, France, [5]Dipartimento di Scienze della Terra e del Mare, Università di Palermo, Italy, [6]Universität Heidelberg, Heidelberg, Germany ,[7]LOCEAN, Jussieu, Paris Cedex, France

During the past million years the earth's climate has evolved through an alternation of extended glacial periods and relatively short-lived interglacials. Accordingly, the global mean sea-level (msl) has fluctuated in pace with the waxing and waning of continental ice sheets, as recorded by proxy records from deep-sea sediment cores. Glacial isostatic adjustment, geodynamics and local tectonics contributed to vertical movements and gravitational perturbations that left a regionally varying signal of relative sea-level (rsl) change. Absolutely-dated rsl markers for periods older than the Last Interglacial are rare. Here we present a geological evidence of four early Pleistocene marine transgressions that have been recorded by a stalactite recovered at ~ 100 m above msl from a karst cave that is located in the North West Sicily (NWS) coast (Italy). The nearby occurrence of post-middle Pleistocene coastal terraces presently distributed around the NWS at elevations up to ~160 m indicates that the NWS experienced sustained Quaternary long-wavelength uplift that led to the interception of the cave with the fluctuating sea-level. The formation and preservation of the cave and speleothem benefited from a shift from horizontal and short-wavelength, to vertical long-wavelength tectonic movements. Within the speleothem, three concentric hiatuses mark consecutive marine ingressions that occurred between 1.274 and 1.159 Ma and correspond, respectively, to Marine Isotope Stage (MIS) 39, 37 and 35. An outer coral overgrowth, which sealed the entire stalactite and draped the cave ceiling, formed during the MIS 31 marine transgression and right before the mid-Pleistocene transition. An attempt was made to directly date the spelean carbonate through the U/Th dating technique. The U/Th ages of two carbonate pieces extracted from the innermost and outermost layers of the stalactite fell beyond the upper limit of the ^{230}Th age range. Based on these results, the age of the stalactite was indirectly determined by dating the coral overgrowth. Three small fragments collected from three different coral specimens encrusting the stalactite were analysed for Sr isotopes. The $^{87}Sr/^{86}Sr$-derived ages are identical within uncertainty and give an average age of 1.124±0.2 Ma (±2σ SD). This implies that the coral portions, which were carefully selected from the internal part of the coral thecal wall, were most likely pristine and the ages are reliable and in agreement with the U/Th ages of the continental layers beyond the upper limit of the U-series chronometer. The continental layers of the stalactite are composed of calcite, with $\delta^{18}O$ values ranging between -4.24 and -1.32‰ . This range is narrower than the $\delta^{18}O$ variation (~ 4‰) observed in a speleothem dated at ~ 175 ka from the Argentarola cave. In addition, the $\delta^{18}O$ values of the Argentarola stalagmite are significantly lower, with values as low as ~ -7.5‰. Being located very close to the sea in the Central Mediterranean it is very likely that both caves shared similar climatic and altimetric conditions. Therefore, the difference in the d $\delta^{18}O$ range is the result of a climatic configuration characterized by milder transgressive-regressive phases during the early

Pleistocene compared to the mid and late-Pleistocene. This supports an early Pleistocene age of the stalactite, in line with the radiometric dating.

SOUTHERN HEMISPHERE CLIMATE DRIVERS FOR ANTARCTIC ICE-SHEET VARIABILITY

A. Timmermann[1], M. Tigchelaar[1], D.Pollard[2], T. Friedrich[1]

[1]*IPRC, SOEST, University of Hawaii, Honolulu, HI, USA*
[2]*EMS Earth and Environmental Systems Institute, Pennsylvania State University, University Park, PA, USA*

Using a 784 ka-long transient climate model simulation, we identify the dominant orbital-scale mechanisms that are responsible for generating sub-surface temperature changes around Antarctica. CO_2 and precessional forcing cause massive changes in the extent and seasonality of Southern Ocean sea ice which in turn affect Southern Ocean upwelling and poleward heat and salt transport. The response of the Antarctic ice-sheet to the simulated changes in subsurface temperatures, surface accumulation, ablation and sea level are estimated using the Penn State ice-sheet model. The overall Antarctic ice-sheet evolution over the past 800 ka is largely controlled by the balance between CO_2 and obliquity-paced accumulation, surface ablation and basal melt. Mass loss through subsurface oceanic melt and sea level-driven calving plays a key role in the Weddell and Ross Seas.

The presentation will further highlight the sensitivities of the Antarctic ice-sheet to individual radiative perturbations (orbital and greenhouse gases), by using respective transient LOVECLIM single forcing experiments as boundary conditions for the Penn State model.

CONSTRAINING MID-HOLOCENE EUSTATIC RISE BY COMBINING WELL-DATED SEA-LEVEL RECORDS FROM SCANDINAVIA AND GLOBAL ICE SHEET MODELING

Vasskog, K[1], Svendsen, JI[1], Mangerud, J[1], Hughes, ALC[1], Tarasov, L[2]

[1]*Department of Earth Science and Bjerknes Centre for Climate Research, University of Bergen, Norway*
[2] *Department of Physics and Physical Oceanography, Memorial University, Canada*

The Late-glacial and Holocene relative sea-level changes in Scandinavia are mainly the combined results of glacio-isostatic uplift, eustatic sea-level changes, and temporal deformation of the geoid in response to changing ice sheet configurations. An increasing number of well-constrained relative sea-level (RSL) curves are becoming available from southern- and western Norway. Here we attempt to isolate the eustatic component by removing the effects of local land uplift and geoidal changes using an integrated data-modeling approach.

The sea-level curves from the outer Norwegian coast show a distinct sea-level rise from 10 ka until about 7 ka BP, known as the Tapes transgression. Subsequently the relative sea level has dropped until the present time, showing that glacio-isostatic uplift has been the dominating factor over the last 7 ka. However, in many of the Norwegian RSL records the rate of sea-level fall is observed to accelerate around 4-3.5 ka BP. Changes in shoreline configuration indicate that the rate of land uplift decreased exponentially after the Scandinavian Ice Sheet (SIS) retreated from its Younger Dryas position around 11.5 ka BP, and this implies that eustatic sea level must have continued to rise after 7 ka BP, although at a slower pace than before. The increasing rate of sea level fall in the Norwegian RSL records around 4-3.5 ka BP is therefore interpreted to reflect that eustatic sea level rise finally ceased, and following this point in time the RSL records are thought to reflect a more-or-less pure land uplift signal. Our results are based on an approach combining empirically reconstructed shorelines with global ice sheet modeling, where the modeling is used to determine e.g. geoidal changes as a result of local and global ice sheet configurations.

The SIS had vanished before the onset of the Tapes transgression and thus meltwater from this ice sheet could not have contributed to the recorded sea level rise. Considering that the North American ice sheet was gone by around 7 ka BP, we suggest that the eustatic rise between 7 and 3.5 ka BP must stem mainly from ice-sheet melting in Antarctica. A more precise finger-printing of the source of this eustatic rise could be accomplished by applying the same approach using RSL data from other regions of the world.

EVALUATING THE POSSIBILITY OF SUB-ORBITAL SEA LEVEL OSCILLATIONS USING SEDIMENTOLOGY, BIOTIC ASSEMBLAGES AND STRATIGRAPHY OF MARINE ISOTOPE STAGE 5E REEFS FROM THE SEYCHELLES

Vyverberg, K.[1], Dechnik, B.[2], Dutton, A.[1], Webster, J. M.[2], Zwartz, D.[3]

[1]*University of Florida, Gainesville, Florida, USA,* [2]*University of Sydney, Sydney, New South Wales, Australia,* [3]*Victoria University of Wellington, Wellington, New Zealand*

The granitic Seychelles islands are located far from the former margins of Northern Hemisphere ice sheets, and hence provide a relative sea level history that approximates that of global mean sea level. While recent work in the Seychelles has focused on constraining the peak sea level recorded during Marine Isotope Stage (MIS) 5e in the Seychelles, here we focus on assessing the potential for dynamic ice sheet changes during the sea level highstand. Such sub-orbital sea level oscillations have been posited based on observations of other MIS 5e sedimentary sequences (e.g., Bahamas, Red Sea, Western Australia, Yucatan Peninsula), but interpretations of these rapid sea level changes remain debated and inconsistent from site to site.

Around the granitic Seychelles islands, corals and other reef biota nucleate directly on the sheer faces of granite boulders, and the reef accretes upwards and in some cases also laterally. Remnants of the MIS 5e coral reef are preserved where overhangs provided by granite boulders have protected them from weathering. These reefal units are generally heavily encrusted by coralline algae, which are commonly found in association with vermetids and encrusting foraminifera. Here we rely upon the stratigraphic relationships and successions of coralgal assemblages with distinct paleoenvironmental constraints (e.g., exposure, paleowater depth) and on observations of sedimentary features to interpret the depositional history of the reef with particular focus on inferences of the past position of local relative sea level.

In multiple outcrops we observed a hardground that consists of a fine-grained sediment layer that is rich in coral barnacles between distinct reef units of in situ coralgal reef framework. One outcrop contains two vertical successions of a reef framework unit capped by the fine-grained hardground. All of the other outcrops we studied contained a common succession of facies from in situ reef units overlain by cemented coral rubble.

We also observed four distinct coral assemblages within the in situ reef units, one of which commonly occurs at the top of the sequence within each outcrop. These assemblages are compared to observations of modern assemblages to aid in the interpretation of paleowater depth, in particular. The potential for meter-scale sub-orbital sea level oscillations is evaluated in the context of these observations, and compared to sedimentary evidence from other MIS 5e reefs around the globe.

On the Climatic lead of the Southern Hemisphere in Termination-II and the Last Interglacial

Matt Whipple[1], Dan Lunt[1], Joy Singarayer[2]

1 Department of Geographical Sciences, University of Bristol
2 Department of Meteorology, University of Reading

Recent data studies are firmly suggesting the significant discrepancies between Termination-I and Holocene, and Termination-II and Last Interglaciation (LIG). Although vast numbers of studies have just assumed that climate is a slave to 65°N insolation, data is slowly unraveling this assumption, showing a small but significant Southern Hemispheric lead to sea-level contribution during Termination-II, beginning with a contribution during Southern Hemisphere insolation maximum. HadCM3 climate modeling is able to reproduce this Southern Hemisphere lead through Termination-II, and here we explore the climate feedbacks in this system.

A series of HadCM3 snapshot scenarios generates a 2 kyr Antarctic lead to warming relative to present through Termination-II and LIG. However, for the Southern Hemisphere, a significant seasonality is notable, with ten months of the year simulated as colder than preindustrial, but with October/November temperatures up to five degrees above present, producing a net annual warming. Significantly reduced Antarctic cloud during these months results in reduced sea ice coverage, and higher humidity, allowing for net Southern Hemisphere warming, of the Southern Ocean in the austral summer months, and fast retreat of the Antarctic Ice Sheet. We examine this signal, and compare to that produced during Termination-I and the Holocene.

Although much has been made of past response to warmer climates, here, we start to examine this applicability of past climates with respect to understanding future climate, and therefore gain understanding as to why sea level has been able to rise at such a significant rate in past transient climates.

SCENARIOS FOR VARIATION OF THE MIS 6 EURASIAN ICE SHEET

Williams FH[1], Hibbert FD[1], Rohling EJ[1,2] , Tamisiea ME[3], Grant KM[2]

1. Ocean and Earth Science, National Oceanography Centre, University of Southampton, UK
2. Research School of Earth Sciences, The Australian National University, Canberra, Australia
3. National Oceanography Centre, Liverpool L3 5DA, UK

The Hanish and Camarinal sills are key locations for the generation of the Red Sea and the Mediterranean Sea relative sea level (RSL) curves, respectively. Although the response to glacial isostatic adjustment at both sills is complex, we can describe the first order relationship between RSL and changes in global mean sea level to be linear. These curves therefore provide us with an insight into changes in global ice volume. To improve our reconstructions of global ice volume we need to further understand the impact of different configurations of ice volume.

The Eurasian ice sheet is believed to have achieved a greater extent and volume during MIS 6 than at the last glacial maximum, though achievement of maximal extent is not thought to be synchronous across all locations. We find that RSL modelled at both the Hanish and the Camarinal Sills displays a different response between changes in ice volume in the far field, e.g. Laurentide and Antarctic ice sheets, and ice volume changes over Eurasia. The first order response for the Eurasian ice sheet is such as to reduce the amplitude of RSL changes when compared with RSL changes driven by an identical ice volume change in a far field location over the period of a glacial cycle. Further complexity is seen in the response of the Camarinal Sill to large Eurasian ice volume changes, and we work to constrain this behaviour.

We use a newly developed database of dated glacial extent markers and a glacial isostatic adjustment model to develop some scenarios of ice volume change across Eurasia. These scenarios are incorporated into global ice volume histories constructed using the Red Sea and the Mediterranean Sea relative sea levels to test the impact on reconstructions of global ice volume through MIS 6 and MIS 5.

HOLOCENE ANTARCTIC MELTING HISTORY AND LONG TERM PLATE BOUNDARY TECTONICS INFERRED FROM SEA LEVEL OBSERVATION IN SOUTHWESTERN JAPAN

Yokoyama, Y[1,2], Miyairi, Y[1], Maeda, Y[3], Okuno, J[4] , Kosuge, T[5]

[1]Atmosphere and Ocean Research Institute, University of Tokyo, Tokyo 113-0033, Japan; [2] Department of Biogeochemistry, Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushima-cho, Yokosuka 237-0061, Japan; [3] Institute of Environmental Science, University of Hyogo, Kobe, Hyogo 651-2197, JAPAN; [4] National Institute of Polar Research, Tachikawa, Tokyo 190-8518, JAPAN; [5] International Society for Mangrove Ecosystems c/o Faculty of Agriculture, University of the Ryukyus, Nishihara, Okinawa 903-0219 JAPAN.

Relative sea level deduced from fossil oysters and mangroves are reported for Iriomote Island, Ryukyus, southwestern Japan. Radiocarbon-dated fossil oysters, as well as previously analyzed mangrove muds, are compared to geophysical and glacio-hydro-isostatic adjustment (GIA) models that describe Earth deformation due to changing surface loading. The Holocene-high-stand (HHS) inferred from oyster fossils (*Saccostrea echinata* and *Saccostrea malaboensis*) is 2.7 m at ca. 3,500 years ago, after which sea level gradually fell to present level. The HHS magnitude attributed to GIA for the last ca. 4,000 is between 1 - 1.5 m above present day sea level, and the residual indicates the long-term lithospheric uplift rate of the island. Given that meltwater contributions from the major North American and European ice sheets had largely ceased by 7,000 years ago, these independent lines of evidence, taken together, indicate that major melting of the Antarctic ice sheet ended by 4,000-3,000 years ago and is consistent with the record obtained from northern Japan (Yokoyama et al., 2012) as well as other geophysical studies (eg., Mitrovica et al., 2006).
Iriomote Island is located in the southern Ryukyus where the Okinawa trough is expanding northward and the Philippines Sea Plate (PSP) is subducting in south. Global positioning system (GPS) measurements indicate northward movement of the PSP at up to 8 cm/year. The status of plate coupling (strong or weak) in the region is not well understood, which has implications for the likelihood of future large thrust-related earthquakes (Mw > 8). In 1771 AD, a tsunami in the southern Ryukyus caused approximately 12,000 casualties, but no other devastating tsunami of similar size are recorded in historical documents. However a number of large boulders casted onshore by tsunamis (tsunami boulders) have been dated by both radiocarbon and Uranium series methods, indicating a recurrence time of 150-400 years over the last 2,400 years in the southern Ryukyu (Suzuki et al., 2008; Araoka et al., 2013). Long-term tectonic implication according to the sea level data is also discussed (cf. Yokoyama et al., 2015).

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THE EFFECT OF ICE SHEETS ON CLIMATE IN EARLY HOLOCENE

ZhangY[1 & 2] RenssenH[2] & SeppäH[1]

1 Department of Geosciences and Geography, University of Helsinki,P.O.BOX 64,FI00014 Helsinki, Finland
2 Faculty of Earth and life Sciences, VU university Amsterdam, De Boelelaan 1085,1081 HV Amsterdam, Netherlands

The Holocene is characterized by a good understanding of forcing factors and by the high number of proxy-based reconstructions which allow us to study the mechanisms behind the Holocene climate changes. Early Holocene was a critical transient period from the deglaciation to the relative stable Holocene climate. The Younger Dryas and the 8.2 ka cooling events represent the abrupt climate changes typical to the glacial-interglacial transition. These two events have been well studied, using both proxy-based reconstructions and from the model simulations.

It is generally accepted that the ice sheets have played an important role in triggering these events. For instance, the effect of melt water flux has been studied by using several models in which different amounts of freshwater have been introduced at varying locations and flow rates. Climatic response to the ice sheets before 9 ka is, however, still an open question.

In this paper, we employ an earth system model of intermediate complexity LOVECLIM to attempt to disentangle how the different forcing factors contributed to the climate change. We use various experiments focusing on a variety of forcing combinations. Finally, the simulation results are compared with some proxy records to validate the reliability of the model results. Our results suggest that apart from the orbital forcing and greenhouse gases, the appearance of ice sheets and its dynamics contributed to the temperature in the early Holocene. The flat ice sheets cool down the temperature up to 2-4 ℃ at the limited local scale (e.g in Scandinavia and Laurentide regions). By contrast, the elevation of ice sheet produces stronger cooling over larger area.. The fresh water produced by the ice sheet deglaciation influence the ocean circulation by slowing it down. Albedo that is related to the ice coverage, surface dynamics associated with vegetation, atmosphere circulation and ocean circulation due to freshwater flux have all played an essential role in the early Holocene climate, especially in the high latitudes.