Workshop

PALSEA - SERCE

Improving understanding of ice sheet and solid earth processes driving paleo sea level change

Organizers: Jacqueline Austermann (PALSEA) and Alexander Simms (SERCE)

Cite this volume as: Improving understanding of ice sheet and solid earth processes driving paleo sea level change (2021). Austermann, J. and Simms A. (Eds.). PALSEA-SERCE virtual workshop, 13-16 September 2021.

Workshop rationale

This meeting will focus on developing a better understanding of the physical processes that drive ice sheet collapse and solid earth deformation. These processes are highly uncertain due to a lack of observational constraints, yet they are the dominant drivers for local sea level change. Overcoming this uncertainty requires drawing from observations and expertise from a variety of fields complementary to PALSEA and SERCE including rheology, hydrology, glaciology, and geodesy. In this meeting, we aim to bring empiricists and modelers from the sea level and ice sheet communities together in order to unify solid Earth deformation and ice sheet evolution across time and spatial scales. Pairing our improved understanding of physical processes with enhanced paleo datasets will allow us to narrow in on ice sheet contributions to past and future sea level rise.

Scientific program

General information

Presentations will be 18 mins + 2 mins for questions, followed by time for further discussion at the end of each session.

Posters: We request that each poster presenter records a 2-minute summary talk on your poster to be shown Tuesday and Wednesday immediately preceding the poster session as a way to advertise your poster. Please save the recorded talk as a MP-4 file. Recordings can for example be done via powerpoint or zoom. During the poster session we plan on presenting the posters via "sharing your screen" through zoom. We ask that you set up a link to a zoom meeting from 11:30 am to 12:30 pm US Eastern Time on the day of your poster presentation (either Tuesday, September 14th or Wednesday, September 15th - see the program). If you have trouble or need help setting up the zoom or making the recording, please let us know. Please email your MP-4 file and zoom link to N.L.M.Barlow@leeds.ac.uk AND asimms@geol.ucsb.edu by 12:00 pm Eastern on September 9th.

Please note all talks and the poster "speed dating" sessions will be recorded unless the speaker asks not to be in advance.

Timetable

All times are in Eastern Standard time.

Monday September 13th

Session 1. Palaeo ice sheets and their mass balance

Starting at 8.30 AM EDT - Find time in your timezone

Time (EDT)	Speaker	Title
8.30		Welcome and Introduction
8.40	Marie-France Loutre	Past Global Changes celebrating its 30th Anniversary
8.55	Lauren Gregoire (invited)	Simulating past ice sheet collapse to prepare for the future
9.15	Benoit S. Lecavalier	History matching analysis of the Antarctic ice sheet evolution over the last glacial cycle
9.35	Natalya Gomez	Resolving GIA in response to modern and future ice loss at marine grounding lines in West Antarctica.

9.55	Sophie Coulson	The Global Fingerprint of Modern Ice-Mass Loss on 3-D Crustal Motion
10.15		Discussion
10.25		Break
10.50	Christopher Halsted	Rapid Laurentide Ice Sheet mass loss (and associated sea level rise) during the Bølling/Allerød constrained by 10Be elevation transects in the northeastern United States
11.10	Oliver Pollard	Reconstructing the MIS 6 Eurasian Ice Sheet to Improve Our Understanding of Last Interglacial Sea-Level Change
11.30	Ana Carolina Moraes Luzardi	Effect of topography and isostatic adjustment on Antarctic Ice Sheet evolution using a simple ice sheet model
11.50	Anna Glueder	Paleo ice history of Petermann Glacier, NW Greenland, constrained by relative sea level and isostatic adjustment modeling
12.10		Discussion
12.30		End of day 1

Tuesday September 14th

Session 2. Palaeo sea-level and ice sheet data

Starting at 8.30 AM EDT - Find time in your timezone

Time (EDT)	Speaker	Title
8.30	Tanghua Li	Deglacial relative sea-level changes and Glacial Isostatic Adjustment modelling in the Russian Arctic
8.50	Danielle LeBlanc	Northern Hemisphere ice sheet persistence across Pleistocene interglacials
9.10	Udita Mukherjee	Partitioning early Holocene North American v. Antarctic ice melt from high-resolution reconstructions of sea-level rise and glacial isostatic adjustment modeling
9.30	Andrew Christ	Resolving the global mean sea level budget during MIS 11: direct terrestrial evidence for an ice-free northwest Greenland in the Camp Century subglacial sediment
9.50		Discussion
10.00		Break
10.20	Kerry Callaghan (invited)	Incorporating lake and groundwater volumes into global sea-level estimates during the deglaciation
10.40	Surendra Adhikari (invited)	Reconciliation of the Paleo Sea-level Record with Modern Crustal Uplift of Greenland
11.00		Poster overview 1
11.30		Virtual poster session 1
12.30		End of day 2

Wednesday September 15th

Session 3. Glacial Isostatic Adjustment

Starting at 8.30 AM EDT - Find time in your timezone

Time (EDT)	Speaker	Title
8.30	Matt King	Geodetic evidence for spatially-varying upper mantle viscosity along a 1000 km transect of the Antarctic Peninsula
8.50	Caroline van Calcar	The effect of GIA feedback on the evolution of the Antarctic Ice sheet over the last glacial cycle using a coupled 3D GIA – Ice Dynamic model
9.10	Wouter van der Wal	Stress-dependent viscosity in GIA models for Greenland and Antarctica
9.30	Parviz Ajourlou	Inference of 3D Earth structure beneath Greenland and eastern Canada using a joint inversion of regional datasets
9.50		Discussion
10.00		Break
10.20	Linda Pan	Rapid postglacial rebound amplifies global sea level rise following West Antarctic Ice Sheet collapse
10.40	Joerg Schaefer	GreenDrill Project overview and update
11.00		Poster overview 2
11.30		Virtual poster session 2
12.30		End of day 3

Thursday September 16th

Session 4. Glacial Isostatic Adjustment

Starting at 8.30 AM EDT - Find time in your timezone

Time (EDT)	Speaker	Title
8.30	Glenn Milne	Quantifying the influence of glacial isostatic adjustment on current and future sea-level change using 3-D Earth models
8.50	Andrew J Lloyd	3D Viscosity Inversions of Post-Glacial Deformation as Recorded by Relative Sea Level: Proof of Concept
9.10	Evelyn Powell	Exploring the Resolving Power of Antarctic Datasets Using the Adjoint Method: A Novel Route to Improving GIA Models
9.30	Rene Gassmoeller	Benchmarking and output sharing - lessons learned from the geodynamics community

9.50		Benchmarking discussion
10.20		Break
10.40	Kaixuan Kang	The Effects of Non-Newtonian Rheology in the Upper Mantle on Relative Sea Level Change and Geodetic Observables Induced by Glacial Isostatic Adjustment Process
11.00	Shijie Zhong	Can non-Newtonian rheology help reconcile far-field and near-field relative sea-level observations?
11.20	Erik R. Ivins	Island Subsidence During Melt Water Pulse Events and the Extended Burgers Model of Transient Mantle Rheology
11.40	Harriet Lau (invited)	Frequency Dependent Mantle Viscoelasticity via the Complex Viscosity: cases from Antarctica
12.00		Code and output sharing discussion
12.30		End of day 4

Session 1: Palaeo ice sheets and their mass balance

Past Global Changes celebrating its 30th Anniversary

Loutre, M.F. (1); Eggleston, S. (1)

(1) PAGES (Past Global Changes)

PRESENTATION

The PAGES (Past Global Changes) project is an international effort to coordinate and promote past global change research. The primary objective is to improve our understanding of past changes in the Earth system in order to improve projections of future climate and environment, and inform strategies for sustainability. PAGES is open and inclusive to all scientists interested in past global changes. Science within PAGES is conducted by working groups, which are open to all paleoscientists working on the topic.

Simulating past ice sheet collapse to prepare for the future

Gregoire, L. (1)

(1) University of Leeds

INVITED PRESENTATION

Ice sheet have undergone period of accelerated retreat in the past, sometime referred to as ice sheet collapse. The same physical mechanisms that caused these rapid changes will operate in the next few centuries leading to potentially devastating rates of sea level rise.

I will discuss the main mechanisms of ice sheet collapse focussing in particular on the saddle collapse mechanism, which involves a height-mass balance feedback. This occurs when two ice domes connected via an ice saddle separate to form distinct ice sheets. This causes an acceleration in surface melt in the ice saddle region that was likely a key process in producing the Meltwater Pulse 1a sea level rise, 14.5 thousand years ago and the 8.2 kyr cooling event.

Geological data describing past ice sheet collapses offers a goldmine of information that could be used to improve and constrain the numerical ice sheet models used for future sea level projections… if only we had a way to handle the complex uncertainties in the system. I will present our current efforts to combine coupled climate-ice sheet modelling and new Artificial Intelligence techniques to sample through uncertainties in past climate and ice sheet surface mass balance. Simulating the North American ice sheet at the Last Glacial maximum is already providing a challenging target for models of ice sheet surface mass balance.

History matching analysis of the Antarctic ice sheet evolution over the last glacial cycle

Lecavalier, B. (1); Tarasov, L. (1)

(1) Memorial University of Newfoundland

PRESENTATION

To better interpret contemporaneous change of the Antarctic ice sheet and to make improved predictions of its future sea-level contribution, reconstructions of past ice sheet evolution are required. A calibration of a glaciological model against paleo and present-day observational constraints offers a route to quantify uncertainty estimates. Transient continental-scale reconstructions over glacial cycles require glaciological models, but the latter depend on parameterisations to account for deficiencies inherent in any numerical model. Recent studies have explored parametric uncertainties with only a few ensemble parameters, this work is distinguished by a much stronger emphasis on quantifying all model uncertainties.

An updated Glacial Systems Model (GSM) is used to simulate the Antarctic ice sheet over the last glacial cycle using 36 ensemble parameters. An expanded Antarctic observational constraint database termed AntICEdat is applied to evaluate model performance. The constraint database consists of observations of past ice extent, past ice thickness, past relative sea level, ice core borehole temperature profiles, present-day uplift rates, present-day ice sheet geometry and surface velocity. The data-constrained large-ensemble analysis focused on history matching and involved over 30,000 full transient Antarctic ice sheet simulations. The GSM parameter space was explored through history matching using multi-million Markov Chain Monte Carlo sampling of Bayesian artificial neural network emulators. This study aims to carefully account for structural uncertainty when evaluating model results against observations. The key results of the history matching analysis are presented as confidence intervals of key metrics including the Antarctic equivalent sea-level contribution to the last interglaciation, LGM, and MWP-1a. The observational data does not rule out simulations that yield excess LGM volumes up to 25 mESL with respect to present-day. Moreover, as part of the analysis glacial isostatic adjustment parameters were also sampled to produce confidence intervals on present-day glacial isostatic adjustment estimates.

Resolving GIA in response to modern and future ice loss at marine grounding lines in West Antarctica.

Wan, J.X.W. (1); Gomez, N. (1); Latychev, K. (2, 3); Han, H.K. (1)

(1) Earth and Planetary Sciences Department, McGill University, (2) Department of Earth and Planetary Sciences, Harvard University, (3) Lamont-Doherty Earth Observatory, Columbia University;

PRESENTATION

Improvements to GIA models allow for computation of the viscoelastic response of the Earth to surface ice loading at sub-kilometre resolution and dynamic ice-sheet models and observational products now provide the inputs to GIA models at comparably unprecedented detail. However, the resolution required to capture GIA in models remains poorly understood, and high-resolution calculations come at heavy computational expense. We adopt a 3-D GIA model (Latychev et al., 2005) with a range of Earth structure models based on recent seismic tomography and geodetic data to perform a comprehensive analysis of the influence of grid resolution on predictions of GIA. We focus on the Amundsen Sea Embayment (ASE) in West Antarctica, where ice is underlain by laterally varying mantle viscosities that are up to several orders of magnitude lower than the global average, leading to a faster and more localized response of the solid Earth to ice sheet retreat. We begin by quantifying the relationship between the required grid resolution and the wavelength of ice loading changes through a suite of 85 sensitivity simulations adopting an elastic Earth model, sub-kilometer grid resolution and idealized, spatially isolated ice loading changes. We then move to considering more realistic, spatially coherent ice loss scenarios based on modern observational records (Shepherd et al., 2019) and future ice sheet model projections (Golledge et al., 2019; DeConto et al., 2021) with 3-D viscoelastic Earth structure from Lloyd et al. (2019). We find that errors of less than 5% along the grounding line can be achieved with a 7.5 km grid, and less than 2% with a 3.75 km grid, even when the input ice model is on a 1 km grid. Furthermore, by comparing simulations with elastic and viscoelastic Earth models, we show that low mantle viscosities beneath the ASE lead to viscous deformation that contributes to the instrumental record on decadal timescales and equals or dominates over elastic effects by the end of the 21st century. Our findings suggest that for the range of resolutions of 1.9-15 km that we considered, the error due to adopting a coarser grid in this region is

small compared to the effect of neglecting viscous effects and the uncertainty in the adopted mantle viscosity structure.

The Global Fingerprint of Modern Ice-Mass Loss on 3-D Crustal Motion

Coulson, S. (1,2); Lubeck, M. (1,3,4); Mitrovica, J. X. (1); Powell, E. (1); Davis, J. L. (5); Hoggard, M. (1,5,6)

(1) Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA. (2) Fluid Dynamics and Solid Mechanics Group, Los Alamos National Laboratory, Los Alamos, NM (3) Department of Geosciences, University of Arizona, Tucson, AZ. (4) Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA. (5) Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY. (6) Research School of Earth Sciences, Australian National University, Canberra, Australia

PRESENTATION

Crustal motion generated by rapid ice-mass loss from Earth's glaciers and ice sheets has previously been considered in GNSS analyses and numerical models across regions proximal to ice retreat. However, the fingerprint of recent ice-mass loss is not limited to glaciated areas, but is characterized by a global pattern of 3-D crustal deformation. We compute “far-field” vertical and horizontal deformation rates that occurred in response to early 21st century mass flux from the Greenland and Antarctic Ice Sheets, global glaciers and ice caps, and associated ocean loading. We demonstrate that mass changes in the Greenland Ice Sheet and high latitude glacier systems each generated average crustal motion of 0.1-0.4 mm/yr across much of the Northern Hemisphere, with significant year-to-year variability in magnitude and direction depending on the geometry and magnitude of ice-mass loss. Large north-south gradients in deformation rates are present across large areas of North America, Europe and Northern Asia, and horizontal motions associated with ice-mass loss exceed vertical rates in many areas. These far-field deformation rates (and in particular, horizontal rates) have a unique spatio-temporal fingerprint that is likely detectable in analysis of GNSS network data sets. Moreover, the fingerprint has not been accounted for in previous studies of GNSS data, suggesting that a reappraisal of conclusions from some previous studies may be warranted. Incorporating these far-field crustal motion predictions into geophysical analyses of GNSS measurements has the potential to improve a range of applications, including estimating modern ice-mass changes, and isolating ongoing GIA signals in the crustal deformation field.

Rapid Laurentide Ice Sheet mass loss (and associated sea level rise) during the Bølling/Allerød constrained by 10Be elevation transects in the northeastern United States

Halsted, C. (1); Shakun, J. (2); Corbett, L. (3); Bierman, P. (4); Davis, P. (5); Goehring, B. (6); Koester, A. (7); Caffee, M. (8)

(1) University of Vermont; (2) Boston College; (3) University of Vermont; (4) University of Vermont; (5) Bentley University; (6) Tulane University; (7) Purdue University; (8) Purdue University

PRESENTATION

A lack of empirical data constraining the thinning history of the Laurentide Ice Sheet (LIS) has resulted in uncertainty about the timing of ice volume changes and thus its contribution to deglacial sea-level rise. To provide insight about the timing and rate of LIS thinning and retreat, we sampled 133 bedrock and boulder surfaces for in-situ 10Be cosmogenic exposure dating from a transect of elevations on 12 mountains across the northeastern United States. By calculating ages of exposure at different elevations (i.e., ice sheet "dipsticks"), we reconstruct the lowering paleo-ice surface of the southeastern LIS. Samples collected above 1200 m a.s.l. (n=38) exhibit isotopic evidence of burial with minimal subglacial erosion, consistent with a paleo-ice surface not far above the tops of these mountains. Lower elevation (<1200 m a.s.l.) 10Be samples (n=95) agree with published deglacial chronologies from valley bottoms in all but the southernmost locations in the region and suggest rapid ice thinning during retreat. Mountain-top exposure ages located within 150 km of the terminal moraine indicate that near-margin thinning began early in the deglacial period (~19.5 to 17.5 ka), coincident with the slow initial margin retreat indicated by varve records during Heinrich Stadial 1. Further inland (>400 km north of the terminal moraine), exposure ages collected over ~1000 m elevation ranges suggest rapid ice thinning between 14.5 and 13 ka, occurring at about the same time that varve records indicate accelerated ice margin retreat during the Bølling-Allerød warm period (14.6–12.9 ka). Ages across the inland vertical transects are similar within 1σ internal uncertainties, indicating that ice thinning was instantaneous within the resolution of the chronometer, taking place over hundreds of years at most. These results suggest a sea-level rise contribution from the southeastern LIS of at least 0.5 m during meltwater pulse 1a and more than 2 m over the Bølling-Allerød.

Reconstructing the MIS 6 Eurasian Ice Sheet to Improve Our Understanding of Last Interglacial Sea-Level Change

Pollard, O.G. (1); Barlow, N.L.M. (1); Gregoire, L.J. (1); Gomez, N. (2); Cartelle, V. (1); Ely, J.C. (3); Astfalck, L.C. (1)

(1) University of Leeds; (2) McGill University; (3) University of Sheffield

PRESENTATION

The Last Interglacial (LIG) was the most recent time in the Earth's history that global ice sheets retreated to a size comparable to our contemporary ice sheets. Improved reconstructions of the rates, magnitudes and timings of relative sea-level change that occurred during the LIG are therefore important if we are to use the LIG to help our understanding of potential future ice-sheet responses to climate change. When reconstructing past sea-level change we must correct for the effects of solid Earth deformation from past ice-sheet loading, especially in areas close to or previously covered by former ice sheets. As part of the ERC-funded RISeR project, this work focuses on modelling LIG glacial isostatic adjustment (GIA) at a near-field site, the southern North Sea. Relative sea-level change in this region is likely most sensitive to changes in the neighbouring Eurasian ice sheet during the Penultimate Glacial Period (PGP), however large uncertainties exist in the geometry and evolution of ice sheets during this time. Geological evidence of ice sheet extent combined with proxy records for total global ice-sheet volume indicate that the total Eurasian ice sheet volume at the PGM was at least equal in size to the PGM North American ice sheet.

In order to evaluate the sensitivity of the North Sea region to the range of uncertainty in the Eurasian ice sheet we employ two key models: (i) a simplified ice-sheet model, ICESHEET (Gowan et al. 2016), that assumes static, plastic behaviour that can rapidly produce physically consistent ice-sheet reconstructions; (ii) a gravitationally self-consistent sea level model (Kendall et al. 2005). In this work, we modify inputs to the ICESHEET model in order to account for physical effects such as the presence of ice streaming at the southern Eurasian PGM margin, the influence of cold based ice towards the interior of the ice sheet, and a maximum distance from the margin at which ice streaming is expected to occur. We employ a perturbed physics ensemble approach to explore the full range of uncertainty in our model parameters and calibrate our model against published reconstructions of ice sheet history for Last Glacial Period. We then produce reconstructions of the PGP Eurasian ice sheet with our calibrated parameter ranges and use these new ice sheet models as input to the sea-level model in order to evaluate the sensitivity of relative sea-level change in the North Sea region to changes in the PGP Eurasian ice sheet.

Gowan, E.J., et al., 2016. ICESHEET 1.0: a program to produce paleo-ice sheet reconstructions with minimal assumptions. Geoscientific Model Development.

Kendall, R.A., et al., 2005. On post-glacial sea level–II. Numerical formulation and comparative results on spherically symmetric models. Geophysical Journal International.

Effect of topography and isostatic adjustment on Antarctic Ice Sheet evolution using a simple ice sheet model

Luzardi, A.C.M. (1); Shaffer, G. (1,2).

(1) GAIA Antarctica Research Center, University of Magallanes, Chile; (2) Niels Bohr Institute, University of Copenhagen, Denmark

PRESENTATION

The Antarctic Ice Sheet (AIS) has been one of the major controllers of sea level variability since its inception at about 34 Ma. It has the potential to raise the global mean sea level by 58 meters, and parts of AIS have already begun to melt as a response to anthropogenic global warming. The rising concern about how much ice could melt in the future has brought attention to numerical modelling. Our capability to appropriately tackle this issue depends on our knowledge of AIS dynamics and its sensitivity to climate change and hence our ability to simulate it. However, many current ice sheet models disagree on basic issues related to ice sheet dynamics. Part of that disagreement comes from uncertainty in boundary conditions such as the bedrock topography or the glacial isostatic adjustment (GIA) framework. In that context, we evaluate here how bedrock topography and GIA influence the AIS evolution in different timescales. We perform sensitivity analyses and simulations of AIS evolution over the past 200 kyr with the simple Danish Center for Earth System Science Antarctic Ice Sheet (DAIS) model here extended to include variable topography and GIA. We modified the idealized single-sloped bedrock topography of the original model to accept an axisymmetric set of multiple slope segments fitted to observed and relaxed Antarctic bed topography. In addition, we modified the immediate isostatic adjustment of the original model so as to be distributed exponentially in time for chosen relaxation times. For the same original model parameter values, we found that changing the input topography in this way could almost double ice sheet volume at cold conditions like the present while ice sheet inception could be initiated in considerably warmer temperatures. Moreover, we found that decreasing bedrock resolution could lead to an decrease in more than 10% of ice volume during such cold conditions. Our sensibility tests show that increasing the rate of temperature change amplifies the hysteresis effect and could delay both ice sheet inception and shrinkage. At relatively fast temperature change rates the ice sheet initiates for more than 1°C warmer conditions with a delayed GIA. Recent studies have suggested that GIA plays a negative feedback in ice sheet evolution due to its control on the water depth at the grounding line and the equilibrium line position respective to ice sheet height. In our simulations, the use of delayed rather than immediate isostatic adjustment had a moderate effect on GIA's negative feedback amplitude. Simulations where GIA was broadly distributed in time resulted in an amplification of this negative feedback leading to less AIS volume variability during the past 200 kyr. Our results emphasize the need for accounting for realistic topography and GIA setups in ice sheet models. In addition, results presented here have implications for ice sheet inception at the Eocene-Oligocene boundary, and work is under way to address this matter.

Paleo ice history of Petermann Glacier, NW Greenland, constrained by relative sea level and isostatic adjustment modeling

Glueder, A. (1); Mix, A.C. (1); Milne, G.A. (2); Reilly, B.T. (3); Clark, J. (1); Jakobsson, M. (4); Fallon, S. (5); Southon, J.R. (6); Padman, J. (1); Ross, A. (1); Cronin, T.M. (7); McKay, J. (1)

(1) Oregon State University; (2) University of Ottawa; (3) University of California, San Diego; (4) Stockholm University; (5) The Australian National University; (6) University of California, Irvine; (7) United States Geological Survey.

PRESENTATION

Understanding the timing, rate and mechanism of deglaciation in the vicinity of Petermann Glacier in Northwest Greenland since the Last Glacial Maximum gives us insight into the ice-ocean interactions at the margins of large marine outlet glaciers and their sensitivity to future warming. Relative sea level (RSL) reconstructions derived from marine bivalves have been long used as limiting data to constrain parameters in glacial isostatic adjustment (GIA) models – notably, the ice evolution and viscosity structure of the solid Earth. Here we present a new way to reduce uncertainties associated with these limiting datasets by combining new measurements of the oxygen isotopic expression of the upper-ocean salinity gradient with the isotope signature of each dated shell in order to estimate their depth habitat. Based on these new RSL data, we find that the onset of rapid loss of terrestrial ice mass occurred at or prior to ~9 ka after which RSL fell rapidly at a rate of 31-37m/ka until ~6 ka when the rate dropped to values close to 1-2 m/ka and RSL remained above present for the remainder of the Holocene. Our findings suggest that: 1) low values of upper mantle viscosities in NW Greenland are likely needed to explain the rapid rate of RSL fall in the early Holocene; 2) the likely driver of early land ice thinning was atmospheric warming rather than loss of ice stream buttressing by a floating ice tongue; 3) a re-growth of regional ice caps is one possible explanation for the remarkably stable and positive RSL during the mid-to-late Holocene which underscores a need for higher resolution modeling including regional ice caps to reconcile ice models with observed relative sea levels, especially in areas that are underlain by low upper mantle viscosities.

Session 2: Paleo data

Deglacial relative sea-level changes and Glacial Isostatic Adjustment modelling in the Russian Arctic

Tanghua Li (1), W. Richard Peltier (2), Gordan R. Stuhne (2), Timothy Shaw (1), Alisa V. Baranskaya (3), Nicole Khan (4), Patrick Wu (5), and Benjamin P. Horton (1,6)

(1) Earth Observatory of Singapore, Nanyang Technological University, Singapore; (2) Department of Physics, University of Toronto, Toronto, Canada.; (3) Laboratory of Geoecology of the North, Lomonosov Moscow State University, Russia; (4) Department of Earth Sciences and Swire Institute of Marine Science, University of Hong Kong, Hong Kong; (5) Department of Geoscience, University of Calgary, Canada; (6) Asian School of the Environment, Nanyang Technological University, Singapore

PRESENTATION

The western Russian Arctic was partly covered by the large Eurasian ice sheet complex during the Last Glacial Maximum and is an additional focus area for Glacial Isostatic Adjustment (GIA) studies. There have been few studies conducted in the Russian Arctic that focus on GIA due to the lack of high quality deglacial relative sea-level (RSL) data. Recently, Baranskaya et al (2018, QSR) released a quality-controlled deglacial RSL database for the Russian Arctic that consists of ~400 sea-level index points, which define the RSL at a given point in time and space, and ~250 marine and terrestrial limiting data, which constrain the lower and upper limits of RSL. Here, we use the deglacial RSL database to validate the latest iterations in the development of 1D GIA models ICE-6G_C (VM5a) (Peltier et al., 2015, JGR) and ICE-7G_NA (VM7) (Roy and Peltier, 2017, GJI) and new 3D GIA models (inferred on the basis that the loading history is fixed to ICE-6G_C). GIA models with a 3D structure have the potential to better fit deglacial RSL data because seismic tomography models show notable lateral heterogeneity in the Russian Arctic.

The RSL predictions of the 1D models are found to fit the RSL data well along the southern coast of Barents Sea and on Franz-Josef-Land, but notable misfits are evident in the White Sea region. We find 3D model predictions (with a fixed ice model) improve the fit in the White Sea while retaining comparable fits in other regions. Similarly, by locally tuning of the ICE-7G_NA ice model in the White Sea area (with a fixed 1D Earth model), we show improved fit with deglacial RSL data in the White Sea. The comparable fits of the best-fit 3D model and the ICE-7G_NA (VM7) model with locally modified loading history to the deglacial RSL data implies that the uncertainty in the ice model might be improperly mapped into 3D viscosity structure when a fixed model of deglaciation history is employed. We conclude that the uncertainty in the ice model and correlation/interaction between the ice and Earth models need to be carefully considered in future GIA studies.

Northern Hemisphere ice sheet persistence across Pleistocene interglacials

LeBlanc, D. (1); Shakun, J. (1); Bierman, P. (2); Corbett, L. (2), Caffee, M. (3)

(1) Boston College; (2) University of Vermont; (3) Purdue University

PRESENTATION

Models that seek to explain the 100-kyr periodicity and saw-toothed structure of mid-to-late Pleistocene glacial cycles commonly invoke complete (or near complete) disintegration of Northern Hemisphere ice sheets between glaciations. However, reconstruction of ice sheet history beyond the Last Glacial Maximum is complicated by the sparsity of terrestrial evidence (erased by subglacial erosion) and the ambiguity of the marine δ18O record (a tracer of both ice volume and ocean temperature). To investigate long-term persistence of Northern Hemisphere ice complexes, we measured cosmogenic nuclides 10Be and 26Al in ice-rafted debris (IRD) in marine sediment cores spanning the last glacial period.

Because cosmogenic nuclides accumulate in land surfaces exposed to cosmic rays, but decrease in concentration when surfaces are ice covered due to radioactive decay and erosion, nuclide concentrations in IRD reflect an integrated history of exposure and erosion along flow lines discharging icebergs to the ocean. The differential decay of 10Be (t1/2 = 1.4 Myr) and 26Al (t1/2 = 0.7 Myr) causes the 26Al/10Be ratio to decrease below the production value of ~7 due to extended burial after exposure, yielding information about the duration of ice cover in sediment source regions. We measured cosmogenic nuclides in the six most recent Heinrich layers, as well as between Heinrich layers, from sediment cores on the western and eastern sides of the North Atlantic (13 samples from each side) spanning the last ~60 kyr.

We find that IRD from the western and eastern North Atlantic has markedly different 10Be concentrations over time, with lower values in the west relative to the east, except during Heinrich events 1, 2, 4, and 5 when values are similar. These results, together with previous provenance work, suggest Laurentide-sourced icebergs predominated in the western North Atlantic over the last glaciation and spread across the basin during Heinrich events 1, 2, 4, and 5, while other sources dominated in the east. 26Al/10Be ratios (~4-5) on both sides of the North Atlantic are substantially below the production ratio (~7), implying source regions were buried much of the past ~1 Myr. These ratio data suggest that Northern Hemisphere ice sheets persisted in some sectors across many interglacial cycles.

Partitioning early Holocene North American v. Antarctic ice melt from high-resolution reconstructions of sea-level rise and glacial isostatic adjustment modeling

Mukherjee, U. (1); Törnqvist, T. (1); Milne, G. (2); Tarasov, L.(3); Lecavalier, B. (3); Vetter, L. (4); Steponaitis, E. (5); Cahill, N. (6); Rosenheim, B. (7)

(1) Tulane University; (2) University of Ottawa; (3) Memorial University of Newfoundland; (4) University of Arizona; (5) ASRC Federal; (6) Maynooth University; (7) University of South Florida

PRESENTATION

According to the SROCC report, under RCP8.5, the rate of sea level rise in 2100 will be 10-20 mm/yr and extreme sea level events will become common. Past relative sea level (RSL) change informs our understanding of future sea-level rise and the threat that acceleration of RSL rise poses in low-lying areas around the world. The Early Holocene (EH), the most recent time interval with rapid ice-sheet retreat and rapid sea level rise, contains critical gaps in RSL history that are considered to be among the remaining outstanding questions regarding eustatic sea level (Khan et al., 2019). A better understanding of the rates and sources of RSL change between 10-7 ka can help in better predictions of future sea level rise, particularly since the melting of the Antarctic ice sheet was a potential key contributor to this high rate of sea level rise.

In this project, a global RSL database spanning 10-7 ka has been prepared, using a rigorous set of criteria to control the quality of the indicators. To be included in the database, a RSL indicator has to be an in situ and relatively uncompacted intertidal sea level index point (SLIP) with a quantifiable 2σ vertical (<2m) and horizontal (<600 years) resolution, from an area reasonably unaffected by vertical land movement. This procedure has resulted in a database of four well-constrained RSL histories from both intermediate and far-field locations around the world. We use a Bayesian model (Cahill et al., 2016) to calculate rates of RSL change from the RSL proxy data, which takes into account the noise in both temporal and spatial axes of the RSL data. The observed RSL rate of change at the four locations is compared to model output calculated using a suite of Earth viscosity models and ice sheet chronologies from approximate Bayesian calibrations of glaciological models for the Antarctic and North American Ice Sheets to determine the ice sheet histories and north-south partitioning that best fit the data.

Cahill, N., Kemp, A. C., Horton, B. P., and Parnell, A. C., 2016, A Bayesian hierarchical model for reconstructing relative sea level: from raw data to rates of change: Climate of the Past, v. 12, no. 2, p. 525-542.

Khan, N. S., Horton, B. P., Engelhart, S., Rovere, A., Vacchi, M., Ashe, E. L., Törnqvist, T. E., Dutton, A., Hijma, M. P., and Shennan, I., 2019, Inception of a global atlas of sea levels since the Last Glacial Maximum: Quaternary Science Reviews, v. 220, p. 359-371.

Resolving the global mean sea level budget during MIS 11: direct terrestrial evidence for an ice-free northwest Greenland in the Camp Century subglacial sediment

Christ, A.J. (1); Rittenour, T.M. (2); Bierman, P.R. (1); Schaefer, J.M. (3); Knutz, P.C. (4); Thomsen, T.B. (4); Keulen, N. (4); Fosdick, J.C. (5); Hemming, S.R. (3); Keisling, B.A. (3); Blard, P.-H. (6,7); Tison, J.-L. (7)

(1) University of Vermont; (2) Utah State University; (3) Lamont-Doherty Earth Observatory, Columbia University; (4) Geologic Survey of Denmark and Greenland; (5) University of Connecticut; (6) CNRS, Université de Lorraine; (7) Université Libre de Bruxelles

PRESENTATION

Climate warming is rapidly melting the Greenland Ice Sheet (GrIS) and accelerating Greenlandic contribution to sea-level rise. Past interglacial periods when the GrIS was smaller and global mean sea level (GMSL) was higher than today are critical analogues for the future. Age constraints from ice core basal materials suggest the absence of the GrIS at least once during the last 1 Myr, but the timing(s) and extent(s) of such large-scale ice sheet retreat(s) is not known. One possible scenario was during Marine Isotope Stage (MIS) 11c (395 to 424 ka), which was a prolonged interglacial period marked by GMSL 6-13 m higher than present requiring a smaller GrIS; however, direct terrestrial evidence of former ice-sheet extent during this time has been elusive.

Here, we show evidence of an ice-free period in the last 400 kyr in northwestern Greenland recorded in the sub-glacial sediment from the Camp Century ice core. Infrared stimulated luminescence (IRSL) measurements indicate that the upper-most sediment (directly beneath the ice-sediment interface) was last exposed to sunlight 380 ± 40 ka, which suggests an ice-free event during the MIS 11c interglacial. The IRSL data considered with cosmogenic 26Al/10Be measurements mandate no more than about 13 kyr of surface exposure under ice-free conditions. Ice-sheet models that maintain ice-free conditions at Camp Century explain at least 1.6 m and up to 5.7 m of sea level equivalent contribution from Greenland during MIS 11c. Mineralogical analyses and multiple geochronometers (U-Th/He ages of apatite, 40Ar/39Ar ages of hornblende, and U-Pb ages of zircon, apatite, and rutile) indicate similar provenance between the upper-most sediment and underlying, older sediment in the Camp Century ice core; this implies that the IRSL data records an ice sheet advance that reworked and buried local surface material as climate cooled.

The Camp Century sub-glacial sediment adds to a growing body of evidence for a smaller GrIS during MIS 11c. Excellent preservation of fossil vegetation in the same sub-glacial sediment indicates that a tundra ecosystem emerged in northwestern Greenland during MIS 11c, while offshore records in the Labrador Sea suggest an ice-free and forested southern Greenland at the same time. Ice-free conditions at Camp Century provide an absolute lower limit of 1.6 m of sea-level contribution from Greenland but yield less insight into the maximum contribution. Resolving the extent of ice retreat into central Greenland during MIS 11c will further constrain the GMSL budget, and ultimately improve our understanding of past GrIS stability and sensitivity to future climate change. Nevertheless, the demise of northwestern and southern GrIS during the long MIS 11c interglacial highlights ice-sheet sensitivity to prolonged periods of warmth.

Incorporating lake and groundwater volumes into global sea-level estimates during the deglaciation

Callaghan, K.L. (1); Austermann, J. (1); Wickert, A.D. (2,3)

(1) Lamont-Doherty Earth Observatory, Columbia University; (2) Department of Earth and Environmental Sciences, University of Minnesota; (3) Saint Anthony Falls Laboratory, University of Minnesota

PRESENTATION

At every time scale, water on Earth moves between ocean, atmosphere, and land. The volume of water at each location, as well as its impact on the gravity field and local isostatic adjustment, determines both local and global sea level. When modelling global sea-level change during the last deglaciation (21,000 years ago to present), existing sea-level models ingest reconstructed ice-sheet models to calculate volume balances and isostatic adjustment. Here we add changes in lake and groundwater volumes to address how these water stores impact sea level.

Using the Water Table Model (WTM), we simulate water-table depth – including both lakes and groundwater – on a global scale over the past 21,000 years. Changes in the water volume stored in these reservoirs directly impacts the volume of water available to be stored in the ocean, and therefore impacts sea level. In addition, this water is a load on the Earth surface, causing isostatic adjustment, and it changes the gravity field that is a vital component in calculations of relative sea level. We use these results in conjunction with a sea-level model to obtain an initial estimate of changing sea level during the deglaciation that includes these impacts of groundwater and lake storage.

Reconciliation of the Paleo Sea-level Record with Modern Crustal Uplift of Greenland

Adhikari, S. (1); Milne, G. (2); Caron, L. (1); Ivins, E. (1); Khan, S. (3); Kjeldsen, K. (4); Nilsson, J. (1); Larour, E. (1)

(1) Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, USA; (2) Department of Earth and Environmental Sciences, University of Ottawa, Ottawa ON, Canada; (3) Department of Geodesy and Earth Observations, Technical University of Denmark, Kgs. Lyngby, Denmark; (4) Geological Survey of Denmark and Greenland, Copenhagen, Denmark.

PRESENTATION

The observed crustal uplift rates in Greenland are caused by the combined response of the solid Earth to both ongoing and past surface mass changes. Existing elastic Earth models and Maxwell linear viscoelastic GIA (glacial isostatic adjustment) models together underpredict the observed uplift rates. We hypothesize that the ongoing mantle deformation induced by significant ice melting since the Little Ice Age explains the data-model misfits. Using a simple Earth model within a Bayesian framework, we show that this hypothesis is true but only when a reduced mantle strength is considered. The inferred viscosity for sub-centennial timescale mantle deformation is roughly one order of magnitude smaller than the upper mantle viscosity inferred from GIA analysis of geological sea-level data. Reconciliation of geological sea-level and modern crustal motion data may require that the model effective viscosity be treated with greater sophistication than in the simple Maxwell rheological paradigm.

Session 3: Glacial Isostatic Adjustment

Geodetic evidence for spatially-varying upper mantle viscosity along a 1000 km transect of the Antarctic Peninsula

King, M. (1); Samrat, N. (1, 2)

(1) School of Geography, Planning, and Spatial Sciences, University of Tasmania; (2) School of Engineering and Technology, Central Queensland University

PRESENTATION

GPS estimates of bedrock motion along the Antarctic Peninsula have revealed varying rates of uplift associated with recent and present-day ice mass loss that cannot be explained by elastic deformation alone. In the north, Nield and others (2014) explained strong increases in GPS uplift rates to be a result of viscoelastic deformation due to glacier mass loss associated with the breakup of Larsen B Ice Shelf, with good agreement with models using upper mantle viscosities <~10^18 Pa s. In a further GPS study of the Fleming Glacier/Wordie Ice Shelf system 500km further south, Zhao et al (2017) suggest upper mantle viscosities 1-2 orders of magnitude higher. In a new study in northern Marguerite Bay, between the above two regions, non-linear uplift rates are also revealed due to very recent ice mass changes. These also cannot be explained by elastic only models and suggest upper mantle viscosities somewhere between the two previous studies, or overlapping that of the northern study. This presentation will review these and other geodetic and modelling studies along the full transect of the Antarctic Peninsula, compare them with seismic estimates of viscosity, and discuss the possibility of transient deformation being the dominant deformation mechanism instead of simple viscous deformation.

The effect of GIA feedback on the evolution of the Antarctic Ice sheet over the last glacial cycle using a coupled 3D GIA – Ice Dynamic model

Van Calcar, C.J. (1,2); de Boer, B. (3); Blank, B. (1); van de Wal, R.S.W. (2,4); van der Wal, W. (1,5)

(1)Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands; (2) Institute for Marine and Atmospheric research Utrecht, Utrecht University, Utrecht, the Netherlands; (3) Earth and Climate Cluster, Faculty of Science, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands; (4) Department of Physical Geography, Utrecht University, Utrecht, the Netherlands; (5) Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

PRESENTATION

A recent comparison of 15 ice sheet models has shown that the Antarctic Ice Sheet (AIS) will contribute -7.8 to 30 centimeters of sea level rise between 2015 and 2100. This projection comprises an uncertainty of tens of centimeters. To better constrain projections of the evolution of the Antarctic Ice Sheet, more accurate simulations of the evolution of the AIS are needed. It is known that Glacial Isostatic Adjustment (GIA) has a stabilizing effect on the evolution of the AIS; directly by affecting the angle of the bedrock surface and indirectly by stabilizing the position of the grounding line. The timescale on which GIA feedback occurs is mainly dependent on the significantly varying viscosity of the Earth's mantle under West and East Antarctica. GIA is especially relevant when one simulates the evolution of the West Antarctic Ice Sheet, where the response time of the bedrock could be as fast as 100 years due to relatively low mantle viscosities of approximately 1018 Pa s. However, most studies assume a much higher laterally homogeneous response time and the stabilizing GIA feedback is neglected or accounted for on relatively long timescales. We present a new method to include the radially and laterally varying GIA feedback in simulations of the AIS evolution by coupling an ice sheet model to a 3D GIA model on relatively short timescales of 5000, 1000 and 500 years. The method is applied using ice sheet model ANICE coupled to a 1D GIA model and a 3D GIA model. At the beginning of the Last Glacial Cycle, it is shown that the grounding line position changes with up to 80 kilometers, at the same time the total ice volume of the AIS increases by 0.5 percent over 5000 years if the lateral variations are included. These results quantify the local importance of including the GIA feedback on short timescales in ice dynamical models when simulating the Antarctic Ice Sheet

evolution. We will also present new results of the full Last Glacial Cycle up till present day and compare the results using 1D and 3D GIA to ANICE using ELRA.

Stress-dependent viscosity in GIA models for Greenland and Antarctica

van der Wal, W. (1); Blank, B. (1); Barletta, V.R. (2)

(1) Delft University of Technology; (2) University of Technology Denmark

PRESENTATION

In GIA models relaxation is mainly controlled by viscosity. Laboratory experiments show that viscosity of Earth materials depends, among others, on stress. In this study we investigate the influence of stress on the pattern of viscosity through time. We use a composite rheology which consists of diffusion and dislocation creep, with the latter introducing stress-dependent viscosity. For a model with non-linear rheology (dislocation creep) only, a larger background stress result in smaller stress dependence. However, we show with a schematic example that for a composite rheology with reasonable parameters the stress-dependence of viscosity can become larger when the background stress is larger.

Background stress in the mantle could originate from a process such as convection, but here we investigate the influence of stresses from post-LGM ice sheets in Greenland and Antarctica on viscosity and current GIA. In Greenland the stress dependence causes a viscosity drop of 1 order of magnitude around 8 kyear before present. In the Amundsen Sea Sector in Antarctica, the stress dependence due to the post-LGM ice melt changes viscosity by 1.5 order of magnitude resulting in a significant change in present-day uplift rate. The results show that the viscosity ‘felt’ by the GIA process is smaller than the viscosity in the absence of stresses.

Inference of 3D Earth structure beneath Greenland and eastern Canada using a joint inversion of regional datasets

Ajourlou, P. (1); Salajegheh, F. (2); Milne, G.A. (3); Afonso, J.C. (4); Civiero, C. (5); Lebedev, S. (6)

(1) Department of Earth and Environmental Sciences, University of Ottawa, Ottawa, Ontario, Canada; (2) Department of Earth and Planetary Sciences, Macquarie University, Sydney, Australia; (3) Department of Earth and Environmental Sciences, University of Ottawa, Ottawa, Ontario, Canada. (4) Department of Earth and Planetary Sciences, Macquarie University, Sydney, Australia; (5),(6) Geophysics Section, School of Cosmic Physics, Dublin Institute for Advanced Studies, Dublin, Ireland

PRESENTATION

Accurate knowledge of Earth structure in Greenland and eastern Canada region is important because both glacial isostatic adjustment (GIA) and Greenland ice sheet evolution are dependent on this structure. Understanding how the ice-sheet has responded to past climate change and our ability to accurately predict its future evolution for a given climate change depends, therefore, on our knowledge of solid Earth structure in this region. The key Earth model parameters for simulating GIA and ice sheet evolution are viscosity and density. Here, we apply a 3D multi-observable probabilistic method (Afonso et al., Journal of Geophysical Research, Solid Earth, 118, 2013) to quantify the earth structure of Greenland and eastern Canada by jointly inverting Rayleigh wave phase velocity dispersion curves, geoid elevation, surface heat flow, and topography. Preliminary results show that temperature and compositional variations are relatively well resolved. We compare our results to those inferred using a different surface wave dataset to demonstrate the importance of this data constraint in governing the inversion results. Finally, our inversion results are used to estimate a regional 3D viscosity model (with uncertainty), which is compared to those determined using other methods (e.g., Milne et al., Geophysical Journal International, 214, 2018).

Rapid postglacial rebound amplifies global sea-level rise following West Antarctic Ice Sheet collapse

Linda Pan (1), Evelyn M. Powell (1), Konstantin Latychev (1,2), Jerry X. Mitrovica (1), Jessica R. Creveling (3), Natalya Gomez (4), Mark J. Hoggard (1,2,5), Peter U. Clark (3)

(1) Department of Earth and Planetary Sciences, Harvard University, (2) Lamont-Doherty Earth Observatory, Columbia University; (3) College of Earth, Ocean, and Atmospheric Sciences, Oregon State University; (4) Department of Earth and Planetary Sciences, McGill University; (5) Research School of Earth Sciences, Australian National University.

PRESENTATION

Studies of peak global mean sea level (GMSL) during the Last Interglacial (LIG; 130-116 ka) commonly cite values ranging from ~2-5 m for the maximum contribution from grounded, marine-based sectors of the West Antarctic Ice Sheet (WAIS). This estimate does not include postglacial rebound and the associated meltwater flux out of marine sectors as they are exposed, a contribution typically considered to be small and slowly-accumulating. However, geodetic, seismic and geological evidence indicate that West Antarctica is underlain by low-viscosity shallow mantle, and thus the assumption that the contribution to GMSL from the outflux mechanism is negligible should be revisited. We incorporate both the outflux mechanism and complex 3-D viscoelastic mantle structure in new sea-level predictions and find that the water outflux mechanism contributes ~1 m of additional GMSL change within ~1 kyr of the collapse. This conclusion has important implications for the sea-level budget not only during the LIG, but also all previous interglacials. Finally, we demonstrate the importance of including this mechanism in analyses of site-specific sea-level indicators. The presentation by Powell et al. at this meeting discusses inaccuracies introduced in predictions of sea-level changes (including the outflux mechanism) driven by collapse of WAIS by the assumption that the Earth's viscoelastic structure varies with depth alone.

Session 4: Glacial Isostatic Adjustment

Quantifying the influence of glacial isostatic adjustment on current and future sea-level change using 3-D Earth models

Milne, G.A . (1); Yousefi, M. (2,3); Latychev, K. (4)

(1) University of Ottawa; (2) McGill University; (3) Penn State University; (4) Harvard University

PRESENTATION

Ongoing deformation of the Earth in response to past ice-ocean mass exchange is a significant contributor to contemporary sea-level changes and will be an important contributor to future changes. Calibrated models of this process have been used to quantify its influence on current and future sea-level changes. To date, the majority of these models have assumed a spherically-symmetric (1-D) representation of Earth viscosity structure. Here we apply a model that can simulate the isostatic response of an Earth with 3D viscosity structure to consider the contribution of lateral structure to model estimates of current and future sea-level change. We will present results from a global analysis based on two independent ice history reconstructions and a suite of 3-D models with viscosity structure constrained using different seismic velocity models and recent estimates of lithosphere thickness variations. In total, over 50 model runs were performed to quantify the impact of lateral structure on estimates of the glacial isostatic adjustment (GIA) signal. The accuracy of the explored model parameter sets is assessed by comparing model output to a recently published data set of vertical land motion specifically intended to provide a robust measure of the GIA signal (Schumacher et al., Geophysical Journal International, 2018). Using the model parameter sets that best match the GPS constraints to predict the contribution of GIA to contemporary sea-level change indicates that lateral viscosity structure impacts the model estimates by order 1 mm/yr in some regions and that the model uncertainty is of a similar amplitude. Simulations of the GIA contribution to future sea-level change are also significantly affected, with differences, relative to a 1-D Earth model, reaching several decimeters on century timescales and several meters on millennial timescales.

3D Viscosity Inversions of Post-Glacial Deformation as Recorded by Relative Sea Level: Proof of Concept

Lloyd, A. J. (1); Crawford, O. (2); Al-Attar, D. (2); Austermann, J. (1)

(1) Lamont-Doherty Earth Observatory of Columbia University; (2) University of Cambridge

PRESENTATION

The recent development of the adjoint method within the context of Glacial Isostatic Adjustment (GIA) provides a unique opportunity to perform data driven inversions of key GIA parameters, such as 3D mantle viscosity. Central to this approach is the accurate and efficient determination of sensitivity kernels for a range of possible GIA observables (e.g. relative sea level, RSL). These kernels require just two numerical simulations – a forward simulation driven by the ice history and an adjoint simulation driven by a 'fictitious' load applied at the observation point. This 'fictitious' load when weighted by an appropriate misfit functional results in the gradient of the misfit function with respect to the model parameter(s), which can be used in a gradient based optimization scheme to iteratively update the model parameter(s) and minimize the data misfit. While providing an overview of this approach, we examine a series of synthetic inversions, in which the goal is to recover a prescribed 3D mantle viscosity structure. Observations of RSL used in the inversions are obtained by solving the forward GIA problem for a given ice history (e.g., ICE6G) and 3D mantle viscosity model, which is inferred from seismic tomography. The location, timing, and uncertainties of RSL index points across the globe are used as a template for constructing our synthetic RSL observations. These are used to explore two different inversions that either update 3D mantle viscosity or both 3D mantle viscosity and initial sea level at 26 Kyr. In the latter inversions, the goal is to also match 'present-day' sea level. In addition, we explore the sensitivity to the ice history model by using a different ice history model for the inversion. The key takeaway is that the 3D mantle viscosity structure can be recovered in regions of the Earth sensed by the observations.

Exploring the Resolving Power of Antarctic Datasets Using the Adjoint Method: A Novel Route to Improving GIA Models

Powell, E. (1); Lloyd, A. (2); Austermann, J. (2); Al-Attar, D. (3); Crawford, O. (3); Mitrovica, J. (1)

(1) Harvard University; (2) Columbia University; (3) Cambridge University

PRESENTATION

Constraining the evolution of the glacial isostatic adjustment (GIA) process across the Antarctic is challenged by major uncertainties in the history of regional ice cover and viscoelastic Earth structure. The latter effort confronts the complex geological and rheological setting across and beneath the continent: East Antarctica is characterized by a thick (~200 km) lithosphere overlying an upper mantle with a viscosity typical of cratons, 1020-1021 Pa s, and, in contrast, the lithosphere thins to ~50 km and viscosity within the shallow mantle may be as low as ~1018 Pa s beneath the West Antarctic Rift System. A series of recent studies have inferred 1-D mantle viscosity profiles beneath the Antarctic Peninsula and the Amundsen Sea Embayment from GNSS-determined crustal uplift rates (e.g., Nield et al., 2014; Zhao et al., 2017; Barletta et al., 2018). However, sensitivity studies based on 3-D GIA modeling have shown that these inferences can be biased by an order of magnitude or more relative to average viscosity values below the sites, and that they will significantly underestimate the full range of viscosity variations (Powell et al., 2021). In this presentation, I use recent theoretical advances based on the adjoint method (Al-Attar and Tromp, 2016; Crawford et al., 2018) to explore the sensitivity of relative sea-level data and crustal uplift rates in the West Antarctic to 3-D variations in mantle viscosity, i.e., the spatial resolving power of the various data sets. The method also allows one to constrain the time window across which the ice history must be known for accurate predictions of these observations, i.e., the temporal resolving power of the data; the geographic variation of this window will, at some level, reflect the underlying viscosity field. These preliminary calculations will highlight a new direction of research that will more rigorously constrain the GIA process across the region, and ultimately improve our understanding of the evolution of the Antarctic Ice Sheet in the face of both paleo and modern climate change.

The role of community software and community benchmarks for reliable numerical modeling: Lessons learned by the Computational Infrastructure for Geodynamics

Rene Gassmoeller (1)

(1) University of Florida

PRESENTATION

Over the past decades numerical models have become important tools for solving problems in the Earth Sciences just as in many other disciplines. Increasing computing power has allowed models of more complex systems and the underlying mathematical algorithms have increased in efficiency and complexity at the same time. However, this progress generates challenges to keep scientific models reliable and reproducible. Open software and community benchmarks are one option to create trust in numerical models and are increasingly requested or required by reviewers and funding agencies. However, developing community software and community benchmarks is not without its challenges. Questions about fair benchmarks, open collaboration, and appropriate credit can create barriers that slow down or even prevent the evolution of a robust community software ecosystem. In this talk I will summarize lessons learned in the Computational Infrastructure for Geodynamics and the ASPECT project, and hope to spark an exchange about open and reliable modeling practices between the CIG and the PALSEA community.

The Effects of Non-Newtonian Rheology in the Upper Mantle on Relative Sea Level Change and Geodetic Observables Induced by Glacial Isostatic Adjustment Process

Kaixuan, K. (1); Shijie, Z. (2); Geruo, A. (3); Wei, M. (4)

(1)Department of Physics, University of Colorado at Boulder, Boulder CO, USA; (2)Department of Earth System Science, University of California, Irvine, CA, USA; (3)Seismological Laboratory and Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, United States, 91106

PRESENTATION

The viscoelastic response of the solid earth to the surface mass redistribution caused by the process of glaciation and deglaciation, e.g, glacial isostatic adjustment (GIA), can provide important constraints on the Earth's mantle viscosity. Most GIA models assume Newtonian viscosity through the mantle that the strain rate changes linearly with stress. But most recent laboratory experimental studies of rock deformation, observational studies of seismic anisotropy, and modeling studies of mantle dynamics show that non-Newtonian viscosity may also operate in the upper mantle. Our current study explores the non-Newtonian effects on the GIA induced variations in mantle stress and viscosity and on surface observables including vertical displacement, relative sea level (RSL) and gravity change. The recently updated and fully benchmarked software package CitcomSVE is used for GIA simulations. We adopt the ICE-6G ice deglaciation history, VM5a lower mantle and lithospheric viscosities, and a composite rheology that combines Newtonian and non-Newtonian viscosities for the upper mantle. Our results show that: 1) The mantle stress beneath glaciated regions increases significantly during deglaciation, leading to regionally reduced upper mantle viscosity by more than an order of magnitude. Such effects can be rather localized at the periphery of glaciated regions. Due to ocean loading, upper mantle stress at the periphery of continents is also increased, causing local viscosity reduction. However, non-Newtonian effects on far-field mantle viscosity are negligibly small. GIA induced stress is also significant in the lithosphere (~10's MPa) and lower mantle (~2 MPa). 2) The predicted RSL changes from non-Newtonian models display distinct features in comparison with the Newtonian model, including more rapid sea-level falls associated with the deglaciation followed by a more gradual sea-level variation for sites near the centers of formerly glaciated regions, and an additional phase of sea-level falls for the last ~8000 years for sites at the

ice margins of the LGM. Similar time-dependence associated with the deglaciation is also seen for rate of vertical displacement, suggesting a relatively slow present-day rates of vertical displacement and gravity change. These features can be explained by the non-Newtonian effects associated with a loading event which manifest a fast relaxation stage followed by a relative slow relaxation stage. Our results may provide GIA diagnoses for distinguishing non-Newtonian and Newtonian rheology.

Can non-Newtonian rheology help reconcile far-field and near-field relative sea-level observations?

Zhong, S.J. (1); Kang, K.X. (1)

(1) Department of Physics, University of Colorado

PRESENTATION

ICE-6G and VM5a are constructed mostly by fitting observations of relative sea-level (RSL) change, GRACE time varying gravity, and GPS in formerly glaciated and surrounding regions (i.e., North America and Fennoscandia) [Peltier et al., 2015]. However, we found that GIA model using ICE-6G and VM5a consistently predicts sea level rise that occurs ~1,500 years too early compared with the observed for far-field sites (e.g., in the Pacific, and along coasts of Australia, India, and Asia) during the rapid sea level rise period (i.e., between ~15,000 and 7,000 years). Another way to say is that the GIA model over-predicts the RSL by ~20 m for the far-field sites during this period. GIA models using different 1-D viscosity do not appear to help resolve the discrepancy. Here, we hypothesize that non-Newtonian rheology helps explain both far-field and near-field RSL data simultaneously. A recent study by Kang et al. [2021] demonstrated that non-Newtonian rheology causes more than one order of magnitude reduction in upper mantle viscosity below the formerly glaciated regions during the rapid ice melting, while its effect on mantle viscosity elsewhere is minimal. As a result, RSL falls more rapidly for near-field sites from non-Newtonian GIA models than from the model with VM5a, while RSL at far-field sites is not affected. Indeed, near-field RSL data at certain sites show more rapid sea-level falls than predicted by GIA model with VM5a and ICE-6G. These unique characteristics of non-Newtonian GIA models form the basis of our hypothesis. In this presentation, we will present the far-field and near-field RSL data and their comparison with GIA model with ICE-6G and VM5a. We will test our hypothesis using GIA models with non-Newtonian viscosity and show how far-field and near-field RSL data may be simultaneously explained in our models.

Island Subsidence During Melt Water Pulse Events and the Extended Burgers Model of Transient Mantle Rheology

Ivins, E.R. (1); Caron, L. (1); Adhikari, S. (1); Larour, E. (1)

(1) Jet Propulsion Lab, California Institute of Technology, Pasadena, CA 91109-8099

PRESENTATION

We formulate a mathematical description of a compressible version of the extended Burgers material (EBM) model paradigm. The latter is typically used for parameterizing attenuation and high temperature background transient responses in the rock physics and mechanics laboratory setting. The model has demonstrated useful application to modelling the S-wave velocity of the sub-oceanic olivine-rich shallow mantle and in understanding planetary dissipation and dynamics. We present a new generalization of this practical anelastic model in tensor form and apply it to the glacial isostatic adjustment momentum equations. Our goal is to provide a useful standard for initial-value boundary problem-solving software for quite general coding strategies. The solutions for surface loading response reveal a short-term transience of substantial amplitude. We discuss the implications of the EBM rheology on the predictions of the time-evolution of the solid Earth subsidence under the physical conditions imposed by Melt Water Pulse 1A. Enhanced subsidence is predicted during short-term melt inundation and we discuss the potential implications for paleo-sea-level interpretation and future modelling. These simple models of sea-floor subsidence during the larger post-LGM melt-water inundations reveal the potential importance of including realistic transient rheology in solid Earth models used for interpreting paleo-sea-level data at island sites.

Frequency Dependent Mantle Viscoelasticity via the Complex Viscosity: cases from Antarctica

Lau, H.C.P. (1); Austermann, J. (2); Holtzman, B. (2); Havlin, C. (3); Lloyd, A. (2); Book, C. (4); Hopper, E. (4)

(1) University of California, Berkeley; (2) Columbia University; (3) University of Illinois; (4) Unaffiliated

INVITED PRESENTATION

Studies of glacial isostatic adjustment (GIA) often use paleoshorelines and present-day deformation to constrain the viscosity of the mantle and the thickness of the lithosphere. However, different studies focused on similar locations have resulted in different estimates of these physical properties even when considering the same model of viscoelastic deformation. We argue that these different estimates infer apparent viscosities and apparent lithospheric thicknesses, dependent on the timescale of deformation. We use recently derived relationships between these frequency dependent apparent quantities and the underlying thermodynamic conditions to produce predictions of mantle viscosity and lithospheric thickness across a broad spectrum of geophysical timescales for two locations (Amundsen Sea, and the Antarctic Peninsula). Our predictions require the self-consistent consideration of elastic, viscous, and transient deformation and also include non-linear steady state deformation, which have been determined by several laboratories. We demonstrate that these frequency dependent predictions of apparent lithospheric thickness and viscosity display a significant range and that they align to first order with estimates from GIA studies on different timescales. Looking forward, we suggest that observationally based studies could move towards a framework of determining the frequency trend in apparent quantities – rather than single, frequency independent values of viscosity – to gain deeper insight into the rheological behavior of Earth materials.

Poster Session 1: Observations of RSL Change

Relative Sea Level in Norway since Last Glacial Maximum

Creel, R. (1), Austermann, J.A. (1), Khan, N.S. (2), D'Andrea, W. (1), Balascio, N. (3), Dyer, B. (4), Ashe, E. (5), Menke, W. (1)

(1) Lamont-Doherty Earth Observatory, Columbia University, New York, USA; (2) University of Hong Kong, Hong Kong; (3) College of William and Mary, Virginia, USA; (4) University of Victoria, Victoria, Canada; (5) Department of Earth and Planetary Sciences and Rutgers Institute of Earth, Ocean, and Atmospheric Sciences, Rutgers University, New Jersey, USA

POSTER

We present the first comprehensive database of relative sea level (RSL) data from Norway. Composed of 414 index points and 383 limiting data and covering the Norwegian coastline from Oslo to the Barents Sea, the database spans from 19.7 ka to the present and is composed of radiocarbon dated samples from isolation basins, raised beaches, marine terraces, peat bogs, salt marshes, and archaeological data. The data are quality controlled, given standardized indicative meanings, and calibrated to current standards. We employ an ensemble of Bayesian hierarchical statistical models, trained on the database's index points and weighted by their fit to both index and limiting points, to analyze the spatiotemporal patterns of Norwegian RSL change.

Continuous RSL fall driven by isostatic rebound in response to Eurasian ice sheet collapse dominates the sea-level signal at every inland location in Norway. A first transgression (sea-level highstand) occurred in Southwest Norway during the Younger Dryas (14 - 11.7 ka). We conjecture that this event, which increased RSL by as much as 15 meters, occurred because of local ice sheet readvance in a region of weak solid earth structure.

A second transgression, named the Tapes transgression, took place during the early-mid Holocene (10 ka - 5.5 ka). The statistical model ensemble constrains the timing, amplitude, and spatial pattern of the Tapes transgression and suggests that a global mean sea level rise that temporarily outpaced sea-level fall due to glacial isostatic adjustment was the chief cause of this event. We also discuss the effect that peripheral bulge migration may have had on the local sea-level response. Our work demonstrates that compiling high resolution data and combining them with statistical models can help improve understanding of how nearfield sea level changes through space and time over glacial-interglacial time scales.

A 5000-year record of relative sea-level change in New Jersey: implications for glacial isostatic adjustment models

Walker, J.S. (1); Li, T. (2); Shaw, T.A. (2); Cahill, N. (3); Barber, D.C. (4); Brain, M. (5); Kopp, R.E. (1); Switzer, A.D. (2); Horton, B.P. (2)

(1) Rutgers University; (2) Nanyang Technological University; (3) Maynooth University; (5) Bryn Mawr College; (6) Durham University

POSTER

Glacial isostatic adjustment (GIA) is the dominant driver of late Holocene relative sea-level (RSL) rise along the U.S. mid-Atlantic coast, due to its proximity to the margin of the former Laurentide Ice Sheet. Geological reconstructions of past RSL are of particular importance to constrain the geophysical properties of GIA models, since they record the temporal and geographical evolution of coastlines. Accurate and precise RSL reconstructions can be provided by salt marsh sediments; however, salt-marsh based sea-level reconstructions must take into account local processes such as sediment compaction and tidal range change. Here, we produced a mid- to late-Holocene RSL reconstruction from a salt marsh in southern New Jersey and accounted for these local processes.

The RSL reconstruction is based on a suite of vertically- and laterally-ordered basal peats that were collected along a transect with a uniform gradient in the basal sand contact from a depth of ~2 m which deepens towards the coast to a depth of ~9 m. We used a multi-proxy approach (foraminifera and geochemistry) to identify the indicative meaning of the basal peats. We produced 14 sea-level index points (SLIPs) that include a vertical uncertainty for tidal range change and sediment compaction and a temporal uncertainty based on high precision Accelerator Mass Spectrometry radiocarbon dating of salt-marsh plant macrofossils. We combined our RSL data with published SLIPs from New Jersey and found that RSL rose continuously by approximately 7.5 m at an average rate of 1.6 ± 0.2 mm/yr (1σ) since 4,700 cal. yr BP. The New Jersey sea-level database (n = 53 SLIPs) is compared to an ensemble of ten site-specific 1D (laterally homogenous) and 3D (laterally heterogeneous) GIA models. Most of the GIA models appear to overestimate the magnitude of sea-level rise over the last 5 ka by as much as ~4 m at 4,500 cal. yr BP. The 3D viscosity models exhibit an improved fit compared to the 1D model; however, the continued discrepancy between RSL data and GIA models highlight the importance of using a wide array of ice and viscosity models in GIA models to more precisely fit site-specific RSL data along the U.S. mid-Atlantic coast.

Relative sea-level changes in Micronesia, Western Pacific Ocean

Sefton, J. (1); Kemp, A. (1); Engelhart, S. (2); Karegar, M. (3); Taylor, F. (4)

(1) Tufts University; (2) Durham University; (3) University of Bonn; (4) University of Texas Austin

POSTER

Relative sea-level (RSL) reconstructions provide insight into the causes of sea-level change by recognizing spatially- and temporally- consistent trends that are the telltale fingerprint of specific physical processes. However, Late Holocene RSL records are unevenly distributed, with most data coming from the North Atlantic Ocean. We present a detailed new Late Holocene RSL reconstruction derived from mangrove sediment preserved in the tropical western Pacific Ocean (Federated States of Micronesia; FSM). FSM is a far-field site and all reasonable combinations of Earth-ice models predict a Mid-Holocene highstand and subsequent Late Holocene RSL fall (<0.5 mm/yr) that is uniform across FSM. This pattern is typical of the tropical Pacific and hinders efforts to produce RSL reconstructions from coastal sediment because accommodation space is not created. However, previous studies and our observations show that ~4 m thick mangrove sequences of Late Holocene age are preserved on Pohnpei and Kosrae islands where tidal range is ~0.8 m. These sediments indicate sustained RSL rise because mangroves inhabit a narrow and quantifiable elevation range with respect to mean tide level. This net RSL rise (~0.86 mm/yr) most likely arose from ongoing regional-scale subsidence at a sufficient rate (>1 mm/yr) to enable continual accretion of mangrove sediment. The occurrence and anomalous nature of this subsidence is further confirmed by a network of permanent GPS stations, the difference between satellite altimetry and tide gauge records, the modern location of archaeological sites, and notable absence of any geomorphic evidence for a Mid-Holocene highstand. However, the cause of this subsidence remains elusive under reasonable assumptions about possible processes and the geological history of Pohnpei, Kosrae, and the surrounding oceanic crust. Fingerprints of sea-level change from melting land-based ice demonstrate that FSM experiences the same rise regardless of melt source and that fingerprints do not vary by location within FSM. Therefore, it is an ideal location to constrain global mean sea level because interpretation of RSL reconstructions with respect to ocean mass are not dependent on any assumed spatial pattern of ice melt. Incorporating the reconstructed RSL history of FSM into an existing database of Common Era RSL records allows us to recalculate GMSL change.

Coastal Highstand Deposits Archive Late-Pleistocene Regional Sea-Level Variability Along the US Mid-Atlantic Coast

Kayla M. Cahoon (1), Cameron G. Clarke (1), Michael S. Fenster (2), Joseph P. Vaughn (2), Christopher J. Hein (1)

(1) Virginia Institute of Marine Science; (2) Randolph-Macon College

POSTER

The United States Mid-Atlantic Coast is experiencing one of the fastest rates of sea-level rise in the country due to combined post glacial isostatic rebound and regional oceanographic forcings. Quantifying the elevation, rates, and directions of sea-level change during past highstands provides an important constraint on future sea-level rise and associated coastal-system responses. However, contradictory and confounding ages of Late-Pleistocene sedimentary deposits in this region have hindered the development of a reliable and reproducible regional sea-level curve. We hypothesize this is likely due to misinterpretation of the depositional history of the Wachapreague Formation (Qw), the youngest of several Pleistocene highstand units comprising the southern Delmarva Peninsula. Here, we present a depositional model for Qw using new and previously published morphological (LiDAR), geophysical (ground-penetrating radar), stratigraphic (sediment cores), geochemical (carbon/nitrogen), and geochronological (optically stimulated luminescence, amino acid racemization) data. From these data, we infer that Qw, formerly treated as a single unit, was constructed during two sequential sea-level highstands separated by ~20,000 years. Its western component was deposited ca. 75 ka and is characterized by medium-fine, 1-3o southeastern (seaward) dipping sandy beach and foredune ridges. In contrast, the eastern segment of Qw is characterized by fine sand with heavy mineral laminations and contains evidence of washover, dune, and channel fill deposits overlying a 3-12 m thick layer of clayey sandy silt with mulinia shells. It is interpreted as a transgressive backbarrier and barrier-island system partially welded to the regressive western Wachapreague at ca. 55 ka. This new chronostratigraphic interpretation refines the depositional model for the southern Delmarva and indicates that the direction of sea-level change in this region reversed at least once following the last interglacial highstand. These data indicate that sea level was at or higher than present in the Mid-Atlantic US ~10,000 years earlier than shown by other field and modeling studies,

but nonetheless confirm that such elevations were reached multiple times during a period when global eustatic sea level was ~40 m below present.

Glacial-isostatic deformation of the Last Glacial Maximum Mississippi River terrace

Wickert, A. D. (1); Clubb, F. J. (2); Larson, P. H. (3); Glade, I. (3)

(1) University of Minnesota; (2) Durham University; (3) Minnesota State University Mankato

POSTER

Records of glacial isostatic adjustment (GIA) abound in nearshore environments, where uplift and/or subsidence of coastal terraces, beach spits, coral reefs, and mangrove forests provide datable archives of relative sea level and/or lake level. Within regions of the continental interior that lack large lakes, we likewise lack such ready-made and initially horizontal surfaces, and must turn to other records. Here we map the Last Glacial Maximum (LGM) Savanna Terrace of the upper Mississippi River from the Twin Cities in Minnesota to Cape Girardeau in Missouri, USA, a distance of approximately 1250 km. The largely north–south course of the Mississippi sends it near-directly away from the Laurentide Ice Sheet margin, making it a spatially distributed probe of the profile of post-LGM GIA. Alluvial rivers with significant headwaters sediment input, like the glacial-stage Mississippi, typically have straight-to-concave-up long profiles; our modern-day Savanna Terrace broadly follows this pattern, but also contains significant undulations, which indicate relative uplift and subsidence that postdate its ~17 ka abandonment. By applying the GIA field calculated by Gowan et al. (2021), we are able to restore a smoother river long profile, although it still contains an anomalous upwarp near the Des Moines River Rapids. This may be the result of the shallow bedrock impeding alluvial-river change. Alternatively, it could indicate that the uniform solid-earth paramters chosen (120 km elastic thickness; upper and lower mantle viscosities of 4×10^{20} and 4×10^{22} Pa s, respectively) do not adequately represent the lithospheric and mantle conditions of North America as one traverses from the Canadian Shield (where they are more likely appropriate) towards the Paleozoic basins and New Madrid Seismic Zone.

Last Interglacial global mean sea level derived from U-series dated coral reefs of the Bahamian islands

Dumitru, O.A. (1), Dyer, B. (2), Austermann, J. (1), Sandstrom, M.R. (1), Cashman, M. (1), Goldstein, S.L. (1), D'Andrea, W. (1), Creel, R. (1), Raymo, M.E. (1)

(1) Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, 10964, USA; (2) School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, Canada

POSTER

The timing, magnitude, and evolution of sea-level change during the Last Interglacial period (Marine Isotope Stage (MIS) 5e) are subject of ongoing debate. Previous estimates of global mean sea level (GMSL) appear to converge on values of 6 to 9 meters above present levels, with one or more oscillations of up to several meters. However, more recent observational and modeling studies challenge this range suggesting values might be considerably lower. Major difficulties in resolving this debate are uncertainties in MIS 5e chronologies and lack of understanding of Earth deformation processes, such as glacial isostatic adjustment and dynamic topography, which deform local sea level relative to GMSL.

Here we present a new series of high-precision U-Th ages combined with detailed elevation measurements of emergent in-situ corals from four Bahamian islands: Crooked Island, Long Cay, Long Island, and Eleuthera. We identified and sampled corals from several paleo-habitats, including platform edge reefs and both isolated corals and patch reefs from the paleo-lagoon. The elevations of surveyed corals range from 0 to 4.4 m above present sea level. Following a rigorous screening protocol to evaluate and maximize the likelihood of closed-system behavior of our samples, the ages we deem reliable range from ~126 to ~118 ka (with δ234Ui values between 143.8 and 151.3 ‰). We infer GMSL from these local sea level observations by correcting our data for glacial isostatic adjustment via a probabilistic assessment of sea-level predictions from a set of ice histories and Earth deformation models consistent with sea-level data from across the Bahamian archipelago. The corals' chronology and the estimated paleo-water depth associated with the structural zone of each reef, provide important constraints on model uncertainties. This analysis allows us to test hypotheses about the susceptibility of ice sheets to melting in the face of global warming.

Holocene sea level change in the South Shetland Islands revisited

Romero, M. (1); Simms, A.R. (2); Strelin, J.A. (3)

(1) Universidad Nacional de Córdoba; (2) UC Santa Barbara; (3) Instituto Antarctico Argentino

POSTER

During the last decades, the Antarctic Peninsula has experienced unprecedented rapid regional warming (Vaughan et al., 2003). Increased glacier-surface melt during the twenty-first century has contributed to ice-shelf collapse and the widespread acceleration, thinning, and recession of glaciers (Davies et al., 2014). These changes resulted in rapid uplift (Thomas et al., 2011) and highlighted the importance for better constraints on the ice unloading history. If the amount of isostatic uplift outpaces eustatic sea-level rise, relative sea level (RSL) falls, resulting in the creation of raised marine features. Therefore, dating marine features can be used to create past records of sea-level change to test geophysical models of rebound, as well as other cryospheric changes.

Holocene ice mass changes are recorded in the geological record of the northern Antarctic Peninsula as changes in the elevation of RSL. In order to provide robust centennial to millennial-scale RSL records, we conducted fieldwork in the South Shetland Islands during the 2020/2021 austral summer. We conducted a comprehensive survey employing differential GPS and an uncrewed aerial vehicle (UAV) of the beach ridges in Nelson Island and King George Island, within the South Shetland Islands, including Duthoit Point, Potter Peninsula and Barton Peninsula, respectively. The Holocene beach ridges are found at elevations reaching 18-20 m above sea level. Moreover, we sampled organic remains preserved in the beaches to determine the age of formation and sea level change. We assess ice mass changes during the Holocene in one of the most rapidly changing regions of the world.

Postglacial Relative Sea-Level Changes in the Gulf of Maine, USA: A Challenge for GIA Models

Baril, A. (1); Garrett, E. (2); Milne, G. (3); Gehrels, R. (2); Kelley, J. (4), Tarasov, L. (5)

(1) Department of Physics, University of Ottawa, Ottawa, Canada; (2) Department of Environment and Geography, University of York, York, UK; (3) Department of Earth and Environmental Sciences, University of Ottawa, Ottawa, Canada; (4) Department of Earth and Climate Sciences, University of Maine, MA, USA; (5) Department of Physics and Physical Oceanography, Memorial University, St John's, Canada

POSTER

Relative sea level (RSL) reconstructions from paleo records are often the most valuable data set in testing and constraining glacial isostatic adjustment (GIA) models. In some regions, the amplitude and rate of the reconstructed RSL changes are large making the data difficult to fit (e.g. Yousefi et al., Geophysical Journal International, Vol. 193, 2018). Arguably, the reconstructed RSL curve from Maine, USA, is the classic example of such a data set with peak values at about 120 m dropping to a lowstand of around -40 m within a few kyr. To our knowledge, no GIA model has captured these extreme variations and the record has been somewhat neglected by the GIA community. Here we critically assess and present a revised pre-10 ka RSL data base for this region and combine it with a recent Holocene compilation (Engelhart and Horton, Quaternary Science Reviews, Vol. 54, 2012). To determine if a successful model fit can be found, a parameter set of about 15 ice models combined with 330 spherically-symmetric, Maxwell Earth viscosity models is considered. The majority of ice models comprise North American deglacial histories from an ensemble calibration (Tarasov et al., Earth and Planetary Science Letters, Vol. 315-316, 2012) combined with the ICE-5G model as background (Love et al., Earth's Future, Vol. 4, 2016). We also include the ANU and ICE-6G global ice models. Results to date show that none of the ice models produce a good fit for the large suite of 1D viscosity models considered. Specifically, the modelled timing and rate of RSL fall are generally too early and low, and the RSL low stand from the models is significantly higher than that observed. If a model fit is not possible regardless of the adopted ice model, the next step will be to consider more complex models of Earth rheology (e.g. those including transient and/or non-linear effects).

A standardized database of last interglacial (MIS 5e) sea-level indicators in the Western Atlantic and Southwestern Caribbean, from Brazil to Honduras

Rubio-Sandoval, K. (1); Rovere, A. (1); Cerrone, C. (2); Stocchi, P. (3);Lorscheid, T. (4); Felisa, T. (1); Petersen, A.K. (1) Ryan,D. (1)

(1) MARUM - Center for Marine Environmental Sciences, University of Bremen, Germany; (2) Dipartimento di Scienze della Terra, Universitá degli Studi di Pisa, Italy; (3) NIOZ, Royal Netherlands Institute for Sea Research, Coastal Systems Department, and Utrecht University, PO Box 59 1790 AB Den Burg (Texel), The Netherlands; (4) Department of Geography - Research Group for Earth Observation (rgeo), Heidelberg University of Education, Germany

POSTER

Interglacials are generally characterized by warmer temperatures and decreased ice sheet extent. In particular, the Last Interglacial (MIS 5e, ~128-116 ka) is often regarded as a process-analog for a future climate projections. During this period, global average temperatures were 2°C higher than pre-industrial time, and the global mean sea level was higher. Estimates of MIS 5e sea levels in the Western Atlantic and Southwestern Caribbean coasts (from Brazil northwards to Honduras) range approximately from 2 to 12 m above the present level; however, there are large uncertainties associated with these values. We use the World Atlas of Last Interglacial Shorelines (WALIS) database to standardize and evaluate the quality of the sea-level record and its uncertainties. Using WALIS, we reviewed published data for the countries of Brazil, French Guiana, Suriname, Guyana, Venezuela, Colombia, Panama, Costa Rica, Nicaragua, Honduras as well as the islands Bonaire, Curaçao and Aruba. Our review produced 55 standardized datapoints, each assigned to one or more age constraints. Sea-level indicators are well preserved along the Brazilian coasts, providing an almost continuous north-to-south transect. Despite this and the variety of relative sea-level indicators (i.e. beach deposits, coral reef terraces, marine terraces, *Ophiomorpha* burrows, and tidal notches) our data compilation highlights several concerns related to age control and the accuracy of elevation measurements. We identify that the coasts of Northern Brazil, French Guyana, Suriname, Guyana, and Venezuela would benefit from a renewed study of Pleistocene sea-level indicators, as it was not possible to identify sea-level datapoints for the last interglacial coastal outcrops along the coasts of these countries. Future research must also be directed at improving the chronological control at several locations, and to

evaluate the effect of tectonics in the area, since with the exception of the Caribbean islands, there is a controversy about the effect it may have on the rest of the region, finally several sites would benefit from re-measurement of sea-level indicators using more accurate elevation measurement techniques. Improving our knowledge of sea-level changes during the Last Interglacial is key to assessing the future of the coastlines under warmer climatic conditions.

Exploring new archives of Holocene relative sea-level changes and their importance in enabling the assessment of Glacial Isostatic Adjustment models.

Richards, G.T. (1); Li, T. (1); Ikhsan, M.H. (1); Horton, B.P. (1); Anderson, W.P. (2); Gehrels, W.R. (3)

(1) Earth Observatory of Singapore, Nanyang Technological University, Singapore; (2) Appalachian State University, Department of Geological and Environmental Sciences, USA; (3) University of York, Department of Environment and Geography, United Kingdom

POSTER

Glacial Isostatic Adjustment (GIA) model predictions of Holocene relative sea-level (RSL) change for the Irish Sea are spatially variable. The deglaciation of the British-Irish Ice Sheet from the Last Glacial Maximum induced an isostatic gradient north to south along the Welsh and Irish coastlines. Moreover, this region is also affected by the deglaciation of Fennoscandian Ice Sheet. Constraining the complex GIA process of the Irish Sea, however, is hampered due to a sparsity of geological data.

The sparsity of Holocene RSL data arises from absence of traditional archives of RSL change (e.g., salt marshes) along much of the Irish Sea coastlines. Here, we present a new archive from a back-barrier freshwater marsh in Pembrokeshire, Wales which show RSL rise of ~8m between ~7 ka BP to ~3 ka BP. We combine new and published RSL data to produce a standardized database of sea-level index points (SLIPs) from the Irish Sea and compare them against both 1D (laterally homogeneous) and 3D (lateral heterogeneous) GIA model predictions. The database contains more than 80 SLIPs, covering ~11 ka of RSL history.

The 3D GIA model, which is tuned for North America and Fennoscandia, fits the RSL data in the early Holocene (e.g., northern Wales) while overpredicts the RSL during the middle to late Holocene at most sites. The 1D GIA model ICE-7G_NA (VM7) can capture the RSL history for the middle to late Holocene but underpredicts the RSL for the early Holocene. Our research implies that the GIA parameters (e.g., mantle viscosity, deglaciation history) in this region need to be further refined with the new standardized RSL database.

WALIS Explorer: A tool to visualize sea level indicators

Garzón, S. (1); Rovere, A. (2)

(1) University of Münster; (2) Center for Marine Environmental Sciences - MARUM

POSTER

Standardization of sea-level indicators (SLI) has been one of the common goals of sea-level scientists to improve the sharing and discovery of new data. Recent efforts include the World Atlas of Last Interglacial Shorelines (WALIS), a standardized database structure resulted from the WARMCOASTS project (ERC-StG 802414), and PALSEA (a PAGES-INQUA working group). Beyond the advantages of standardization for interoperability of data from multiple research groups, sea-level model fitting, and reproducibility of research results, WALIS facilitates the development of interactive tools to explore sea-level data. In this sense, we present WALIS-Explorer, an R-Shiny application to visualize the sea-level index points and limiting data available in WALIS. With WALIS-explorer, we aim to create an easily accessible entry point to explore sea-level data and serve as an academic tool for sea-level concepts. This application allows users to rapidly visualize sea-level indicators from different parts of the world without coding skills or download the dataset. The application includes filtering options by age, relative sea level, and geographical parameters (e.g., dating technique and vertical uncertainty of measurements), relative sea-level graphs, geo visualizations of indicators, and summary tables with complementary information. The publication process of the first release of WALIS-Explore suggests that the database structure facilitates the development of tools providing the required metadata of sea-level indicators.

On the Cause of the Mid-Pleistocene Transition

Tijn Berends (1)

(1) Utrecht University

POSTER

The Mid-Pleistocene Transition (MPT), where the Pleistocene glacial cycles changed from 41 to ~100 kyr periodicity, is one of the most intriguing unsolved issues in the field of paleoclimatology. Over the course of over four decades of research, several different physical mechanisms have been proposed to explain the MPT, involving non-linear feedbacks between ice sheets and the global climate, the solid Earth, ocean circulation, and the carbon cycle. Here, we review these different mechanisms, comparing how each of them relates to the others, and to the currently available observational evidence. Based on this discussion, we identify the most important gaps in our current understanding of the MPT. We discuss how new model experiments, which focus on the quantitative differences between the different physical mechanisms, could help fill these gaps. The results of those experiments could help interpret available proxy evidence, as well as new evidence that is expected to become available.

A Holocene relative sea-level database for the Baltic Sea

Klemann, V. (1); Rosentau, A. (2); Bennike, O. (3); Steffen, H. (4) and the Baltic SL Data Team

(1) GFZ-Potsdam, Germany; (2) University of Tartu, Estonia; (3) Geological Survey of Denmark and Greenland, Denmark; (4) Lantmäteriet, Sweden

POSTER

We present a compilation and analysis of ~ 1000 Holocene relative shore-level (RSL) indicators located around the Baltic Sea including relative sea-level data points as well as data points from the Ancylus Lake and the following transitional phase. The spatial distribution covers the Baltic Sea and near-coastal areas fairly well, but some gaps remain mainly in Sweden. RSL data follow the standardized HOLSEA format and, thus, are ready for spatially comprehensive applications in, e.g., glacial isostatic adjustment (GIA) modelling. We apply a SQL database system to store the nationally provided data sets in their individual form and to map the different input into the HOLSEA format as the information content of the individual data sets from the Baltic Sea area differs (https://doi.org/10.5880/GFZ.1.3.2020.003).

The majority of the RSL data is related to the last marine stage in Baltic Sea history after 8.5 ka BP (thousand years before present). These samples were grouped according to their dominant RSL tendencies into three clusters: regions with negative, positive and complex (transitional) RSL tendencies. Overall, regions with isostatic uplift driven negative tendencies dominate and show regression in the Baltic Sea basin during the last marine stage. Shifts from positive to negative tendencies in RSL data from transitional regions show a mid-Holocene highstand around 7.5-6.5 ka BP which is consistent with the end of the final melting of the Laurentide Ice Sheet. Comparisons of RSL data with GIA predictions including global ICE-5G and ICE-6G_C ice histories show good fit with RSL data from the regions with negative tendencies, whereas in the transitional areas in the eastern Baltic, predictions for the mid-Holocene clearly overestimate the RSL and fail to recover the the region where a mid-Holocene RSL highstand derived from the proxy reconstructions should appear. These results motivate improvements of ice-sheet and Earth-structure models and show the potential and benefits of the new compilation for future studies.

Poster Session 2: Modelling

The Impact of 3D Earth Structure on Predictions of Far-Field Sea-Level Changes Since the Last Glacial Maximum

Linda Pan (1), Glenn A. Milne (2), Konstantin Latychev (1,3), Jacqueline Austermann (3), Mark J. Hoggard (1,3,4), Samuel Goldberg (5), Jerry X. Mitrovica (1).

(1) Department of Earth and Planetary Sciences, Harvard University; (2) Department of Earth and Environmental Sciences, University of Ottawa; (3) Lamont-Doherty Earth Observatory, Columbia University; (4) Research School of Earth Sciences, Australian National University; (5) Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology.

POSTER

The mapping between far-field relative sea level (RSL) records and changes in ice volume or global mean sea level (GMSL) involves a correction for glacial isostatic adjustment (GIA). This mapping is thus sensitive to uncertainties inherent to GIA modeling, including the spatio-temporal history of ice mass changes and viscoelastic Earth structure. Austermann et al. (2013) demonstrated that lateral variations in mantle viscosity in the vicinity of Barbados, in particular the presence of a high viscosity slab associated with the subduction of the Caribbean Plate, would significantly alter post-LGM crustal dynamics in the region. They conclude that, to maintain a fit to the coral record of RSL change at this site, the total excess ice volume at LGM must be increased by ~7 m relative to inferences based on standard 1-D Earth modeling.

Here, we extend the 2013 analysis using four models for the 3-D viscosity field within the Earth's mantle, two models for lithospheric thickness variations, as well as two ice histories. We present global maps of the differences between these runs and a set of 1-D runs at the LGM. This allows us to systematically isolate effects associated with ice history, lithospheric thickness, as well as the seismic model upon which lateral variations in the viscosity field are based. Finally, we focus on RSL histories at 3 sites in addition to Barbados that have been previously analyzed to estimate excess GMSL at LGM: Great Barrier Reef, Bonaparte Gulf and Huon Peninsula. We find that the effect of introducing lateral variations in Earth structure on estimates of GMSL peaks at ~7 m in Barbados, with the largest differences occurring around the LGM.

The Impact of 3-D Earth Structure on Far-Field Sea Level Following Interglacial West Antarctic Ice Sheet Collapse

Powell, E. (1); Pan, L. (1); Hoggard, M. (2); Latychev, K. (1); Gomez, N. (3); Austermann, J. (4); Mitrovica, J. (1)

(1) Harvard University; (2) Australian National University; (3) McGill University; (4) Columbia University

POSTER

Prior to inferring ice sheet stability from interglacial sea-level records, these data must be corrected for glacial isostatic adjustment (GIA) driven by ice-ocean mass flux. In this presentation we focus on the GIA signal driven by excess (relative to present day) mass flux from the West Antarctic Ice Sheet (WAIS) during interglacials and explore the importance of incorporating realistic, 3-D Earth structure in the modeling. The mantle beneath the Antarctic has a complex rheological setting: East Antarctica is characterized by a thick (~200 km) lithosphere overlying a shallow mantle with a viscosity typical of cratons, 1020-1021 Pa s; in contrast, the lithosphere thins to ~50 km and viscosity within the asthenosphere is as low as ~1018 Pa s beneath the West Antarctic Rift System. Hay et al. (J. Clim., 2017) considered the impact of this structure on predictions of near-field sea-level change following WAIS collapse. We extend this work to consider the impact of lateral variations in Earth structure on sea level in the far field of WAIS collapse. We demonstrate – consistent with the arguments of Crawford et al. (GJI, 2018) – that the signal reflects variability in structure both under the load and observation site. Near to WAIS, this signal includes the impact of both the rebound of exposed marine-based sectors of the ice sheet, and the associated outflux of water from these regions (Pan et al., Science Adv., 2021), and the subsidence of the surrounding peripheral bulge. The net effect of lateral variations in lithospheric thickness and mantle viscosity on far-field sea-level predictions peaks at ~0.3 m. While this is ~10% of the GMSL change associated with our adopted collapse scenario, it is comparable in magnitude to departures from GMSL within the far field.

Does glacial isostatic rebound provide a stabilizing mechanism along rapidly retreating marine-based ice streams?

Alexander R. Simms (1), Louise Best (2), Ian Shennan (3), Sarah L. Bradley (4), David Small (3), Emmanuel Bustamante (3), Amy Lightowler (3), Dillon Osleger (1), Juliet Sefton (3).

(1) UC Santa Barbara; (2) University of Gloucestershire; (3) Durham University; (4) University of Sheffield University

POSTER

The record of ice-sheet demise since the last glacial maximum (LGM) provides an opportunity to test the relative importance of instability mechanisms, including relative sea-level (RSL) change, controlling ice-sheet retreat. Glacial isostatic adjustment (GIA) in the form of post-glacial rebound is thought to provide a possible stabilizing mechanism during marine ice sheet retreat. Here we examine the record of RSL changes accompanying the retreat of the Minch Ice Stream (MIS) of northwest Scotland during the deglaciation following the LGM. We use new and existing records of RSL change obtained from isolation basins in Wester Ross along the flanks of the former MIS to test available glacial- GIA predictions of the deglacial RSL history for the region. Using these GIA models we examine the nature of RSL change across the retreating front of the MIS through the early deglaciation. Our new radiocarbon ages from these basins confirms the timing of deglaciation within the inner trough of the MIS as well as refines the age of the Wester Ross Readvance, both established by earlier cosmogenic-based studies. We find that the Wester Ross Readvance culminated around 16.3 ± 0.5 ka, slightly older than recent suggestions. Near Gairloch, Wester Ross, RSL fell from a marine limit ~20 m above present, with an estimated age ~16.1-16.5 ka. Three isolation basins record RSL fall over the following ~0.8 ka. Our new RSL constraints are more consistent with GIA model predictions that use thicker ice over northwest Scotland; however, these same GIA models over predict RSLs for other regions of the British Isles. Our new analyses suggest that the rate of RSL rise increased at the ice front, in concert with the MIS encountering a landward sloping bed potentially aiding the rapid retreat of the MIS from 17.6 to 16.4 ka BP. This observation suggests that deglaciation does not necessarily induce a stabilizing RSL change to ice streams. Along indented ice margins, the RSL field at the front of individual ice streams may be governed by the regional RSL signal driven by the ice sheet as a whole, rather than the local ice front. In addition, the stabilizing impact of post-glacial rebound is dependent on an Earth rheology weak

enough to respond quickly to the ice-sheet retreat. In the case of the MIS, the RSL experienced at the front of the ice stream was likely governed by the earlier ice mass extent, the larger ice masses lying to the east and south of the highly indented ice front, and the relatively strong Earth rheology beneath the British Isles. Thus the geometry of the ice sheet margins, such as those in Greenland and Antarctica today, and the Earth rheology beneath them need to be taken into account when considered the stabilizing impact of post-glacial rebound on marine ice sheet retreat.

Reconciling inferences of Greenland's upper mantle viscosity across a range of timescales using transient rheology models

Paxman, G. J. G. (1); Lau, H. C. P. (2); Austermann, J. (1); Holtzman, B. K. (1)

(1) Lamont-Doherty Earth Observatory, Columbia University; (2) University of California, Berkeley

POSTER

Contemporary crustal uplift in Greenland is caused by the combined response of the solid Earth to both ongoing and past ice mass changes. Glacial isostatic adjustment (GIA) models seek to constrain the ice history and/or Earth rheology that best matches the uplift rates observed today by geodetic instrumentation and the long-term uplift history constrained by geological sea level data. Historically, most GIA studies have employed a linear Maxwell viscoelastic rheology, with an instantaneous elastic response superimposed on a longer-term viscous relaxation with a temporally-constant mantle viscosity, which governs the rate of the viscous deformation. In Greenland, however, it has been recently demonstrated that upper mantle viscosities inferred from modern crustal motion data (sub-centennial timescales) are approximately one order of magnitude lower than viscosities inferred from geological sea level data (multi-millennial timescales). Reconciling these observations may require a more complex mantle rheology than the classical Maxwell model.

Here, we use an open-source code library known as the 'Very Broadband Rheology calculator' (VBRc) to calculate the frequency-dependent apparent upper mantle viscosity for a range of 'higher order' constitutive rheological models. Our approach is divided into two steps. First, we use the shear wave velocity (Vs) and attenuation (Q^-1) from seismic tomography models to constrain the thermodynamic state parameters (e.g., temperature, melt fraction, and grain size) of the upper mantle beneath Greenland. Second, we apply the inferred thermodynamic state to a range of broadband constitutive models (e.g., extended Burgers, chi-fit with pre-melting scaling) to calculate the mechanical properties of the mantle, including the apparent viscosity, across a range of timescales between 10^1 and 10^6 years. We find that the apparent upper mantle viscosity increases with the timescale of the loading, with values of 10^19–10^20 Pa s associated with Little Ice Age (ca. 200 yr) timescales, and values of 10^20–10^21 Pa s associated with Last Glacial Maximum (ca. 20 kyr) timescales. These values are in good agreement with observations from geodetic uplift rates and geological sea level data, respectively. Complex (transient) rheologies therefore provide a means of reconciling geological and geodetic inferences of upper mantle viscosity. Future GIA studies in Greenland and other glaciated or recently deglaciated regions should therefore consider the use of broadband rheological models to more fully capture mantle relaxation across a broad range of timescales.

GPS-observed elastic deformation due to surface mass balance variability in the southern Antarctic Peninsula

Koulali, A. (1); Clarke, P.J. (1); Whitehouse, P.L. (2); van den Broeke, M.R. (3); Nield, G.A. (2); King, M.A. (4); Bentley, M.J. (2); Wouters, B. (3,5); Wilson, T. (6)

(1) Newcastle University, UK; (2) Durham University, UK; (3) Utrecht University, Netherlands; (4) University of Tasmania, Australia; (5) Delft University of Technology, Netherlands; (6) Ohio State University, USA.

POSTER

Antarctic time series of vertical surface displacement from the Global Positioning System (GPS) show non-linear signals over a range of time scales. The Earth's instantaneous elastic response to contemporary ice mass change is one of the main contributors to variability in Antarctic GPS records. To study the time-evolution of this contribution, we use surface mass balance (SMB) models to derive time series of elastic surface deformation at four GPS locations in the southern Antarctic Peninsula. We show that interannual variations of SMB anomalies cause measurable elastic deformation. After correcting for SMB-related elastic effects, GPS time series show a reduction in the misfit when fitting linear trends, implying that to infer rheological properties of the mantle from GPS data, it is necessary to remove the elastic component associated with present-day ice mass change.

Towards an improved understanding of vertical land motion and sea-level change in eastern North America

Parang, S. (1); Milne, G. A. (1); Karegar, M. A. (2); Tarasov, L. (3)

(1) Department of Earth and Environmental Sciences, University of Ottawa, Ottawa, Ontario, Canada; (2) Institute of Geodesy and Geoinformation, University of Bonn, Bonn, Germany; (3) Department of Physics and Physical Oceanography, Memorial University of Newfoundland, NL, Canada

POSTER

Many coastal cities are an early casualty in the sea-level battle because of processes resulting in land subsidence and thus enhanced relative sea-level (RSL) rise. Much of the Atlantic coast of North America has been sinking for thousands of years, at a maximum rate of ~20 cm per century as a consequence of solid earth deformation in response to deglaciation of the Laurentide ice sheet (between ~18,000 and ~7,000 years ago) [e.g. Love et al., Earth's Future, 4(10), 2016]. Karegar et al. [Geophysical Research Letters, 43(7), 2016] have shown that vertical land motion along the Atlantic coast of the USA is an important control on nuisance flooding. A key finding in this study is that while glacial isostatic adjustment (GIA) is the dominant process driving land subsidence in most areas, there can be large deviations from this signal due to the influence of anthropogenic activity impacting hydrological processes. For example, between Maine (45°N) and New Hampshire (43°N), the GPS data show uplift while geological data show long-term subsidence. The cause of this discrepancy is not clear, but one hypothesis is increasing water mass associated with the James Bay Hydroelectric Project in Quebec [Karegar et al., Scientific Report, 7, 2017].

The primary aim of this study is to better constrain and understand the processes that contribute to contemporary and future vertical land motion in this region to produce improved projections of mean sea-level change and nuisance flooding. The first step towards achieving these aims is to determine an improved GIA model for this region. We make use of two regional RSL data compilations: Engelhart and Horton [Quaternary Science Reviews, 54, 2012] for northern USA and Vacchi et al. [Quaternary Science Reviews, 201, 2018] for Eastern Canada, comprising a total of 1313 data points (i.e. sea level index points and limiting data points) over 38 regions distributed throughout our study region. These data are well suited to determine optimal GIA model parameters due to the magnitude of other signals being much smaller, particularly in near-field regions such as Eastern Canada. We consider a large suite of ~30 ice history models that is comprised mainly of a subset from Tarasov et al. [Earth and Planetary Science Letters, 315–316, 2012] as well as the ICE-6G and ANU models. We have computed RSL for these ice histories using a state-of-the-art sea-level calculator and 440 1-D earth viscosity models per each ice history model to identify optimal model parameter sets and estimate model uncertainty using both heuristic and Bayesian approaches.

Examining patterns of transient deformation in predictions of relative sea level

Simon, K. M. (1); Riva, R.E.M. (1)

(1) Delft University of Technology

POSTER

In this study, we examine the effect of transient mantle creep on the prediction of glacial isostatic adjustment quantities. Specifically, we compare predictions of relative sea level change from GIA from a set of Earth models in which transient creep parameters are varied to a reference case with a standard Maxwell viscoelastic rheology. The model predictions are evaluated in two ways: first, relative to each other to quantify the effect of parameter variation, and second, for their ability to reproduce well-constrained sea level records from selected locations.

The influence of the solid Earth on the contribution of marine sections of the Antarctic ice sheet to sea level change

Yousefi M. (1&2); Gomez, N. (1); Latychev, K. (3,4); Pollard D. (2); DeConto R. (5)

(1) McGill University, Earth and Planetary Sciences, Montreal, Canada; (2) College of Earth and Mineral Sciences, Department of Geosciences, Penn State University, USA; (3) Department of Earth and Planetary Sciences, Harvard University, Cambridge, USA; (4) Lamont-Doherty Earth Observatory, Columbia University, USA; (5) Department of Geosciences, University of Massachusetts Amherst, Amherst, MA, USA.

POSTER

The future retreat of marine-based sectors of the Antarctic Ice Sheet (AIS) and its consequent global mean sea level (GMSL) rise is driven by various climatic and non-climatic feedbacks between ice, ocean, atmosphere, and solid Earth. The primary mode of ice loss in marine sectors of the AIS is dynamic flow of ice across the grounding line into the ocean. The flux of ice across the grounding line is strongly sensitive to the thickness of ice there, which is in turn proportional to the water depth (sea level) such that sea level rise enhances ice loss and grounding line retreat while sea level fall acts to slow or stop migration of the grounding line. In response to the unloading from removal of ice mass, the underlying bedrock deforms isostatically leading to lower local sea surface which promotes stabilization of the grounding line. In addition to its effect on AIS evolution, solid Earth deformation also alters the shape and size of the ocean basin areas that are exposed as marine areas of ice retreat and influences the amount of meltwater that leaves Antarctica and contributes to global sea-level rise (Pan et al., 2021).

The solid Earth deformational response to surface loading changes, in terms of both magnitude and timescales, depends on Earth rheology. Seismic tomography models indicate that the interior structure of the Earth is highly variable over the Antarctica with anomalously low shallow mantle viscosities across the western section of the AIS. An improved projection of future evolution of the AIS and its contribution to global sea level requires a consideration of this complexity in Earth structure. Here we adopt a state-of-the-art seismic velocity model (Lloyd et al. 2019) to build a high-resolution 3D viscoelastic structure model beneath Antarctica (Wan et al., submitted). We incorporate this structure into simulations with a high spatiotemporal resolution sea-level model coupled to a dynamic ice model (Gomez et al., 2018) to simulate the influence of solid Earth deformation and sea level on contributions of the AIS evolution to future sea-level change for a range of climate forcing scenarios. We show that the influence of applying a spatially variable Earth structure is significant, particularly in the regions of West Antarctica where upper mantle viscosities are lower and the elastic lithosphere is thinned. Although the focus of this study is on future projections, our findings and coupled framework can be applied to understand Antarctica's role in past warm periods.

The Potential Role of Late-Holocene Regional Ice History and Sea-Level Change in Viking Out-Migration from Southwest Greenland

Borreggine, M. (1); Coulson, S. (2); Powell, E. (1); Latychev, K. (1); Mitrovica, J.X. (1), Alley, R. (3)

(1) Harvard University, Department of Earth and Planetary Sciences; (2) Los Alamos National Laboratory; (3) Pennsylvania State University, Department of Geosciences

POSTER

Greenland was first settled around 985 AD when Erik the Red was exiled from Iceland and immigrated to southern Greenland. Erik's family and other colonizers established Eystribyggð (the Eastern Settlement) and Vestribyggð (the Western Settlement), which thrived until the enigmatic out-migration of Vikings in the early 15th century. The literature suggests that Viking out-migration was forced by the climatic shift from the Medieval Warm Period (~900-1350 AD) to the Little Ice Age (~1350-1850 AD) when environmental conditions became unfavorable for continued settlement. Likely, the exodus of Vikings from this region was caused by a combination of environmental and socioeconomic factors. This study further reveals the potential role of sea-level change in the movement of Norse Vikings away from Greenland. Glacial geomorphology and paleoclimate research suggests that large portions of the southern Greenland Ice Sheet (GIS) re-advanced through much of the Holocene, reaching peak size during the Little Ice Age. We propose that Vikings migrated away from Greenland in part as a response to local sea-level rise driven by regional growth of the GIS. The re-advance of the GIS would have caused a rise in sea level near the ice margin due to increased gravitational attraction between the large ice mass and the nearby sea surface, in addition to crustal subsidence. We estimate ice growth in southwestern Greenland during the period of Norse occupation consistent with geomorphological indicators (Weidick, 1988) including a threshold lake core from Larsen et al., 2011. We illustrate the effect of local ice growth on regional sea-level change by applying our ice model to a state-of-the-art finite-volume sea-level model that incorporates lateral variations in mantle viscosity and lithospheric thickness (Latychev et al., 2005). The model has a spatial resolution of ~1 km across southwestern Greenland, covering both the area of ice mass flux and known Norse settlements. We find that peak regional sea level rose by more than 100 times the global mean sea level change associated with the ice history, resulting in coastal

inundation on the order of 100s of meters to several kilometers, and we discuss the effect of such flooding on Viking settlements across the region.

The gravity force applied to (in)compressible flat and spherical finite element GIA models

Reusen, J.M. (1); Huang, P.P. (2); Steffen, R. (3); Steffen, H. (3); Van Calcar, C.J. (1); Root, B.C. (1); Van der Wal, W. (1)

(1) TU Delft; (2) The German Research Centre for Geosciences (GFZ); (3) Lantmäteriet, Sweden

POSTER

Compressibility causes significant effects on modelled displacement, especially horizontal displacement. Modelling compressibility is challenging in GIA models employing commercial finite element model ABAQUS following the method of Wu (GJI 2004). Most of those models are either incompressible, or only employ material compressibility. The latter is done simply by changing the Poisson ratio of the material. However, the compression or extension of the material also leads to a change in buoyancy force, and if we want to fully implement compressibility, we need to take this into account as well.

We study the implementation of this change in buoyancy force based on a Lagrangian formulation in which pre-stress advection is implicitly included. We benchmark our results against earlier results for a flat Earth model and we extend the model to flat Earth model with multiple layers. Gravity is included as a built-in load type with a uniform direction. To extend the method to spherical models requires calculating the gravity force manually and inserting it as body force that is in equilibrium with a prescribed initial stress. We succeeded to do this for a homogeneous spherical model, but when including viscoelastic behavious this did not lead to an equilibrium solution. These results suggest to use a different approach to implement compressibility in spherically layered models by calculating the compressible buoyancy forces from the displacement as in Wong and Wu (GJI 2019).

Searching for the sea level fingerprint of recent melt in the Amundsen Sea Embayment, West Antarctica

Tawil-Morsink, K. (1); Xiu Wen Wan, J. (2); Latychev, K. (1), Gomez, N. (3), Mitrovica, J.X. (1)

(1) Harvard University; (2) Earth Observatory of Singapore; (3) McgGill University

POSTER

It is now well understood that the rapid melting of an individual ice sheet or glacier produces a unique geometry of sea level change that can be predicted with geophysical modeling of glacial isostatic adjustment (GIA), but is challenging to detect in the modern instrumental record of global sea level change. Among the effects that produce this sea level "fingerprint" are crustal rebound after unloading and reduced gravitational attraction towards the melt zone, which cause sea level to fall close to the melting ice sheet or glacier. Because this relative sea level fall can be orders of magnitude greater than the global mean sea level rise corresponding to the melt, efforts to detect fingerprints are best focused on the area proximal to the melt zone. To this end, we are investigating whether recent melt from Pine Island and Thwaites glaciers can be correlated with a localized sea level fingerprint in the Amundsen Sea Embayment (ASE) of West Antarctica. We will produce a time series of sea surface height change from ICESat (2003-2009) and ICESat-2 (2018-present) data collected offshore in the ASE. We will then compare this observational record to the sea surface height change predicted to result from ice mass flux by our 3D geophysical GIA model. If this attempt to detect a fingerprint is unsuccessful, we will use projections of ice mass change through 2100 to estimate when we would expect to detect a fingerprint in instrumental sea surface height data. Identifying the fingerprint of Pine Island and Thwaites melt with a high degree of confidence would demonstrate a novel method of monitoring polar ice mass balances and allow greater insight into the geographic variability of ongoing and future sea level rise.