PALSEA Workshops
University of Bristol, September 20-24, 2010

Relative sea level, ice sheets and isostasy: past, present and future
(understanding the implications for human populations)

Workshop report with contributions from David Richards, Alex Thomas, Simon Engelhart, Torbjörn Törnqvist, Justin Dix, Carrie Lear, Morten Andersen and Mark Siddall

Workshop statements

1. We continue to work towards a global, open source and quality monitored database of relative sea level (RSL) and ice sheet extent.

2. We support efforts to generate new RSL and ice extent records and improve techniques.

3. We support efforts in glacio-isostatic adjustment (GIA) and ice sheet model intercomparison and aspire to the creation of community GIA models in line with other modelling communities.

4. We emphasise the critical importance of close working relationships between climate modellers, ice sheet modellers, GIA modellers, and field scientists who study RSL and ice sheet extent on a variety of time scales.

Introduction

PALSEA workshops bring together researchers from a wide variety of fields related to past and future sea level change to engage in communication and discussion across the discipline, generating funding and research collaborations. Speakers are encouraged to offer 'review with opinion' to promote interaction, and this certainly happened in the workshop sessions, poster sessions and during social events at PALSEA 2010. Our thanks to all for a productive meeting, during which participants were able to reveal some of the inadequacies in their own field of enquiry and also discover some surprises in those of related disciplines. In so doing, positive outcomes and future courses of action emerged that will rely on input from across the data-model landscape.
A wide range of ‘sea-level’ practitioners was invited to discuss **relative sea level, ice sheets and isostacy: past, present and future (understanding the implications for human populations)**, including ice-sheet and climate modellers, geophysicists with expertise in glacial-isostatic adjustment, field scientists engaged in reconstruction of ice sheet extent and relative sea levels, and marine archaeologists. The principal focus for PALSEA meetings is the crucial role that **paleodata** from sea level and ice sheet reconstruction at a range of temporal scales used in concert with geophysical **modelling** efforts plays in our understanding of Earth-system dynamics and predictions of future Earth system states. We cannot rely on the instrumental period alone, critical are the data present in the paleorecord and their use to constrain modelling studies.

Scientific presentations and discussion (Days 1-4) were organised into themes broadly on the basis of temporal scale:

- *Predicting future sea level and ice sheet evolution – framing the questions for paleoresearch*
- *Sea level and ice sheets during Termination I*
- *Ice sheets: observation and modelling*
- *Sea level and ice sheets entering and during warm periods*
- *Sea levels and ice sheets during the Holocene*

The final session (Day 5) comprised panel discussions that focussed on deliverables and future funding strategies. 42 oral and 23 poster presentations were given.

We are extremely grateful for the assistance and funds of the **World Universities Network (WUN), PAGES, IMAGES, UKIODP** and the **University of Bristol “Black Swan”, BRIDGE and Global Change** initiatives. This guaranteed the attendance of key researchers. Our thanks go to Isobel Howe of WUN, who provided administrative support and enabled the evening lectures to be broadcast by video-link to partner institutions across the globe.

**Workshop outcomes**

- **EPSL special issue** – A special issue of EPSL covering the material presented at the workshop has been invited by EPSL editors.
- **EOS cover paper** – PALSEA is preparing a cover page paper in the weekly newsletter of the American Geophysical Union
- **NERC iGLASS** – A consortium grant tied to PALSEA has gone in covering the Dept. of Earth Sciences and Geography at Bristol as well as partners at Durham, Plymouth, Oxford and British Antarctic Survey.
- **Leverhulme International Network Grant** – An application has gone to Leverhulme to support PALSEA.

**Historical context**

Bristol has a long history of maritime interest, a legacy of its position as a crucial port for many centuries. It has also been a centre of scientific and engineering endeavour with global outreach, particularly since the turn of the 19th century. The River Avon that passes through the City has one of the highest tidal ranges in the world, so it is no surprise that sea level variation and underlying causes have been a focus of attention. Some of the earliest and most accurate tidal records were produced in the city in the 1830s by Thomas Bunt, and his...
computations provided William Whewell with some of the crucial material that he needed to introduce his ‘theory of tides’. Not only was this the start of what could be described as a geospatial revolution, where widely separated empirical data was used to inform geophysical understanding, but this partnership was also principally responsible for the promotion of ‘mean sea level’ as a useful reference datum for elevations on land. For some, Whewell was instrumental in bringing about a change in the presentation and understanding of geodetic data that resonates in current practice. In many respects, the efforts of the PALSEA community mirror these early efforts as we attempt to map, not cotidal behaviour, but the geospatial and temporal pattern of relative sea level change.

Summary of discussions from scientific sessions

Session 1: Predicting future sea level and ice sheet evolution
In a brief introduction, Siddall highlighted the issues raised about extrapolating beyond the observational range to estimate future sea level. This presents a prime focus for the PALSEA community: Are the current observed trends a response to anthropogenic forcing or do they represent natural inter-annual variability? The next two talks of the day reviewed current polar ice-sheet mass balance (Bamber) and future behaviour (Payne). Bamber presented a wide range of geodetic, mass-balance and gravimetric methods and also a review of their underlying uncertainties. He considers that the current ‘acceleration’ of melt contribution is ‘unlikely’ to last. Payne reviewed the advances that have been made in terms of modelling ice sheet behaviour, but cautions that there is much still do to ‘capture the coupling processes between oceans and ice sheets’ and especially grounding line migration.

Models of glacio-isostatic adjustment (GIA) play a critical role in revealing the eustatic component of sea-level variation but also understanding the spatially variable response of relative sea level. Milne provided an elegant GIA primer for the audience. Some of these themes continued into Kopp’s presentation of statistical analysis of paleo-relative sea level data for the last interglacial period, during which he
underlined the need for researchers to ‘consistently report’ the error structure associated with palaeo-sea level estimates.

**Session 2: Sea level and ice sheets during Termination I**
The rest of the talks on Monday (Stanford, Stattegar and Shennan) focussed on the nature of the last deglaciation, and particularly the rates of sea-level change associated with Meltwater Pulses 1a and 1b (MWP1a,b). Stanford presented a ‘highest probability sea level curve’ for this period using MCMC methods through data compilation. Stattegar revisited the mangrove data for Sunda Shelf and Shennan stressed the need to use ‘sea-level tendency data’ coupled with GIA modelling to provide constraints on the rate of sea-level change during the meltwater pulse(s).

In the final discussion, the questioning focussed on the interpretation of sea level records from the MWP1b. It was considered by many that coral paleo-bathymetry reconstructions were not sufficiently precise to resolve sea level rise across MWP1b and that more data was needed from near field sites such as isolation basins, where more precise sea level index points can be found. The available data suggests that a MWP1b could exist, but would have to be small to be consistent with near field observations. The question of what defines a meltwater pulse was brought up. There was no consensus as to what acceleration of melting rate would qualify as a “pulse”, or even if one could ever be rigorously defined.

The use of relative sea level markers to constrain changes in ice volume equivalent sea level was cautioned. While the importance of age-elevation reconstructions remain important, it was noted that to make meaningful interpretations about changes of eustatic sea level the effects of GIA must be carefully considered; specifically, if relative sea level records from different localities should be presented together on the same plot, a strong cautionary note should be included.

The issue of reconciling our understanding of the processes that govern the rates of change of ice volume was raised and the point was made that the accuracy of paleodata (specifically the issue of paleo-bathymetric reconstruction) was insufficient to bring into question our current knowledge of maximum possible rates of ice sheet growth and decay.

**Session 3: Ice Sheet Observations and Modelling**
The programme of talks on Tuesday covered reconstruction and modelling of individual ice sheets; Antarctica (Hill, Whitehouse), Eurasian sector (Mangerud), North America (England); global data sets (Tarasov); and their inclusion as boundary conditions in climate models (Abe-Ouchi, Otto-Bleisner). Also presented, postponed from the previous day, was a reconstruction of deglacial sea level history from Tahiti corals (Bard).

Numerous existing topics and challenges were presented by these speakers. Among them, the lack of consensus over ice sheet reconstructions. Future climate model-intercomparison runs (PMIP3) will address this in part by using an ‘average’ ice sheet from the range available, but there is also a call to produce a ‘probabilistic version’ with ‘error bars on the reconstructions’.

The topic that engendered most group discussion in the final session of the day was the nature and effects of MWP1a. There is currently a “conflict” between glaciological and glacio-eustatic modelling of this event that is preventing determination of the attribution of this event (i.e. whether the meltwater was sourced from Antarctica, Northern Hemisphere or both). This has important implications for understanding ice sheet dynamics and the climatic consequences of the event. In order to address this problem, the following requirements were highlighted by the audience:

1) Better integration of varied data sets (e.g combine coral reef sea level data with sedimentological studies such as lagoonal flooding surfaces)
2) Better treatment of errors on sea level data – both the vertical (sea level) data and also the age data.
3) Improved cross disciplinary communication between data and model workers. There was a call for a ‘community’ GIA model, for example.

**WUN evening lecture (21st Sep): Mike Bentley** of Durham University talked of the geological evidence of former Antarctic ice sheet extent, thickness and deglacial chronology. Mike attempted to quantify total excess ice volume in the different sectors of the Antarctic ice sheet during the Last Glacial Maximum (LGM) to establish the role of Antarctica in driving the rapid rise in sea level since the LGM known as Meltwater Pulse 1a (MWP1a). Available data suggest rather modest LGM excess ice volumes in the West Antarctic Ice Sheet and were unlikely to form the dominant source for MWP-1a. The East Antarctic Ice Sheet is more poorly constrained and for large parts of its marine margin there is little information on the LGM extent or thickness. A few locations suggest some marginal thickening and advance, but the wider applicability of these data are not clear, and so total volumes are difficult to assess. There is an urgent need for more glacial geological data around the East Antarctic margin, especially the Queen Maud Land and Wilkes Land sectors. At present, the data-poor East Antarctic Ice Sheet remains the most likely area in which a significant MWP-1a contribution could be accommodated.

**Session 4: Sea Level and ice sheets entering and during past warm periods:**
This varied and lively session highlighted a couple of big discrepancies in our understanding of ice sheets in past warm climates.

The first centred on the East Antarctic Ice Sheet, for which ice sheet models predict a strong hysteresis effect dynamics. Recent model evidence (Pollard) suggests that, once formed (at levels of ~2-3 times pre-industrial levels), the East Antarctic ice sheet would be stable unless pCO₂ reached approximately nine times pre-industrial levels. This does not tally with the geological record, which suggests glacioeustatic sea level variations on the order of several tens of metres through much of the Cenozoic. Further support for significant variations in Antarctic ice sheet volume at levels of pCO₂ roughly 2 times preindustrial levels were presented (Lear) in the form of geochemical proxy evidence. This first issue centres around the suggestion that the Antarctic Ice Sheet has been much less stable in past warm climates than predicted by ice sheet models. The second issue is quite the opposite: that the Greenland ice sheet may have been more stable in past warm climates than currently assumed. The interplay between sea level, CO₂ and temperature were the focus of attention in modelling presentations by Lunt and van de Wal; the first revealed both the problems associated with coupled-ocean atmosphere GCM runs of Pliocene climate and also the robust conclusions that can still be drawn, the latter describes how simple 1-d ice sheet models can successfully model sea level from paleorecord of oxygen-isotopes for the past 35 Ma.

Convincing evidence for “old” (>0.5 million years) ice at the base of the Greenland ice cores (Dahl-Jensen). If true, this most likely implies that the ice sheet did not decay to the extent currently assumed (Alley, 2010), although there are some issues regarding basal ice deformation and lateral transport.

It seems that the question of stability in past warm climates for both the Antarctic and Greenland Ice Sheets will be the focus of further research. An excellent yet relatively untapped archive of fossil beach scarps was highlighted (Raymo) that will improve sea level estimates for the Pliocene Warm Period, thus providing one means of addressing this issue.

Looking to more recent sea levels, the stability of ice sheets during the last interglacial remains a major issue. Despite considerable focus of attention, there remain many unanswered questions, particularly about ice volume and relation to insolation forcing at this time. While Red Sea data based on modelled stable isotopes suggest some higher frequency large amplitude oscillations, unfortunately this cannot be matched by coral data from this region, where ages are mostly low precision and subject to alteration. Lambeck revealed something of the constraints that we have in terms of glacial isostatic adjustment for this region, which are highly susceptible to Earth model parameters. He also reiterates the concern that our interpretation of last interglacial high sea levels depends on the pattern of isotope stage 6 ice loading.
Continuing with the last interglacial theme, Thompson stresses the need for detailed stratigraphy and multiple age determinations for coral reef terraces and suggests that early onset ages from elsewhere are perhaps erroneous. Orbit configuration and greenhouse gases and last interglacial sea level variability were also the focus of Singarayer’s presentation using coupled ocean-atmosphere model.

Session 5 : Sea level and ice sheets during the Holocene
Discussion during this final session of the scientific programme focussed on:

1. Understanding ice-sheet dynamics, pre-7 ka
The meltwater sources responsible for the dramatic rise in sea level from the commencement of deglaciation to 7 ka are still hotly debated. Building on the discussion during prior sessions on the source of MWP-1a, Hall and Carlson provided relevant recent evidence from both hemispheres. Based on extensive surface exposure dating, Hall showed that it is unlikely that MWP-1a could be sourced from the Ross Sea sector of the Antarctic. Carlson demonstrated that the Northern Hemisphere ice sheets were capable of supplying the necessary water volume but raised questions as to whether a Laurentide Ice Sheet that supplied the full MWP-1a volume would be able to survive until 7 ka. This highlights an important point, namely that estimations of mass loss must conform to glaciological theory, in addition to providing acceptable GIA model solutions. Given Northern Hemisphere conditions warmer than present, ice sheet/sea level interactions during the early Holocene provide a potentially useful, yet imperfect analog for the future. A key role is envisioned for sea-level fingerprinting in conjunction with GIA models, to identify the chronic sources of the overall rapid sea-level rise on one hand, and abrupt events (MWPs) on the other. Recent work shows that even fingerprint analysis of catastrophic discharges with well constrained sources such as those associated with the 8.2 ka event is challenging, due to complications from ocean dynamic effects, potential tidal range changes, and uncertain background rates of sea-level rise. This can lead to wide error margins on local measurements (±1.25 m, Cohen) which propagate into fingerprint-corrected magnitudes.

2. Understanding sources of ice-equivalent meltwater input, post-7 ka
There continues to be a persistent lack of understanding regarding the magnitude, if any, of the post-7 ka glacio-eustatic contribution. This is problematic as this partly controls the background rate that needs to be constrained in order to contextualize the post-industrial sea-level rise. Increasingly sophisticated GIA models will likely play a key role in resolving this issue. Horton provided a basis for standardizing RSL data as a means to further constrain GIA models. A high proportion of presently available RSL data carry large uncertainties; error terms are often larger than the magnitude of change involved and may therefore allow for multiple solutions. Clearly, new high-resolution RSL data (centennial to decadal age control, cm to dm vertical control, including consideration of all errors) are required to enhance our understanding. Such new data have the potential to fingerprint sources of 20th century ice melt (Gehrels, Horton) although ocean dynamic effects are difficult to control for. For example, a Greenland source of 20th century eustatic input could explain up to 32% of the difference between RSL records in Connecticut and Tasmania (Gehrels).

3. Past 2 kyr as a context for future sea-level rise
In view of the uncertainties highlighted above, the question was raised whether constraining models for the last 2000 years might provide our best estimate of what to expect for the future. This is due to the availability of better proxy records of temperature variability and the increasing potential for producing high-resolution RSL records during this time period from salt-marsh successions and coral microatolls. Indeed, the prominent role of humans during this time may provide a strong contribution from archaeological reconstructions (Sivan, Dix, Sturt). However, key problems remain, such as the lack of high-resolution constraints on the dynamics of the Greenland Ice Sheet during this period (Long); a criticism that is likely valid for the Antarctic Ice Sheet as well.
Panel discussions

A: Databases (Panel: Condon, Horton, Milne, Richards, Thompson, Lambeck)

The panel and audience discussed:

- **Database content, which may have various types of data:**
  The suggestion that emerged from discussions was to work towards a very broadly inclusive database that would include relative sea-level data of various types and also ice sheet extent. With state-of-the-art database techniques, it is possible to easily select subsets of the database.

- **Quality control of data:**
  Given the experience of previous database efforts it was suggested by Bard that the best option was to have minimal quality control during the initial phase of the database. Database users would be able to filter data using less certain techniques, for example, but even low quality data can be useful where data is otherwise lacking.

  An additional issue is that quality criteria and asking for too much additional information would increase the effort involved in submitting data and reduce the likelihood that workers would submit their data. This approach relies on the appropriate error bars being stated with these indicators.

  Finally, Horton emphasised the importance of clear indication as to the nature of the evidence in the database, for example with respect to the position of sea level with respect to a given sea-level indicator. This issue was underlined by Kopp with respect to the importance of clear uncertainty estimates for probabilistic modelling.

- **How to make best use of existing databases**
  The strategy of essentially making the PALSEA database a meta-database of existing databases. This would involve the publication of existing databases and the creation of a meta-database of published databases. Over time PALSEA would work to improve the coverage and quality of these databases but the initial phase would aim to be inclusive and bear a manageable workload.

- **Funding strategies specific to databases**
  Condon made the point that by working with EARTHTIME, PALSEA could use existing, funded groups to better justify funding for databasing efforts. By coordinating with EARTHTIME, PALSEA will optimise the impact of the database and be adding to an already-funded infrastructure.

  The underlying point specific goals for getting funding in connection with databases which was discussed was the presentation of important questions to obtain funding. By stating specific goals for getting funding in connection with databases it is possible to get databases funded.
• ‘Open source’ databases
Participants underlined their strong support for an open source database which would be used by multiple GIA models and other users.

Tarasov suggested that an open source GIA model should be created. This was supported by PALSEA and ongoing efforts to make inter-model comparisons between GIA models within PALSEA were also highlighted. PALSEA will coordinate with existing efforts with the creation of a GIA model as part of an ongoing EU COST action.

• Immediate actions
The first step towards a database will be to set up working committee which will include representation for different areas of research with need of databases (e.g. coral reef RSL estimates, moraine-based ice sheet extent etc) as well as representation from existing database efforts.

Case study: Improving the quality of U-Th data and its longevity via EARTHTIME, EARTHCHEM and PALSEA (Condon), i.e “Improving the quality of (U-Th) data and improving the half-life of the data”. Lessons learned were presented. Most resonant was the ethos of community spirit (“check your egos in at the door”). Much of this feeds in directly to the requirement for full disclosure of error structures. Some moves are being made here in relation to radiocarbon calibration (INTCALxx), the same model needs to be rolled out for U-series ages and then sea level data also.

A call was made to design a data-base architecture (cyber-space infrastructure) that includes geochronology database, stratigraphy database, relative sea-level database with community tools and standardisation of practice.

Case study: RSL databases from GIA modelers view (Klemann).
Rehearses the need for a global, open-source database with standard output of data, with enough information for wide range of uses (eg. location, age, height range and errors). This will have the benefit that it will online and uniform predictions of datasets. Data will be updated, allowing for re-interpretation, in a format suitable for useful visualization, and linked to related meta-information.

What is required is a central upload and with possibility to split into regions and types of info (e.g. peat RSL, coral RSL etc). The crucial role of journal editors was discussed in terms of ‘gatekeepers’. Templates need to be provided here for best practice.

B: Funding (Bard, Gehrels, Pollard, Bamber, Clough, Bergamino)
The panel discussion was initiated by presentations from representatives of NSF and EC discuss funding potential there.

Speaker – Natalie Bergamino, Research Officer European Commission
- FP7 will increase its budget in the next few years to a total budget 50 million Euro with ~ 2 million for environmental research.
- Key target is enhanced climate research.
- Major projects: ice2sea EC funding €9.9m; Past4future €9.2m: key question of interglacial periods drivers of sea level and climate changes.

Speaker – Lisa Clough: NSF Program Manager
- Total budget $550m with many opportunities for the PALSEA community.
- Databases may be supported in connection with scientific addressed questions.
- For examples of co-ordination see CReSIS (website), polenet.org
The first issue raised was the key 'hot' funding issues that PALSEA research can target. One such issue was the correction of gravimetric data using GIA models. For this purpose, better communication between scientists would be helpful and should be improved (e.g. GIA modelers with GRACE users). In particular the reliance on relative sea level data of GIA models should be more transparent at the user end of gravimetric and eustatic sea-level data. The lack of understanding of the significance of PALSEA data reduces the funding potential of PALSEA research. PALSEA should formulate and highlight targeted scientific questions around which to apply for funding.

The next point of discussion was the general difficulty with funding trans-Atlantic, or other international partnership, collaboration. Existing models for working together, include GEOTRACES. Clough made the point that certain specific NSF calls do support these interactions but others do not. Clarification is available from NSF managers to find out which NSF funding streams are worth applying to.

The third point of discussion was the issue of influencing the direction of funding councils. PALSEA needs to feed into pre-workgroups that to guide funding agencies to set up the important questions for funding. Efforts such as PALSEA statements, positions on consultancy committees, the use of publications in EOS to make clear points with regards to the importance of PALSEA research

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Participants bid farewell having decided upon a set of workshop statements
Sea level community sample the beers. "Looks like it's Mark's round!"