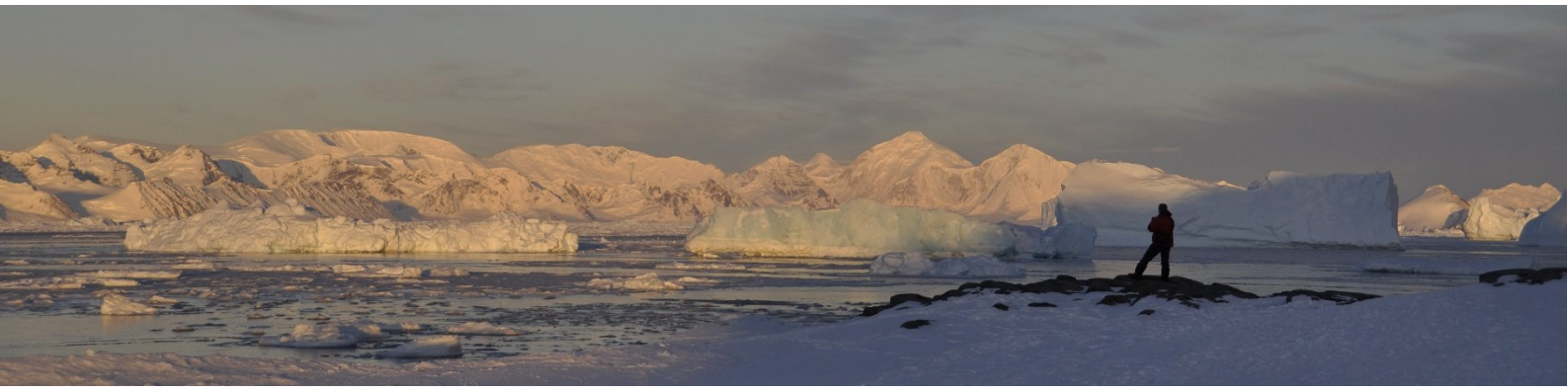
West Antarctica and future sea-level rise

A workshop to identify priorities for research and collaboration in West Antarctica

The Royal Society, London. 3rd and 4th March 2016.

Final Report



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Royal Society, London. 3rd and 4th March, 2016.

Summary

Since the 1990s, satellites have shown accelerating ice-loss driven by ocean change in the neighbouring glacier basins that drain more than one-third of West Antarctica into the Amundsen Sea. The rate of ice-loss here doubled in just six years and now accounts for a significant fraction of global sea-level rise. However, considerable uncertainty remains in projections of future ice-loss from West Antarctica, and in the last 18 months, separate modelling teams working in the UK and US have identified Thwaites Glacier as having the highest potential of all for future rapid ice loss and collapse.

Reducing uncertainty around the future contribution of Thwaites Glacier to sea-level rise requires a substantial and coordinated collaboration involving a multidisciplinary and international scientific community, with logistic support from more than one national Antarctic programme. The recent identification of the projection of sea-level rise as among the highest priorities for Antarctic research, by the Scientific Committee on Antarctic Research Horizon Scan, and by the US National Academies of Sciences, Engineering, and Medicine, has provided compelling stimulus to act to establish an integrated and strategic science plan in this area. This process began in January, 2016 with a workshop in Denver Colorado, and continues with the workshop reported here.

A major multi-disciplinary research programme focused on the Amundsen Sea embayment, and Thwaites Glacier in particular, could substantially improve both decadal and long-term (multi-century) projections of ice-loss and sea-level rise, and support improved management of risk for vulnerable coastal communities in the UK and US and elsewhere. This workshop was convened to build on recent discussions, to identify, refine and agree future priorities for collaborative research in this crucial area of Antarctic science.

Convenors:

Professor D G Vaughan, British Antarctic Survey, UK
Professor R B Alley, Penn State University, USA
Professor R E Bell, Columbia University, USA
Professor M J Bentley, Durham University, UK
Professor A J Payne, University of Bristol, UK
Dr A M Smith, British Antarctic Survey, UK

Sponsors

The conveners gratefully acknowledge support provided by the following organisations:

- The UK Natural Environment Research Council
- The Royal Society – Global Environment Research Committee
- The Environmental Physics Group of the Institute of Physics
- NERC iSTAR Research Programme
- UK National Committee on Antarctic Research (UKNCAR)
- The US Embassy in London who hosted a reception for meeting participants and their guests.

Summary Workshop Report

INTRODUCTION

The vast ice sheet in Antarctica is showing the effects of climate warming. Ice is being lost into the ocean, and projections suggest that this will accelerate in the future with consequent impacts on global sea levels and potentially devastating effects for coastal communities and fragile coastal ecosystems around the world.

Nowhere is ice loss from Antarctica as great as in the group of glacier basins flowing into the Amundsen Sea — together these five neighbouring glaciers drain more than one third of West Antarctica. Since the 1990s, satellites have shown accelerating ice loss from these glaciers, driven by ocean change; the rate of loss doubled in just 6 years and now accounts for ~10% of global sea level rise.

Under moderate projections, more than 90% of the world's coastlines will experience sea-level rise by 2100. Significant impacts will be noted for communities, businesses and infrastructure. But, as highlighted by the recent Intergovernmental Panel on Climate Change (IPCC) assessment, considerable uncertainty remains in projections of future ice loss from West Antarctica and in particular, that from these Amundsen Sea sector glaciers. The most rapid ice-loss at the moment comes from Pine Island Glacier, but new studies, particularly since the IPCC 2013 assessment, show the greatest risk for future rapid sea-level rise now comes from the adjacent Thwaites Glacier.

INTERNATIONAL CONSENSUS

Recently, there have been major efforts across the international science community to identify the most significant questions facing Antarctic science. The two most notable of these were the Horizon Scan activity led by the Scientific Committee on Antarctic Research (SCAR), and the United States National Academies of Science, Engineering, and Medicine's (NAS) "Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research".

Both of these identified understanding the future contribution of the West Antarctic Ice Sheet to global sea-level rise as a key challenge. Indeed, of the three scientific priorities identified in the NAS document, this was identified as the most pressing.

Underpinning this need identified at strategic levels is a growing scientific imperative from studies in the leading science journals that the West Antarctic Ice Sheet is undergoing significant change whose future trajectory cannot be determined without a step-change in effort. There has been clear evidence over the last 18 months, in the UK and US scientific communities at least, in support of such an effort, and both communities have moved to engage in a coordinated approach. To acknowledge this support, and to pursue further international agreement on research priorities and a potential way forwards, an application was made to the Royal Society to host a Scientific Meeting entitled "West Antarctic and future sea-level rise. A workshop to identify priorities for research and collaboration in West Antarctica".

SCIENTIFIC MEETING

A meeting was held at the Royal Society on 3rd and 4th March 2016. It was supported by the Society's Global Environment Research Committee (GERC), with endorsement from the UK National Committee on Antarctic Research (UKNCAR). The meeting comprised 2 days of scientific presentations and discussions, and an evening reception hosted by the US Embassy. A total of 35 participants attended the meeting, including 11 from the US. The majority of participants were from the UK and US science communities, but senior staff of the UK Natural Environment Research Council (NERC), the US National Science Foundation (NSF) and the British Antarctic Survey Operations Team also attended

The stated aim of the meeting was to progress scientific efforts towards reducing the uncertainty in the future contribution of the West Antarctic Ice Sheet to sea level rise. The intention was to achieve this by identifying the most pressing, relevant and immediate science questions; by enabling the sharing of science goals between the UK and US research communities; and by developing a framework to underpin collaboration on key issues.

The number of people attending the meeting was limited. Hence, meeting participants were asked to act as representatives of their particular research communities, rather than their own specific interests. Presentations were invited that would each introduce a thematic area of ice sheet measurement, understanding and prediction.

The presentations were intended to provoke discussion and allow the identification of key science questions. Speakers were asked to conclude with an explicit list of between three and five pressing questions in their thematic area whose scope and scale could be addressed within a typical grant cycle. Moderated discussion at the end of each session was used to challenge the other participants to add their own high-priority questions and identify blockages that would prevent each question being answered.

LOGISTICS AND INTERNATIONAL PERSPECTIVE

For the decades between the 1960s and early 2000s, research in the Amundsen Sea sector of West Antarctica was limited. Vibrant research programmes focused both scientific effort and logistic capabilities on the Siple Coast and on Filchner-Ronne Ice Shelf regions, led respectively by the US and by European consortia. Only with the impetus of satellite results showing rapid ice-loss in the Amundsen Sea sector, did we begin to re-establish scientific momentum there and develop, for the first time, logistics chains capable of supporting significant and complex programmes in this remote area. One session of the meeting was dedicated specifically to the logistics of working in this region.

FUTURE STRATEGY REQUIREMENTS

The workshop concluded with a discussion of the strategic requirement for a collaborative science plan that will provide a framework for the development of ongoing collaboration in this area. It was agreed that the societal imperative of reducing the uncertainty in projections of the West Antarctic contribution to sea-level rise provides the most compelling justification and must remain the principal goal of an emergent strategy. This principal goal aligns well with both the conclusions of the US National Academies' report, and the SCAR Horizon Scan. The workshop discussions (see Appendix 1) further indicated several priority areas where an integrated research programme operating over a five to ten-year period, using the full suite of modern research tools including satellite remote-sensing and oversnow, marine and airborne logistics, would make a major contribution to the principal goal. These are:

1. Quantifying the ongoing changes in ice-flow and mass balance in West Antarctica;
2. Understanding past changes in WAIS, both as a window on the future, and as the crucial tool for validation of ice-sheet models;
3. Identifying and understanding the oceanographic and atmospheric processes driving past, recent and probable future ice-loss from West Antarctica;
4. Acquiring key data on the thickness of the ice, the depth of the water, ice rheology and the conditions at the base of the ice sheet to enable robust forward projections of change;
5. Improving the understanding of environmental changes that will drive ice-sheet change, the processes by which ice-sheets feel those changes, and the internal dynamics that modulate the ice-sheet response to advance our modelling capacity;
6. Improving the projections of the contribution of Antarctica to sea-level rise, and understanding the potential for rapid ice-sheet collapse.

Many separate lines of evidence cited throughout the discussion highlighted Thwaites Glacier as the key site focus for future research, because it:

1. Currently is exhibiting rapid and accelerating change;
2. Contains sufficient ice, that on its own it could make a significant contribution to sea-level rise;
3. Is situated in the location most likely to experience future oceanographic and atmospheric change;
4. Is an exemplar of a high-sensitivity ice stream exhibiting all the characteristics identified as likely to promote rapid, and prolonged, ice-loss (collapse).

Finally, it was agreed that the scale of the scientific questions required to address the principal goal is sufficiently large that it will require collective effort from an international, and multi-disciplinary community to achieve progress within a decade, and that a collective intention to collaborate already exists.

Evidence of the parallel development, in the US science community, is provided in the Science Plan currently being developed as an outcome of an earlier workshop at the University of Colorado in Boulder (13-14 January, 2016). This document, titled 'How Much, How Fast: A Decadal Plan for Quantifying the Rate of Change of the West Antarctic Ice Sheet Now and in the Future' was requested by the US National Science Foundation as a response to the strategic priorities identified in the NAS report, and provides specific research directions and an actionable approach. (The draft Executive Summary and Introduction of this developing WAIS Science Plan are attached in Appendix 2.) In it, four major focus areas were identified under key questions:

(1) Why is the West Antarctic Ice Sheet changing now?
(2) What does the West Antarctic ice sheet really look like?
(3) How do marine ice sheets collapse?
(4) What is our best projection of future sea level rise from Antarctica?

Finally, it was agreed that the maximum opportunity to achieve an integrated collaborative programme will be through co-design, by the US and UK community, of a collaborative science plan for Thwaites Glacier. This should progress through the science community represented at this meeting and through consultation more broadly in the UK and US.

Appendix 1.

Record of the Meeting

Meeting introduction

David Vaughan on behalf of the Convenors

The aim of the workshop was introduced, as to progress scientific efforts towards reducing uncertainty in the future contribution of the West Antarctic Ice Sheet (WAIS) to global sea-level rise. The intention was to achieve this by identifying the most pressing, relevant and immediate science questions; enabling the sharing of science goals between the US and UK research communities; and developing a framework to underpin collaboration in key activities.

To facilitate discussion and deliver an opportunity to achieve collective agreement, short presentations were invited to introduce thematic areas of ice-sheet measurement, understanding and prediction. These presentations were intended to provoke discussion and allow the identification of key questions. Each presentation was requested to conclude with an explicit list of three and five pressing questions in this thematic area, whose scope and scale could be addressed within a typical grant cycle. Moderated discussion at the end of each session was be used to challenge other workshop participants to add their own high-priority questions, and to identify specific blockages that would prevent each question being answered.

Session 1. Assessment of the progress towards understanding the marine ice sheets

Preamble: *The fundamental question over the inherent (in)stability of marine ice sheet margins has been at the forefront of glaciological debate for more than 30 years, and although progress has been made, there appears to be little collective agreement that the issue has been resolved. Even if tacit agreement has been reached within our separate communities, this understanding has not been widely communicated into the science and non-science communities.*

Presenters – Richard Alley, Adrian Jenkins
Moderator – Mike Bentley

Alley – key questions:

- What can we learn about the stability of ice cliffs?
- What are Thwaites, Getz, etc. ice shelves doing?
- How do simple and complex models inter-compare?
- What can we learn at Hercules Dome?

Key points:

- As ice-sheet models get more complex, there's *more* need for the simple models too.
- Getting the physics right in models will be particularly important.
- Ocean temperature at the grounding line? This is important, but global ocean models still don't provide it in a way that can be used to drive the ice sheet models.
- Ice cliff physics is important. "Break-wait-break", which gives rise to tabular bergs or to roll-over icebergs widely separated in time, is a key process as present, but for ice-cliffs higher than ~100m, this could change to "break-break-break". This would produce icebergs with very different properties and have very different influence on ice sheet behaviour.
- How close is Thwaites to becoming Jakobshavns - and Antarctica to being like Greenland?
- Surface water: Is surface water needed to remove an ice shelf? Water keeps open existing flaws, and helps make new ones. How long will it be before surface water is regularly produced on the Amundsen Sea, and other West Antarctic ice shelves?
- Hercules Dome suggested as best place for evidence of Last Interglacial (LIG/Eeemian/MIS5e) collapse. An ice core should give this, but also give the rate of change (only an ice core can give us the rate)

Jenkins – key questions:

- What are the critical processes that control the oceanic regime on the continental shelf, and what are the thresholds for regime shift?
- What are the key drivers of variability in the Mode 2 regime (see Jacobs 1992 – this is water coming in from the "guts of the ocean", not locally-warmed water)
- How does decadal (and other) –scale noise in the ocean forcing lead to the smooth response we observe in the ice?
- When and how were the current phases of rapid change triggered; did it require a change of mean state or was it a particular warm event (variability) or sequence of events?
- Is the process (particularly on Thwaites) reversible, given a particular cold event or sequence of cold events?

Discussion. Moderator - Bentley:

- Long-term (centennial-millennial) evolution of the ice sheet – is it related to "equilibrium" *vs* transient states?
- How do bed conditions evolve?
- What are the stabilising processes (negative feedbacks)? e.g. Glacial Isostatic Adjustment (GIA), ice shelf sidewall friction?
- What's the evidence for WAIS collapse? This impinges on the discussion of *likelihood* of collapse and/or thresholds of change.
- What's happening to marine portions of the EAIS?

Session 2. Whither ice sheet models?

Preamble: *The current generation of ice sheet models are capable of simulating the evolution of the entire West Antarctic Ice Sheet over timescales to millennia, and with a resolution comparable to many observational schemes. What are the requirements of future models, and should effort be put into incorporation of improved processes, or into the improvements in model architecture and efficiency?*

Presenters – Sophie Nowicki, Dan Goldberg
Moderator – Hilmar Gudmundsson

Nowicki – key questions:

- Are ice sheet models becoming limited due to their inputs?
- Should we simply focus on the initialisation problem?
- What is the true complexity required from ice sheet models?
- What is the role of multi-model ensembles and how best to combine all the data generated?

Goldberg – key points:

- What will it take to accurately model Thwaites?
- For short term (50-100 a), improve data assimilation; long-term (100-1000 a) a better incorporation of processes.
- Difficulties include uncertainty in observations (especially bed characteristics) and also that calibrations (initialisations) don't lead to uncertainties in the predictions.

Discussion. Moderator - Gudmundsson:

- What can modellers do to help others/improve models?
- What can others (observationalists) do for the modellers (especially to quantify uncertainties)?
- How do we help people believe the models (credibility)? Back-testing; but using only "recent" is not sufficient.
- Models need more physics (eg coupled subglacial hydrology, damage mechanics)
- Critically need better bathymetry and bed characteristics (basin-wide)
- Improve models by collecting relevant data sets
- Consider which physical processes need including in models (depends on timescales)
- The future is looking very different to the past (e.g. expect extensive surface melt across WAIS); models may need to change.

Session 3. Is Thwaites Glacier the key to WAIS?

Preamble: *Whilst Pine Island Glacier has undergone the most rapid recent ice loss of the glaciers in West Antarctica, Thwaites Glacier has been reported as having the strongest potential for rapid, and irreversible collapse. To what degree is a focus on Thwaites Glacier justified?*

Presenters – Robin Bell, Dominic Hodgson
Moderator – Rob Bingham

Bell – key questions:

- Why is the West Antarctic Ice Sheet changing now?
- What does the West Antarctic Ice Sheet really look like (what's its geometry)?
- How do marine ice sheets collapse?
- What is our best projection of future sea level rise from Antarctica?

Hodgson – key questions:

- If Thwaites Glacier is key to WAIS, it should have retreated in past warm interglacials. Did it?
- Do the geometry of the catchment and GIA provide feedback for future stable states?
- Has ice sheet thinning accelerated when compared with natural variability?
- Are atmospheric and ocean forcing of CDW out of range of natural variability on millennial to centennial timescales?

Discussion. Moderator - Bingham:

- Thwaites Glacier *vs* Pine Island Glacier; which is key, or is it both together that matters?
- PIG has been high profile for good reasons; but overall, indications are that Thwaites will be more important (locus of change, susceptible geometry, modelling indications, bigger potential).
- Likely Thwaites & PIG will evolve together in some way
- What about East Antarctica (and its possible influence on WAIS)?

Session 4. Should we care about the bed?

Preamble: *Most current ice sheet models are initialized to match present-day ice flow by tuning the spatial pattern of bed properties. Projections are then developed from these initializations, but with assumed and idealized relationships between sliding velocities and friction. Could large-scale redistributions of sub-glacial water and sediment lead to unpredicted behaviours during large-scale ice-sheet retreat?*

Presenters – Sridhar Anandakrishnan, Richard Alley
Moderator – Tim Creyts

Anandakrishnan – key questions/points:

- The basal boundary is critical in developing predictive models
- What are the properties of the bed, including the sill?
- What are the properties of the margins?
- How does the bed influence the internal state of the glacier (e.g. layering, fabric, temperature)?

Alley – key questions/points:

- What is the topography/bathymetry of Thwaites grounding-zone bump (and others?) at sub-ice thickness resolution?
- What are the estuarine water system, ice flexure etc. on the Thwaites grounding-zone bump?
- Could sedimentation (with elastic-flexure till compaction, self-gravitation and isostasy on a hot, thin crust) stabilise against the effects of warm water?
- Inland, where are the frozen-thawed, till-rock, plastic-viscous beds, and what do they show about the bed?
- Is the bed itself changing?
- Require better analysis of existing data, targeted modelling, revisit of existing surveys, focused grounding-zone surveys etc.

Discussion. Moderator – Creyts:

- Thwaites bed is spatially variable, maybe not so temporally; still difficult to model.
- Re-emphasis – need bathymetry and bed info.
- Should we concentrate on things we can do easily, rather than difficult ones (grounding zone)? We need to do both. New technology needed in some cases (eg swath radar)
- Can we detect water pumping in/out with tides? (Analogy with estuarine environments.)

Session 5. Thresholds

Preamble: *The profound changes that led to recent near-instantaneous and irreversible retreat of ice shelves along the Antarctic Peninsula, resulted from processes not previously active. It is clear that a threshold was exceeded, most probably in the atmospheric or ocean climate that led to a "state-change" in these ice shelves. Similar thresholds have been postulated in recent modelling studies of marine ice sheets. A question remains as to whether the future of the West Antarctic Ice Sheet is one, not of perturbation of the current system, but one in which currently insignificant processes become dominant and lead to large-scale changes in ice-sheet behaviour.*

Presenters – Rob DeConto, David Vaughan
Moderator – Martin Siegert

DeConto – key points:

- Models are still missing key physics
- Recent work includes hydro-fracture and ice cliff failure into the model
- Realistic ocean warming alone doesn't collapse WAIS in existing models; that requires more of this additional physics.
- Emphasises importance of atmospheric warming
- When does the atmosphere become the dominant driver of change? We will see surface meltwater on the big ice shelves in the near future, it's not far off (perhaps it's even here already – e.g. Ross Ice Shelf in January 2016)
- Will Thwaites exhibit threshold behaviour?
- Relevance of East Antarctic Ice Sheet too (Wilkes and Aurora basins have big influence on long-term trends)

Vaughan – key questions:

- Are there tipping points and thresholds of behaviour in the ice sheets system?
- How far into the future can we rely on models tuned to the present/recent ice sheet system?
- What regime-shifts occur when an ice sheet enters a phase of rapid retreat?
- What process limits the rate of collapse of marine ice-sheet collapse?

Discussion. Moderator - Siegert:

- Don't forget the "unknown unknowns"
- Current modelling confirms Thwaites doesn't go with no warming, no matter how many ensembles are run.
- Ocean warming alone cannot match LIG sea level rise, the atmospheric warming is essential

- What are the couplings and drivers for the new modelling; what makes it work? Primarily parameterising meltwater in crevasses.
- Modelling really benefits from (needs) constraints from real data.
- Is it worth trying to match MIS 11? Constraints probably currently too hard (difficult for GCMs), matching LIG and Pliocene is hard enough at the moment.
- Polar amplification important; does faster motion in the atmosphere than in the ocean matter?

Evening reception at the US Embassy

Speakers:

- Edward P. Heartney (Environment, Science, Technology, and Health Counselor, U.S. Embassy London)
- Prof Duncan Wingham (Chief Executive, Natural Environment Research Council)
- Scott Borg (Head, Antarctic Sciences, National Science Foundation)

Session 6. Logistics & International perspective

Preamble: *For the decades between the 1960s and early-2000s, research in the Amundsen Sea embayment of West Antarctica was limited. Vibrant programmes focused both scientific effort and logistic capabilities on the Siple Coast and on Filchner-Ronne Ice Shelf. Only with the impetus of satellite results showing rapid ice-loss in the Amundsen Sea sector, did we begin to re-establish scientific momentum there and establish, for the first time, logistics chains capable of supporting the significant and complex programmes in this remote area. The question remains, however, do we have the technologies, deployment opportunities and capabilities sufficient to mount significant marine and oversnow campaigns in these areas? In addition, how can international collaborations help achieve the science goals more efficiently?*

Presenter – Scott Borg, Mike Dinn
Presenter – Robin Bell
Chair – Andy Smith

Summary: Scott Borg (NSF) and Mike Dinn (NERC-BAS) spoke on operations and practicalities, in the US and UK, respectively. Robin Bell discussed the background and progress of a writing group meeting held recently in Boulder for a collaborative plan to address the “How Much, How Fast?” question of West Antarctica and sea level rise.

Session 7. What can we hope to learn from records of the past that will inform our projections of future ice-sheet change?

Preamble: *Recent interglacial periods have been widely promoted as analogues for a future high greenhouse gas world, and on more recent timescales, changes in the ice sheet have coincided with measured environmental variations. To what degree do palaeo-records of these periods hold an accessible archive of the oceanographic and climate forcing, and the*

immediate and consequential response of the West Antarctic Ice Sheet? What is our best approach to determine how rapidly WAIS collapsed in the past?

Presenters – Eric Wolff, Rob Larter
Moderator – Ali Graham

Wolff – main points:

- How sensitive is WAIS to a long period of warmth?
- Sea level estimates suggest considerable loss of Antarctic ice at Last Interglacial (LIG); WAIS is prime suspect.
- Cannot yet answer whether WAIS was mainly there at LIG or not (still no compelling evidence)
- Address this with ice cores (existing and new), GIA, ice sheet, and atmosphere/ocean modelling.
- Challenge from Fletcher core – could LIG WAIS be significantly smaller and still be consistent with all the proxy evidence? (That evidence being ice cap at Fletcher and Mt Moulton, climate records consistent with uplift from WAIS loss and re-growth, open Amundsen-Weddell seaway.)

Larter – key questions:

- What has been the history of ice sheet change over the past 10,000 years?
- What are the speed records for retreat and thinning, and what was the forcing at the times of fastest change?
- Did WAIS collapse and if so, when?

Discussion. Moderator - Graham:

- Still no "smoking gun" for LIG WAIS collapse, although there are many "guns".
- How reliable are the far-field sea level records?
- What is the best evidence for and against LIG WAIS collapse? Far-field sea level records (and perhaps Siple Dome)

Session 8. Is it true that "glaciologists are all oceanographers now"?

Preamble: *The role of the oceans in driving changes in the grounded ice sheet, through enhanced melting of floating ice shelves, and the delivery of heat to the ice is now well-established. However, the time-series of key oceanographic data, are too short to allow adequate assessments of natural variability, and our understanding of the detailed processes that govern ice/ocean interaction remains poor. To what degree are the limitations in our understanding of the processes by which oceans and ice sheets behave individually, becoming irrelevant compared to our failure to understand them as a coupled, or integrated, system.*

Presenters – Pierre Dutrieux, David Holland
Moderator – Knut Christianson

Dutrieux – key questions and points

- What actually controls the ocean heat content in the Amundsen Sea?
- What is the role of atmospheric forcing at seasonal/interannual/decadal timescales? What is the role of tele-connections?
- Importance of spatial distribution of melt at kilometre scales?
- How are the ice-base terraces created and how important are they for the bigger picture?
- Coupled dynamics? (Coupling between ocean and ice dynamics is fundamental)
- Highly variable ocean forcing (melting) is not reflected in ice flow
- But recent flow change (2013-15) does match some change in ocean warmth

Holland – key points

- Need a bigger/better conversation across disciplines, communities and methods (glaciology-oceanography; observationalists-modellers; Antarctic science-global climate science).
- What is the value of a few years' observations? (How much of the system will be sampled with 3-5 years of observations and how will models use these?)

Discussion. Moderator - Christianson:

- Changing oceanic conditions are a challenge to understand (they change from 1 year to the next)
- Repeat surveys of ice shelf cavities worthwhile (at least for better coverage; perhaps for changes too)
- If Thwaites de-glaciation has started, is it too late now to understand triggers?

Session 9. What is the future role of satellites in ice-sheet projection?

Preamble: *Recent satellite studies have been instrumental in quantifying ice-loss, variations in glacier flow, changes in grounding-line and ice-front locations. Whilst the continuation of satellite infrastructure required to maintain these important change indicators cannot be assumed to be secure, can we anticipate satellites providing new innovative results that we don't have now?*

Presenter – Andy Shepherd
Moderator – Rob Arthern

Shepherd – key questions:

- How would the loss of CryoSat-2 affect our ability to monitor and understand ice sheet processes?
- How important is a capability to monitor grounding line position?
- How important are observations of slow moving ice?
- Are satellite measurements of surface mass balance required, or are regional climate models sufficient?
- Can Earth Observation be reanalysed within ice sheet models (can we simulate the observations using our models)?

Discussion. Moderator - Arthern:

- Earth observation (EO) is now approaching 30-years duration, comparable to climate modelling assimilation timescales.

- Q. What is the significance of recent publications that have suggested "Antarctic mass-gain"? A. The approach adopted in these was a good one, (i.e., seeking to incorporate correct meteorological physics), but the reliability of the meteorological models used to do this, are probably not up to the task. It should be noted that only one study indicates a net mass gain, compared with >50 similar studies that show the opposite.

Session 10. Are glaciologists paying enough attention to the atmosphere?

Preamble: *What happens in the atmosphere affects the ocean and the ice and can ultimately dictate the ice sheet's future. Recent decades have seen dramatic changes in surface melt and accumulation in West Antarctica and the Antarctic Peninsula along with changes in winds over adjacent seas. What is the scope for improving on existing approaches to integrating atmosphere, ocean and ice in predictions and what benefits could such improvements provide?*

Presenter – Tom Bracegirdle
Moderator – Robert Mulvaney

Bracegirdle – key questions and points:

- To what extent will surface melting increase in future?
- How would regional sea ice change in a warming climate?
- Will winds adjacent to West Antarctica become more westerly in the future?
- How should information from multiple global climate models be combined?
- What is the role and importance of internal variability of the climate system (what timescales are relevant to glaciology/oceanography)?
- Stressed tropical-Antarctic linkages
- Grid resolution is an issue (currently too small in a number of aspects)

Discussion. Moderator - Mulvaney:

- Improved array of met observations would have great value.
- More observations and better (finer) grid resolution might help regional climate models do surface boundary layer and surface temperatures better.
- Coupling atmosphere with ice dynamics can really affect ice sheet model results.
- Understanding the relative roles of atmosphere and ocean on the ice sheet continues to be difficult. When the atmosphere is cold, ocean is the main driver; with warmer atmosphere (surface melt), atmosphere becomes the driver.

Session 11. Conclusions wrap-up

The meeting ended with a presentation by one of the conveners, and a facilitated discussion to summarize the meeting progress.

Presentation – David Vaughan

The presenter made some comments on the long-standing nature of issues surrounding the contribution of West Antarctica to sea level rise, including:

- The ambition that progress in coming years will allow the next generation to move forward from this issue.
- Noting the high level of consensus at the meeting that the future of Thwaites Glacier and its neighbours is the key to reducing uncertainty in sea-level projections; real progress could be made through a coordinated programme of modelling and observations, which would necessarily include specific and targeted palaeo observations.
- Whilst significant opportunities exist to develop collaborative links, continued effort would be required, and that all of the meeting participants could take a role within institutions and disciplines to develop credibility and momentum.
- A note of caution, that attaching the justification of great significant social imperative to an area of science, brings with it responsibilities towards transparency etc.
- Primary discussion was on how to move forwards with making the science case, from a co-ordinated international (UK-US) community, for a significant research effort; the focus remains on the Thwaites Glacier/Amundsen Sea region of West Antarctica, and its potential to make a significant contribution to global sea-level. The perils of allowing this emphasis to be diluted were discussed.

Key discussion points:

- Discussion continued briefly on whether to concentrate solely on the grounding line regions to understand the so called Marine Ice Sheet Instability (MISI), or to see the issue of the contribution of WAIS to sea-level rise as one in which MISI was wrapped together with a response to probable oceanic and atmospheric drivers?
- It was suggested that participants in the present workshop should see ourselves as Ambassadors for the wider UK and US communities, agreeing that the current effort could yield opportunities for all interested partners, not just the participants present at this meeting. To demonstrate this it was agreed that outputs from the workshop should be circulated and transparency should be maintained.
- It was stressed that any document/report from this meeting should not appear parochial (otherwise, will be recognised as such), rather it should have broad reach and support.
- It was pointed out that there exist significant differences between UK and US science communities. For example; in the US similar strategic discussions have taken place many times over many years (e.g. at WAIS Workshops, previous ASE document, NAS report etc). There is less evidence of similar open strategic discussions taking place in the UK.
- It was noted that the SCAR Horizon Scan came to similar conclusions regarding the significance of the West Antarctic ice sheet, as the present meeting, although the present meeting has allowed for considerable expansion on those statements.
- It was similarly noted, that the recent NAS consultation exercise undertook an excellent community outreach, and was thus underpinned by a wider and more thorough level of agreement that could not be expected to be matched in the near-future.

Next steps

- It was agreed that the convenors will work on a meeting report; a starting point will be the speakers Key Questions and main points raised in the discussions.
- Combining output from this meeting with that from the US Boulder writing meeting agreed as the best approach, if it can be done appropriately and sufficiently quick (Boulder document is well underway).
- Aim for a single document showing “converged” consensus and making significant advances.
- The importance of demonstrating our resolve through progress is urgent.

Appendix 2.

Excerpt from draft US community document

How Much How Fast: A Decadal Plan for Quantifying the Rate of Change of the West Antarctic Ice Sheet Now and in the Future

EXECUTIVE SUMMARY

The West Antarctic Ice Sheet is changing. Multiple lines of evidence point to ongoing rapid loss of ice mass in response to changing climate and ocean conditions. Models of its future behavior indicate this ice sheet has the potential to collapse and thereby rapidly raise sea levels globally on the order of meters in the next few decades to centuries. The National Academy Report, "A strategic vision for NSF investment in Antarctic and Southern Ocean Research" indicates that constraining how much and how fast the West Antarctic Ice Sheet will change in the coming decades is the highest priority Antarctic research to be addressed. This document builds on the framework presented in the Academy report and presents an experiment plan designed to improve our future projections of ice sheet change and sea level rise. A dedicated meeting in Colorado January 2015 was held to generate the outline of the plan, drawing on wide scientific community input. The four major focus areas emerging from the Academy Report and the Boulder meeting are:

(1) **Why is the West Antarctic Ice Sheet changing now?** While the rate and extent of the current ice sheet changes are now well-documented, there is an urgent need to better ***identify and measure the drivers of the observed change***. The drivers of the system are inherently complex, interdisciplinary, and global, because together the atmosphere and ocean contribute to the changing ice in West Antarctica. Advancing our knowledge of the drivers of the current change will improve our ability to project future change. Both the observed changes and models indicate that the Thwaites Glacier and Amundsen Sea region are the crucial sites to target.

(2) **What does the West Antarctic ice sheet really look like?** Much of the evidence for change in Antarctic is based on measurements from space. While these observations are compelling, measurements on and near the ice surface and at the ice-sheet margins can tell us in much more detail what the ice sheet really looks like and how it will behave in the future. Accurate projections require accurate knowledge of how thick the ice is, how slippery the base is, and how the ice deforms. It is essential to ***map the boundary conditions*** on the surface of the ice, beneath the ice sheet, and in the surrounding ocean to develop accurate projections of future change. Again the Thwaites Glacier catchment and the adjacent Amundsen Sea are the primary targets for mapping.

(3) **How do marine ice sheets collapse?** Marine ice sheets, like West Antarctica, form in shallow seas and are sensitive to changing ocean and atmosphere temperatures. While ice sheets covered much of North America and Europe just 20,000 years ago scientists have

never witnessed a marine ice sheet collapse. Many of the ***key processes*** inherent in the dynamics of marine ice sheets that will become important in the coming decades are not well understood. These processes require dedicated study to be accurately represented in projections and models. Key processes include the failure of ice cliffs, the intrusion of warm marine air over the ice sheet, the impact of enhanced surface melt, the interaction between ice and ocean water beneath floating ice shelves and at the edge of the grounded ice sheet, the role of sliding at the ice sheet bed, the mechanics of grounding line stability and the potential for ecosystems feedbacks. Some of these processes will be best studied in the Thwaites/Amundsen Sea region, others in other parts of Antarctica.

(4) **What is our best projection of future sea level rise from Antarctica?** Models are fundamental to understanding the observed change and quantify the range of possible future scenarios possible. The modeling effort must ***advance ice-ocean-atmosphere models at all spatial scales***, and focus on the decadal- to century evolution of the system. Modeling efforts to address the 'how much, how fast' question will include models of key processes that will build on data from new field-based studies, and models of the full ice sheet that are optimized for the Antarctic environment and couple the climate-ice-ocean systems.

The primary geographic focus of the How Much How Fast effort outlined here will be the Thwaites Glacier and the adjacent Amundsen Sea. The societally relevant timescale of the major changes possible — decades to centuries — drives the focus on Thwaites Glacier. The Thwaites grounding line is very wide and the ice sheet thickens away from the coast, making it a textbook case of an unstable marine ice sheet. A significant collapse of the Thwaites Glacier system will trigger wider collapse of the complete West Antarctic Ice Sheet. Although Thwaites is the geographic focus, some key processes can be addressed effectively in other parts of Antarctica. Furthermore, modeling efforts will encompass all of Antarctica and the Southern Ocean.

Central to the success of this program will be long-term continuous observations of the atmosphere and ocean; high resolution mapping of the Thwaites Glacier catchment and Amundsen Sea; dedicated studies of key processes to improve models; and improved models with better coupling of the ice, ocean, and atmosphere systems. This document describes the steps necessary to address each of the four questions listed above. The instrumentation and logistical needs are briefly outlined. A decadal scale community effort that will advance our knowledge of how quickly the West Antarctic Ice Sheet will change and how much sea level rise will result.

A host of recent papers have identified major ongoing ice loss from the West Antarctic Ice Sheet (WAIS) in response to recent climate and ocean changes. Moreover, these studies point to the potential for a further dramatic increase in ice discharge in the next few decades leading to eventual collapse of the central WAIS. In adjacent exposed areas, beneath ice shelves, or within the ice itself, records of past WAIS collapses exist as part of the glacial-interglacial cycle. The rate of sea level rise caused by rapid ice loss from WAIS could outpace all other sources and strain our ability to adapt or replace infrastructure in coastal areas. This is particularly true for the coastal U.S. where the impact of a surge in sea

level stemming from Antarctic ice loss would be amplified (due to changes in the gravitational field arising from the ice loss).

There are major gaps in the scientific understanding of of marine ice sheet collapse. Key data needed to evaluate the processes and likely rates of collapse from the focus region are sparse. Few observations exist from the near-ice coastal ocean and beneath the ice sheet surface in the central WAIS. Moreover, our understanding of ice sheet / ice shelf dynamics, and of the continuing changes in Antarctic climate and oceanic circulation are still evolving. In turn the ecosystem is profoundly impacted in the region. All these systems are research targets for the program.

Understanding the fundamental processes driving West Antarctic ice sheet change requires a coordinated research effort with measurements taking place over an extended period in selected, critical regions. The initiative proposed here builds directly upon the recent history of U.S. leadership and investment in West Antarctic research. It also incorporates international partnerships need to undertake a large and coordinated study of global importance. It addresses the top recommendation of the recent NAS report 'A Strategic Vision for U.S. Antarctic and Southern Ocean Research' to invest in a better scientific understanding of this region.

Appendix 3.

Meeting participants

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