SCAR PPG	**AIDSL**
Paper 8	Agenda item 5
Person Responsible:	Tim Naish

SCAR Executive Committee Meeting 2019

Plovdiv, Bulgaria, 29-31 July 2019

Antarctic Ice Dynamics and Sea Level Change (AIDSL)

Draft Science and Implementation Plan

For SCAR guidelines see Appendix
Guideline text for the Science and Implementation plan is in red below

Title Page (1 page)

Science and Implementation Plan for a proposed SCAR Scientific Research Programme

1. Name of the proposed SRP
Antarctic Ice Dynamics and Sea Level Change (AIDSL)

2. Name(s) of the lead proponent(s) (including affiliations and contact information)
Tim Naish (NZ), Antarctic Research Centre, Victoria University of Wellington, PO Box 600, Wellington 6140, New Zealand, timothy.naish@vuw.ac.nz
(ADD OTHERS)

3. Sponsoring SSG(s)
SCAR Geosciences Group (GSSG)
SCAR Physical Sciences Group (PSSG)
SCAR Life Sciences Group (LSSG)

4. Summary of the duration and budget request (in US$ per year)
Duration of 8 years. Budget under discussion.

This draft is incomplete

5. Abstract (250 words or less)

6. Proposal Details (max. 10 pages of text)

Introduction - scientific objectives and statement of task *(including contributions to SCAR's Strategic Plan) [10%]*

This is a draft Science and Implementation Plan (SIP) for a new Scientific Research Programme (SRP), provisionally entitled Antarctic Ice Dynamics and Global Sea Level (AIDSL). The SRP addresses one of the highest priority issues facing climate change science - *the question of Antarctica's uncertain contribution to sea level change*. It utilises an integrated multidisciplinary approach combining geoscience, physical sciences and biological sciences, of the way in which interactions between the ocean, atmosphere and cryosphere have influenced ice-sheets in the past, are influencing observed ice sheet changes, and how they will contribute to future global sea level rise.

The goal of the SRP is, therefore, to ***"quantify the Antarctic ice sheet contribution to past and future global sea-level change, from improved understanding of climate, ocean and solid Earth interactions and feedbacks with the ice, so that decision-makers can better anticipate and assess the risk in order to manage and adapt to sea-level rise and evaluate mitigation pathways"***.

The programme is structured into 4 objectives:

1. **Past climate experiments:** Improved understanding of spatial and temporal changes in Antarctica's ice sheets during: "Earth's last global warming experiment" - the deglaciation from the Last Glacial Maximum, and for past "warmer-than-present" inter-glacials and high CO_2 worlds.
2. **Ice-ocean-climate interactions:** Improved understanding of atmosphere-ocean forcing processes of marine-based ice sheet dynamics.
3. **Ice-solid Earth interactions:** Improved understanding of solid Earth feedbacks on ice sheet dynamics and regional sea-level variations.
4. **Antarctic Ice Sheet futures:** Improved projections of the Antarctic contribution to global sea-level change – consequences and impacts.

The importance of understanding Antarctica's contribution to sea level rise is underscored in the Intergovernmental Panel on Climate Change (IPCC's) forthcoming Special Report on Oceans and Cryosphere (SROC), and recently published Special Report on Global Warming of 1.5°C, as well as SCAR's Horizon Scan outcomes and the 2017-2022 SCAR strategic Plan. Co-ordinating international climate and Antarctic research bodies, such as SCAR and the World Climate Research Programme (WCRP), are developing research strategies that more directly address the role Antarctica plays in the rapid pace of environmental change, the risks facing humanity and the growing global sustainability problems it brings. SCAR also recognises the importance of the global adoption of the UN Sustainable Development Goals (SDGs), and initiatives to give effect to them, such as Future Earth and the Global Framework for Climate Services (GFCS).

The new SRP will draw upon, and realign much of the high-quality, high-impact research previously conducted within the ANTCLIM[21], PAIS, SERCE and ANTECO SRPs in Themes 1-3 to more effectively quantify future sea-level projections. The new SRP will also develop a closer partnership with WCRP's Climate and Cryosphere (CliC) Project and the "Melting Ice and Global Consequences Grand Challenge". A major theme of the WCRP Grand Challenge is "*Shrinking of mountain glaciers and large ice sheets with consequent sea-level rise and impacts on water resource",* and to address this it has the following data-model inter-comparison projects designed to deliver policy-relevant science for the IPCC assessment reports.

- Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6)
- Marine Ice Sheet Ocean Model Intercomparison Project (MISOMIP)
- GlacierMIP – A model intercomparison of global-scale glacier models
- Ice Sheet Mass Balance and Sea Level (ISMASS, which is joint with IACS and SCAR)

Objectives 1-3 will feed into Objective 4, which is a policy-facing work strand and will include social scientists to help deliver and integrate revised sea-level projections within a risk assessment/policy context. The outcomes will include improved ice mass loss projections for scenario-based (IPCC), probabilistic sea-level projections. This will be of broad interest to decision-makers, regulators, planners, civil society, business, industry, agricultural, infrastructure, finance and insurance sectors for anticipating and managing the impacts of sea-level rise.

The overall scientific objectives of our project are closely aligned with the following research priorities and strategies:

- The US National Academies of Sciences Report - A Strategic Vision for NSF investments in Antarctic and Southern Ocean Research Strategic Priorities. https://www.nap.edu/catalog/21741/a-strategic-vision-for-nsf-investments-in-antarctic-andsouthern-ocean-research.
- SCAR's strategic research plan https://www.scar.org/general-scar-news/strat-plan/
- WRCP Grand Challenge - Melting Ice and Global Consequences https://www.wcrpclimate.org/gc-melting-ice-global-consequences
- Draft white paper prepared by SCAR Past Antarctic Ice Sheets Programme outlining future research priorities http://www.scar-pais.org/index.php
- A new SCAR Strategic Research Programme Proposed Planning Group - AntClimNow. https://www.scar.org/scar-library/papers/xxxv-scar-delegates-2018-davos-switzerland/

Outcomes of the new SRP will provide evidence to assess the effectiveness of, and risks associated with, climate change mitigation pathways. They will also guide adaptation approaches required to avoid the potentially profound impacts on society, both economically and in terms of progress against the sustainable development goals.

ECR development, engagement pathways, policy interface.

Scientific rationale & approach - (including synergies with other SCAR programmes and products) [30%]

Rationale –

Over the past eight years, four of SCAR's SRPs, PAIS, ANTCLIM21, SERCE & ANTECO and the ISMASS Project (joint with IACS & WCRP) have seen a convergence of activity concerned with understanding the role of Antarctica and the Southern Ocean in the dynamics of the Earth System. Among the many outcomes thereof, one of the most significant is investigation of interactions between the atmosphere, ocean, cryosphere, and basal topography, and their outcomes for ice-sheet mass balance. In addition to a wide range of more traditional outcomes of the interdisciplinary work, novel areas of endeavour to inform the past behaviour of ice sheets have also been developed. The use of genomics to constrain past ice-sheet configurations provides one example (*Strugnell et al. 2018*).

The global significance of this work is clear. The behaviour of both the West (WAIS) and East (EAIS) Antarctic Ice Sheets has significant implications for global sea level (*Golledge et al., 2015; Ritz et al., 2015; DeConto & Pollard 2016; Edwards et al., 2019; Golledge et al., 2019*). Into the future, quantifying the pace of sea level rise and our long-term commitment to higher seas is essential. Improved understanding of Antarctic ice sheet contribution to future sea-level rise was one of the most urgent research priorities to emerge from the IPCC 5th Assessment Report (*IPCC, 2013*). The outcomes that address this are necessary to provide evidence to assess the risks associated with climate change mitigation pathways (*Rintoul et al. 2018*). They will also determine the adaptation required to avoid the potentially profound impacts on society, both economically and in terms of progress against the sustainable development goals (*Chown & Duffy 2018)*.

Broad agreement exists that although much is known, a great deal of work still needs to be done to understand how ice-sheet behaviour depends on ocean-cryosphere-atmosphere interactions, bed topography, basal conditions, and glacial isostatic adjustment. In effect, understanding how ice sheets have responded in the past to changes in the Earth System, and influenced it, and how they will do so in the future, so affecting sea-level rise, are questions of great international interest and urgency. Indeed, the Horizon Scan made clear that this is one of a small handful of international interdisciplinary scientific endeavours that SCAR should be facilitating.

At the current rate of CO_2 emissions, global mean temperatures will be 1.5°C and 2°C above pre-industrial levels in approximately 10 and 20 years, respectively. Stabilisation at 1.5°C now requires direct carbon removal (DCR) from atmosphere or solar radiation management (SRM) (Fig. 1). The global community depends on Antarctic scientists to generate new insight into ice sheet response to this level of warming and to integrate this knowledge with colleagues working on other components of the Earth system.

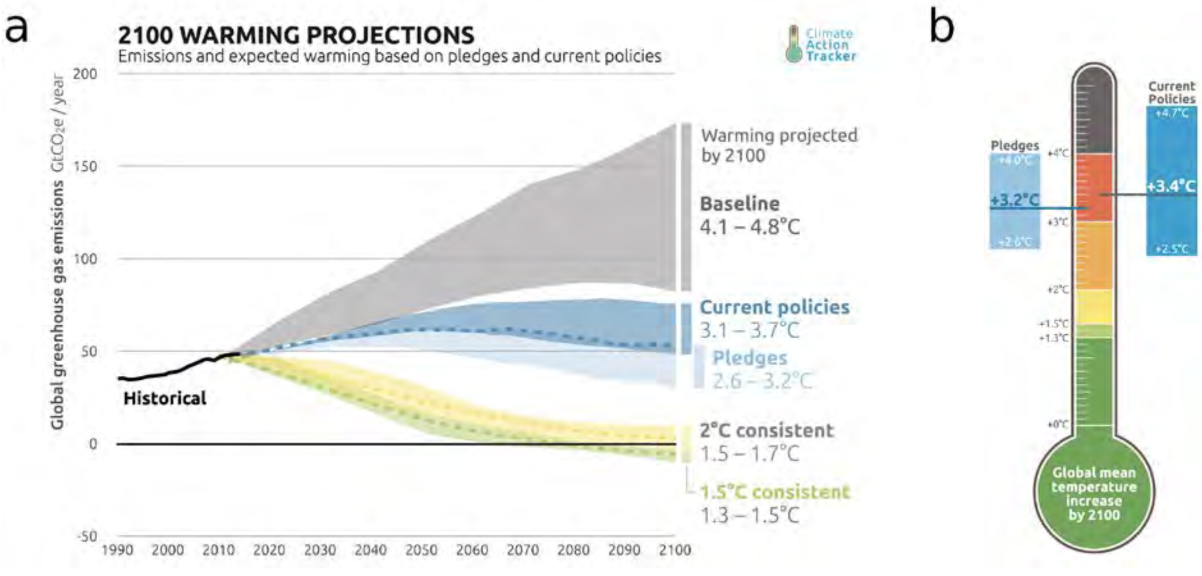

Figure 1: a) Range of possible emissions trajectories over the current century, showing 68% probabilities of resultant global mean air temperatures relative to preindustrial baseline. b) The full range of likely temperature scenarios arising from each emissions pathway, when carbon cycle modelling is included. Pledges refer to those made at the 2009 Copenhagen Summit and further underlined in the 2015 United Nations Paris Agreement (https://climateactiontracker.org).

Global mean sea level (GMSL) has increased by ~22 cm since 1880 and will continue to rise well beyond the 21st century. The IPCC AR5 (*IPCC, 2013*) predicts between 52 and 98 cm of SLR by 2100, for its range of future emission scenarios known as the representative concentration pathways (RCPs). The problem is that since 2013 multiple new lines of scientific evidence indicate a significantly higher plausible GMSL rise for RCP 8.5 - upper bound of the IPPC range. Improved understanding of the complex response of the Greenland and Antarctic ice sheets has led to this correspondingly larger range of possible 21st century SLR than previously thought (*Golledge et al., 2015; Ritz et al., 2015; DeConto & Pollard, 2016; Oppenhiemer & Alley, 2016; Pattyn et al., 2018; Golledge et al., 2019; Edwards et al., 2019*). The models used for sea level projections show that acceleration in mass loss observed by satellites over the last 10 years will continue (e.g. *Shepherd et al., 2012; IMBIE, 2018*), resulting in the polar ice sheets becoming the dominant contributor to GMSL by mid-century.

However, the response of Antarctica to projected warming still remains the single greatest uncertainty in SLR projections for the coming decades to centuries. Central to this uncertainty are poorly observed **rate-determining processes affecting the dynamic response of ice sheets** (*Pattyn, 2018*). Processes warranting attention control grounding zone migration rates, changes in buttressing resisting flowing ice, and ice-shelf and ice-cliff stability (*Joughin & Alley, 2011; Joughin et al., 2014; DeConto & Pollard, 2016*). SCAR scientists are at the forefront of research designed to reduce this uncertainty. Because the vulnerable (marine-based) sectors of the Antarctic ice sheet sit below sea level and are capable of non-linear and rapid melting in response to a warming Southern Ocean (*Golledge et al., 2015; Joughin et al., 2014; Alley et al., 2015*; *Colleoni et al., 2018*) a critical step involves understanding the **role of ocean dynamics and coupling a dynamic ocean model to our ice sheet models**.

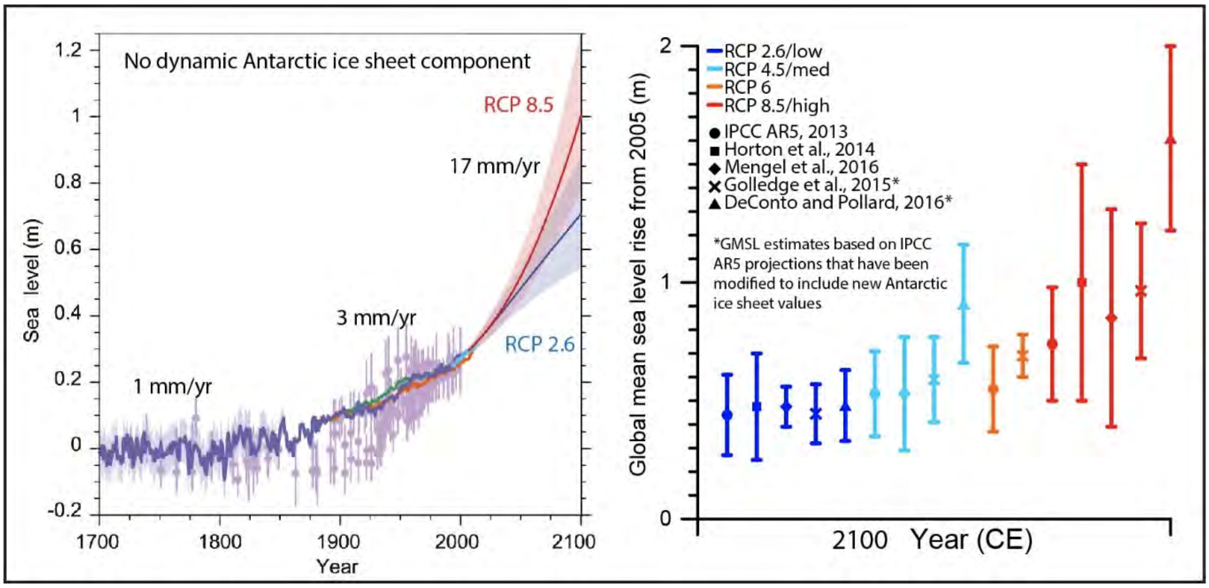

Figure 2: Left - Sea level projections to 2100 from IPCC AR5. Centre - Sea level projections at 2100 updated to include dynamic response of Antarctic Ice Sheet.

Sea-level change from land-based ice melting does not cause globally uniform sea level rise (SLR). The delivery of ice to the ocean changes Earth's gravitational field and rotational state. This, together with the accompanying viscoelastic response of the solid Earth to ice loss (a process known as glacial isostatic adjustment; GIA), means that locations near a melting ice sheet experience less SLR than more distant locations, with deviations reaching 30% of the global mean. Crucially, these solid earth processes also feedback into ice sheet dynamics (*Gomez et al. 2010; Kingslake et al., 2018*). **Understanding the role of GIA and mantle dynamics within the ice sheet system is a critical area of enquiry.**

The skill and performance of the latest generation of ice sheet models (*Golledge et al., 2015; Ritz et al., 2015; DeConto & Pollard, 2016; Golledge et al., 2017*) have been developed and tested within the SCAR programmes (PAIS, ISMASS) on past cold (*Golledge et al., 2014*) and warm climate analogues (*Pollard et al., 2009; Levy et al., 2016; Gasson et al., 2016; Golledge et al., 2017*), constrained by geological data (*Naish et al., 2009; Miller et al., 2012; McKay et al., 2012; Cook et al., 2013; Patterson et al., 2014; Levy et al., 2016; Grant et al., 2019*) The most extreme simulations from these models indicate Antarctica may contribute as much as an additional 80 cm of global SLR by 2100 under the "business as usual", high-emissions scenario where CO_2 levels reach 800 parts per million by the end of the century. The results of the new models show that stabilisation of Earth's temperature below 2°C, the Paris Climate Agreement goal (RCP 2.6), reduces long-term Antarctic ice loss from melting to less than half a metre of SLR. In other words, there appears to be a stability threshold in the Antarctic ice sheet between 1.5-2 °C of global warming, that once exceeded, commits the planet to multi-metre SLR (e.g. *Pattyn et al., 2018*). The threshold response is because of the stabilising role of ice shelves. ***But what processes lead to the destabilisation of Antarctic ice shelves and how do these relate to global mean surface temperature?*** Above 2°C global warming, enhanced melting, calving, and catastrophic collapse of ice shelves could occur, after which ocean heat can rapidly remove marine ice sheets grounded in deep sub-glacial basins.

Because the magnitude of climate forcing projected for the next century has not been experienced by Earth for more than 3 million years, paleoclimate reconstructions of past Antarctic ice sheet response provide critical insights into its future behavior (*Naish et al., 2009; Patterson et al., 2014; Cook et al., 2015; Levy et al., 2016; McKay et al., 2016; Shakun et al., 2018*). The influence of both ocean dynamics and solid Earth deformation on ice sheet dynamics can be assessed against these past warm climate analogues.

Approach –

We will utilise geological and ice core records of past ice sheet change, that provide key constraints on the long-term (multi-centennial to millennial) cryospheric response to climate and ocean conditions different from today. They capture the 'end-game' scenario that incorporates Earth system feedbacks across timescales, allowing a clearer picture of the full equilibrium shift (long-term commitments) that might occur under perturbed environmental conditions. Short-term projections of future ice sheet-derived sea level rise (decades to centuries) are, by contrast, more accurately constrained by satellite-based measurements of ice flow speed or surface elevation changes, but can suffer from process-knowledge gaps, such as incompletely known ice dynamic responses, or ice-ocean-atmosphere interactions that play out over millennial timescales (such as isostatic rebound, dynamic topography etc). **Our programme will specifically implement projects with all of these components, so that we will be able to robustly assess both short-term, policy relevant, scenarios as well as the longer-term changes that will be 'locked-in' by current and forecast emissions trajectories.**

We will achieve the four objectives (Fig. 3) using a 3-pronged, trident approach (Fig. 3, red box) involving:

1. **Modern and paleo observations** (**reconstructions)** to characterize marine-based ice sheet and ocean/climate change during the present previous intervals of warming climate.
2. **Process understanding of present dynamics** to enhance knowledge of ice and ocean dynamics within and at the margins of ice shelf cavities through the instrumental period.
3. **Future response and projections** to more precisely determine the future contribution of the Antarctic ice sheet to global sea-level rise and identify environmental implications for the Southern Ocean and their global implications and consequences.

Our researchers will access geological archives, make observations of modern and recent processes, and develop and use numerical models for forecasting. Sedimentary archives integrated with climate and ice sheet model simulations enable us to reconstruct the size and extent of past ice sheets and evaluate their response to past climate forcings that were similar to those projected for the coming decades and centuries. This approach also enables identification of tipping points and thresholds that have yet to be observed in the modern setting. Sedimentary records also provide details of ice-ocean-sediment interaction and, together with simulations of ocean circulation coupled to dynamic ice sheet and Earth deformation models grounded in an observation-based understanding of modern process, provide powerful insights into how the ice sheets will respond in the future. This approach will allow us to investigate the marine-based ice sheet response to transient and equilibrium climate forcing and better constrain Antarctic contribution to mean global sea level rise over the coming centuries.

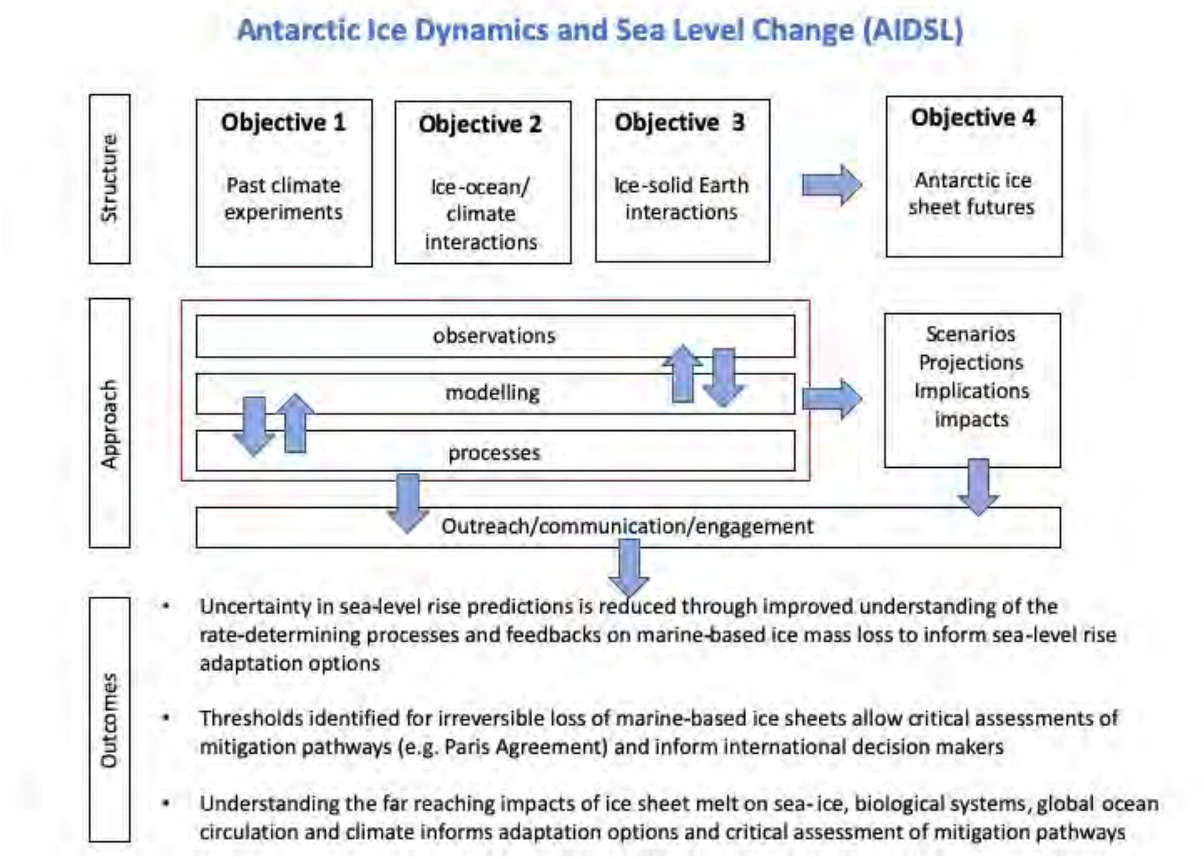

Figure 3: Proposed structure, approach and outcomes of the Antarctic Ice Dynamics and Sea-Level Change (AIDSL) Strategic Research Programme

To address the overarching research aim of the programme (below) we will use our integrated approach to evaluate and test the following high-level hypotheses:

AIM: ***"Quantify the Antarctic ice sheet contribution to past and future global sea-level change, from improved understanding of climate, ocean and solid Earth interactions and feedbacks with the ice, so that decision-makers can better anticipate and assess the risk in order to manage and adapt to sea-level rise and evaluate mitigation pathways"***.

Objective 1 - Past climate experiments

H1: Changes in oceanic circulation at the continental margin exert a primary control on marine ice sheet dynamics (e.g. WAIS advance and retreat).

H2: Sea ice and meltwater modulates marine ice sheet variability via its effect on ocean atmosphere heat exchange across the Antarctic continental shelf.

Objective 2 - Ice-ocean-climate interactions:
H3: Bedrock topography and basal conditions (e.g. sediment and hydrology), and the influence of solid Earth deformation processes (e.g GIA), exert a primary control on marine ice sheet dynamics (e.g. marine-based ice sheet advance and retreat).

Objectives 3 & 4
H4: Irreversible ice shelf loss and retreat of marine-based ice sheets (e.g. WAIS) to their terrestrial margins occurs when mean global surface temperatures exceed a warming threshold of 1.5-2°C above pre-industrial.

Experimental section and methodologies [15%]

We will obtain proxy environmental data (observations) from geological and ice core records (drill cores and outcrop) to establish key environmental boundary conditions including ice sheet extent, surface air temperatures, ocean temperatures, ocean structure and circulation, sea ice extent and persistence, and paleogeography. These data will be used to produce reconstructions of ocean, sea-ice, ice-shelf and ice sheet response to prehistoric climate variability and periods of past warmer-than-present conditions including during intervals of elevated atmospheric CO_2. To inform our paleo interpretations and our projections we will acquire new geophysical, glaciological, and oceanographic data from strategic locations (selected by modelling) along transects from ice shelf cavities and locations near the grounding zone across the continental shelf and rise and onto the deep ocean abyssal plain.

Geological and ice core data and process constraints are essential inputs for ice-sheet model simulations enabling realistic bounds to be imposed on input parameters. Paleoclimate records of past ice extent and behaviour are also commonly the only metric available against which model of warmer-than-recent climate simulations can be independently verified. The recognition that empirical data from geologically-relevant periods of the past are essential for robust numerical simulations has led to various community efforts aimed at providing 'boundary conditions' specifically for ice-sheet and climate modelling studies. Accurate reconstructions of the past are now seen as a necessity to test simulated future scenarios for the Antarctic ice sheet in a warmer world.

To further improve model skill, we will focus on generating new detailed knowledge of the current state and processes that control ice sheet dynamics. To this end we will obtain geophysical and direct measurements from beneath ice shelves, across grounding zones, and from ice streams and outlet glaciers, ice shelf surface and off shore ocean. These constraints will include sub ice-shelf bathymetry, ice stream basal conditions, ice shelf cavity, currents, temperature, and salinity. Sub ice-shelf and ocean moorings are intended to produce multi-annual time series, providing unprecedented observations from the deep interior of the ice shelf cavity to the continental shelf margin. Both paleo and modern constraints will inform simulations using a range of numerical modelling approaches, including high-resolution catchment scale glacial models, regional climate and ocean models, continental scale ice sheet models coupled to both cavity-resolving regional ocean models, climate models and Earth (GIA) models.

Specific projects and geographical locations for data acquisition to be decided by PPG but could include

1. Totten glacier and offshore (IODP drilling, ocean observations, airborne geophysics).
2. WAIS transect from Siple Coast (Ross Sea) to Amundsen Sea to Weddell Sea (oversnow geophysics, ice sheet drilling to bed/sediment sampling and coring).
3. Wilkes Subglacial Basin, (IODP drilling, ocean observations, airborne geophysics linked IODP Leg 318 exp. and offshore ocean measurements and geophysics.
4. Others to be added such as regions for ocean moorings and ocean observations, ice shelf direct access, remote sensing campaigns etc.

Figure 4 – Location map to be added

Objective 1 - **Past climate experiments**

Key question 1: *What was mass change of the Antarctic ice sheet during past warmer-than-present interglacials?*

A primary goal of this project is to acquire records of AIS extent during previous intervals of warmer than present climate with a focus on interglacial episodes through the late Quaternary (past 1 million years). Whereas none of these previous interglacial intervals are perfect analogues for the future (as orbital parameters were different) they offer insights into past sensitivity of AIS to climates that were similar to those projected for the future. Proxy environmental data from the last interglacial period (Marine Isotope Stage [MIS] 5; ca. 130– 115 ka) suggest global mean temperature peaked at 1°C higher than during the pre-industrial period (e.g. *IPCC, 2013; Dutton et al., 2015*) Maximum global mean sea level was 6–9 m above the present-day level (*IPCC, 2013*). Global average temperatures of MIS 11 (ca. 425–395 ka) may have been as high as 2°C higher than pre-industrial levels (*Land & Wolff, 2011; Dutton et al., 2015; IPCC, 2013*). Maximum global mean sea level was 6–13 m higher than today during this interglacial (*Raymo & Mitrovica, 2012; Dutton et al., 2015)*. These sea level data imply that both Greenland and marine-based ice sheets from both WAIS and EAIS were significantly smaller during these recent interglacials and imply a high sensitivity to relatively small increases in global average temperature. However, the amount of volume loss and meltwater contribution from each ice sheet is equivocal.

Workplan & Methods

(To be updated following PAIS-PRAMSO workshop at ISAES & AIDSL Workshop, will also involve genomics)

Key question 2: *What was the pattern, timing and rate of marine-based ice sheet retreat during the last deglaciation?*

Marine ice sheets are inherently unstable due to the reverse slope (deepening bed) under the ice sheet (*Schoof, 2011*). Retreat into a deepening basin can produce an unstoppable deglaciation. As the grounding line retreats into the increasingly deep marine basin, the flux increases at an ever-larger rate - this effect is known as Marine Ice Sheet Instability (MISI; *IPCC, 2013*). If the instability is invoked, retreat is irreversible, even once warming stabilises (e.g. *Waibel et al., 2014*). Another, less understood, effect involves runaway crevassing and iceberg calving at a seaward ice sheet margin where no ice shelf is present. Defining the pattern and timing of marine ice sheet melt and retreat is key as it likely contributed the greatest amount to rising sea levels following the Last Glacial Maximum (LGM; ~20 ka). We aim to improve constraints on the pattern and rate of ice sheet retreat in the Ross Sea region following the LGM and investigate processes that drove MISI (e.g. *Jones et al., 2015; McKay et al., 2016*). Our work will extend the short observational record to encompass these centennial-millennial scale processes providing benchmark data to assess ice sheet sensitivity to ocean and atmosphere forcing using ice sheet modelling.

Workplan & Methods

(To be updated following PAIS-PRAMSO workshop at ISAES & AIDSL Workshop
Should involve ice thinning cosmogenic isotope chronologies, sediment cores, marine geophysics and modelling).

Key question 3: *What was the mass change of the Antarctic Ice Sheet when atmospheric CO_2 concentration was >400ppm, and is there a tipping point for marine-based ice sheets?*

While the current concentrations of atmospheric CO_2 has just breached 400ppm and is 30% higher than it has been for almost 3 million years, we cannot ignore emissions projections that indicate atmospheric CO_2 concentrations could reach 800 to 1000 ppm within the next several centuries with a global mean temperature increase between 4 and 6°C (*PCC, 2013*). There remains a need to determine how the AIS responds to equilibrium climate conditions that will occur under atmospheric CO_2 conditions that exceed 400 ppm and assess whether this is a threshold in the Antarctic cryosphere, that once exceeded causes irreversible loss of ice shelves and marine based sectors (*Golledge et al., 2014; DeConto & Pollard, 2015; Clark et al., 2016; Pattyn et al., 2018*). High-fidelity climate records that span previous periods characterised by higher-than-present CO_2 are only available from geological records that pre-date the Pleistocene.

Workplan & Methods

(To be updated following PAIS-PRAMSO workshop at ISAES & AIDSL Workshop
Should involve panned new drilling Totten, recent drilling Ross, Scotia and Amundsen Seas and legacy core material).

Objective 2 - Ice-ocean-climate interactions

Key question 4: *What is the role of ocean dynamics within and at the margins of the ice shelf cavities through the instrumental period?*

Antarctic ice sheets lose roughly 50% of their mass through the basal melt of ice shelves, with the remaining mass lost by calving at the ice shelf front and a minimal contribution from surface melt (*Rignot et al., 2011*). Typically melt is greatest at the grounding zone (*Joughin & Padman, 2003; Holland et al., 2008*), where it has the most significant reduction on the buttressing of ice flow (*Walker et al., 2008*). Ice shelf melting increases super-linearly with temperature, making ice shelves vulnerable to changing ice shelf cavity circulation. Model and remotely-sensed estimates of melt and freeze beneath ice shelves differ widely, highlighting the need for direct observations (*Rignot et al., 2013; Paolo et al., 2015*). Here we propose the deployment of a long-term (multiannual) sub ice-shelf moorings recording current, temperature, salinity, pressure, and turbidity in the ocean cavity at grounding zones. These direct observations will be complemented by ApRES campaigns spanning weeks to years characterising the spatial and temporal variability of basal mass balance at ice stream grounding zones, across subglacial channels, and around subglacial crevasses.

Workplan & Methods

See Key question 5.

Key question 5: *What are the basal properties and processes relevant for past and future ice stream flow?*

Ice streams draining the interior of West Antarctica are known to accelerate, decelerate, cease flowing, or reactivate over decadal to centennial timescales in response to changes at their boundaries (e.g. *Joughin et al., 2014*). Internal variability in ice flow is well documented (*Retzlav & Bentley, 2017*), but the largest currently observed changes are dominated by forced-change, primarily coming from the ocean (e.g. *Alley et al., 2015*). The response of ice flow to oceanic forcing typically occurs through changes in ice shelf buttressing, whereby increased basal melt or calving, or even ice shelf collapse, lead to a reduction in back-pressure, and a subsequent sustained increase in the flow of ice into the ocean (*Scambos et al., 2004)*. The degree of flow-speed change due to internal variability or in response to buttressing changes is controlled at a first order by the underlying geometry and geology (*Hulbe et al., 2017; Anandakrishnan et al., 1*998), with water, both within the substrate and at the bed, playing a significant role (*Fricker et al., 20007; Sternes et al., 2008*).

Workplan & Methods.

Using geophysical and direct access methods, this task will determine elements of the basal regime beneath ice streams and in ice shelf cavities. Central to this objective is a direct access drilling programme to observe and sample the ocean cavity and glacial substrate. Subglacial water flux is a significant unknown in ice sheet models with ice shelf basal melt parameterization (*Jenkins, 2011*) and centennial-scale ice dynamic models (*Bougamont et al., 2015)* highlighting its importance. Direct access into both the ocean cavity and the subglacial channel will enable water column sampling, shallow sediment coring, ROV/AUV deployment, and the acquisition of time series of currents, temperature, salinity, pressure and turbidity. Direct access will also enable direct measurement of geothermal heat flux (*Fisher et al., 2015*). Alongside direct access we will use passive seismic methods, active source seismology, and radio echo sounding (ApRES and oversnow profiling) to characterise ice ocean interaction, basal processes (including grounding zone sedimentation), and subglacial hydrology. Global Navigation Satellite System (GNSS) surveying will be used to complement mooring and ApRES observations and in a dedicated campaign addressing seasonal velocity variability on] ice shelves.

Key question 6. *What drives oceanic heat exchange across the continental shelves and how does this influence the flow of mCDW into ice shelf cavities and marine ice sheet grounding lines***?**

The influence of global ocean circulation via a modified thermohaline circulation (THC), the ACC, and atmospheric circulation (links to katabatic winds, strength of the westerlies/ easterlies, and heat fluxes) on changes in the characteristic salinity of dense waters formed on the continental shelf (including associated carbon uptake) will be a focus of this project.

Workplan & Methods.

We will build build on the modern-process understanding developed through observations from objectives modelling using paleoceanographic proxies that provide information about sea surface temperature (SST), salinity (melt water), ocean currents and circulation, mixing, stratification, and sea ice, with a focus on exploring the systems response to climate shifts associated with past warmer worlds. Reconstructions will target past warm climate intervals including the most recent deglaciation (a 4-5°C global cooling temperature shift) and mid-Holocene (slightly warmer than preindustrial with ice sheet thinning; *Hein et al., 2016; Jones et al., 2015*), late Pleistocene interglacials (+2°C for short intervals; e.g. *Wilson et al., 2018*), Stage 31 (warmest part of the Pleistocene; *Beltran et al., 2016; Scherer et al., 200*8), and the warm Pliocene (350-400 ppm world; +2°C average global temps; *Dowsett et al., 2012*), with a particular focus on transitions into warm climate states. We will use both new and existing materials, including archived surface sediments and short cores from the continental shelf, new cores collected, and extended records from three recent International Ocean Discovery Program (IODP) expeditions to the Southern Ocean. Records developed from slope, shelf, and rise sites through this objective will be linked to new grounding line-proximal records to form paleoceanographic transects. Holocene and late Pleistocene paleoceanographic reconstructions will be interpreted in the context of ice core records to explore ocean-atmosphere coupling on timescales beyond the instrumental record.

Needs a champion to help develop the modern obs and modelling aspects

Key question 7. *What is the role of, and what feedbacks occur due to, sea ice, polynyas and meltwater in modulating marine ice sheet variability via its effect on ocean atmosphere heat exchange across the Antarctic continental shelf?*

Needs a combination of modern process, obs and paleo work to identify the role of sea-ice and freshwater in ocean stratification and the feedbacks on ice sheet dynamics through heat and gas exchange between the ocean and the atmosphere.

Objective 3 - Ice-solid Earth interactions THIS SECTION NEEDS WORK AND INPUT FROM SERCE FOLK.

Key question 8. *What is the role of gravitational and viscolelastic responses on relative sea-level change in the near-field of melting marine-based ice sheets and how does this influence ice sheet dynamics?*

Coupling of GIA models to ice sheet models to better understand near-field sea-level change and feedbacks on ice sheet dynamics, and reconcile far-field reconstructions of sea-level change for past, present and future. The latter is critical for improving regional sea-level projections.

Key question 9. *What is the role of dynamic topography on relative on sea-level change in the near-field of melting marine-based ice sheets and how what are the feedbacks on ice sheet dynamics?*

Key question 10. *What is the role of geological controls such as erosion and sedimentation on ice sheet dynamics*

Key question 11. *What is the role of Geothermal heat flux on ice rheology and I e sheet dynamics.*

Objective 4 - Antarctic Ice Sheet futures:

Improved projections of the Antarctic contribution to global sea-level change – consequences and impacts.

Key question 12. *Can we simulate the evolution of Antarctic ocean / atmosphere under future climate forcing scenarios?*

The most significant uncertainty in terms of projecting future ice sheet responses to a changing climate is the climate trajectory (or range) that we are most likely to follow. Despite this uncertainty climate model scenarios can be interrogated within a framework of policy-based commitments to provide a 'likely range' of future climate scenarios (Fig. 1). Our approach will use this kind of information to guide climate, ocean and ice sheet simulations to 2100.

Workplan & Methods.

We will first seek to identify climate models that best represent the Southern Hemisphere (*e.g. Naughten et al., 2018*). This subset will then be used to provide initial conditions as well as lateral boundary conditions for regional ocean and atmosphere models that dynamically downscale the coarse-resolution global simulations to provide more representative realisations of the Antarctic continent and surrounding ocean. A key part of this task will be the adaptation of regional model codes to interface with the global model outputs and will require some exploratory work to determine the most effective methodology. The primary aim of this task is to deliver high spatial resolution climate and ocean outputs for the present century, under a range of possible emissions scenarios, for use in subsequent ice sheet model experiments. However, the downscaling approach is not only intended to refine the spatial grid of the outputs, but also allows for the incorporation of finer-scale processes and process interactions than are possible in global models. Such additions allow, for example, circulation and mixing of continental shelf waters to be more realistically captured, or the accurate simulation of regional air flow arising from topographic effects and the consequent spatial variability in surface air temperature and/or precipitation. This work will be closely integrated with work in the WCRP Grand Challenge (MISOMIP, ISMIP-6 etc.)

Sea ice variability is becoming increasingly recognised as an important control on ice sheet and ice shelf behavior (*Miles et al., 2016; Greene et al., 2018*), and acts as a thermal and physical barrier between oceanic and atmospheric systems. Addressing our Hypotheses requires us to couple a sea ice model to our regional ocean (ROMS) and climate model codes. Once these three components are in place, tested, and performance evaluated, we will configure the model components, either individually or together, to link with the ice sheet models (ISM). This work will be closely integrated with work in the WCRP Grand Challenge (MISOMIP, ISMIP-6 etc.)Offline (file system) coupling of each individual component with the ISM will be the first approach, being the simplest to achieve. Subsequent complexity will be added as required and depending on performance. While fully-coupled experiments may be considered the ultimate objective in terms of future Projections, there is also considerable utility in running model components separately, so that particular processes and feedbacks might be isolated, explored, and better understood.

Key question 13. *What is the response of the AIS to future climate forcing scenarios?*

Future melt of the Antarctic ice sheets and ice shelves will reduce ice volume and change sea level with impact at the global scale. Loss of ice to the ocean will affect local water temperature and salinity and will drive regional changes in mixing and circulation that could have far-field consequences. Accurately predicting ice sheet evolution over a range of spatial and temporal scales is therefore a key priority.

Workplan & Methods.

We will conduct a range of ice sheet simulations that include whole-continent, scenario-based, experiments that aim to deliver robust predictions of future contributions to sea level, as well as catchment-scale experiments that focus on aspects of the system at a local scale. We will use a variety of ice sheet models, depending on requirements. We intend to drive our future ice sheet simulations with outputs from regional ocean and climate models.

In the first instance, we will undertake experiments in standalone mode, i.e. no coupling between ice sheet and climate/ocean model components. As our capability and experience grows we will work towards a workflow in which these individual components are coupled, allowing each to evolve in response to changes in the others. This is an important advance, in that it is the most robust way to simulate and understand feedbacks within the ice-sheet / ocean / atmosphere system. However, multi-model coupling is a non-trivial task and comes with significant computational complexity and cost. Our aspiration for this Objective is therefore to pursue this aim as far as possible, working with experts in the international community (e.g. WCRP/CliC) in order to learn from their experiences.

A final component of this Task will be the integration of our ice sheet simulations into a gravitational / rotational sea level model. This global modelling framework allows for a gravitationally self-consistent spatial pattern of sea level change to be predicted, based on changing ice loads in different parts of the world. Because melt and recession of parts of the Greenland and Antarctic ice sheets tend to produce their own unique 'fingerprint' of sea level
change, when combined they yield robust predictions for future relative sea level changes at any given location on the planet.

NOTE THAT THIS WILL BE LINKED WITH OBJECTIVE 3.

a. Management and reporting (including a Scientific Steering Committee) [10%]

b. Milestones, outcomes, outputs[1], and benefits (including metrics of performance) [15%]

c. Data management plan [10%]

d. Capacity building, education and training plan [10%]

e. References

Supporting information (2 pages)
i. Short biosketch and homepage URL for proposed Chief Officer(s) and lead investigator(s)
ii. Justification for SCAR sponsorship (why does SCAR support add value?)
iii. International involvement and partnerships
iv. Budget justification (other potential sources of funds)
v. Other information (information useful to evaluators)

[1] Note that where possible the outreach activities and associated outputs from the SRP should be produced in collaboration with the other SRPs ; joint outreach activities and outputs are encouraged