Latest advances and future research priorities for the Scientific Committee on Antarctic Research (SCAR) Past Antarctic Ice Sheet Dynamics (PAIS) Strategic Research Programme (SRP):

A strategic white paper outlining future research directions

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1. ***Summary of the PAIS Conference, Trieste, Italy, September 10th-15th, 2018.***

The PAIS conference comprised over 200 scientists from 18 countries, coming together to present recent results on the latest understanding of the sensitivity of the Antarctic Ice Sheet and its contribution to past and future sea level and climate. The major goal of the conference was an evaluation of the current state of Antarctic ice sheet and sea-level science in order to outline future research priorities beyond PAIS and aligned with:

I. SCAR's evolving future strategic direction,
II. the recent SCAR Horizon Scan for the next 20 years of Antarctic Research.
III. a new phase of International Ocean Discovery Program (IODP),
IV. science required for the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report
V. United Nations Sustainable Development Goals.

More than half the participants were early career researchers and graduate students. All presentations took place in a single plenary session, which ensured cross-disciplinary participation and each day finished with a facilitated open plenary discussion. Keynote speakers were invited from outside the PAIS community to help stimulate new multidisciplinary research approaches to how Antarctic ice sheet and climate change will impact biological systems and more broadly global climate system and sea-level change.

Conference participants represented solid earth and glacial geophysics, glaciology, oceanography, paleoclimatology (ice core and geology), paleoceanography, paleoecology, paleobiology, molecular genomics, geochemistry, ice sheet modelling, climate modelling, GIA modelling, terrestrial biodiversity research areas. The conference was organised into 5 Themes in a single plenary session, with time allocated at the end of each theme for a facilitated panel discussion and Q and A open to the floor. The focus being to identify the major research advances and future priorities. Themes were:

1. (A) Advances in Antarctic ice-sheet reconstructions from geological and ice core archives: LGM to Recent
   (B) Advances in Antarctic ice-sheet reconstructions from geological and ice core archives - deep time reconstructions
2. Advances in understanding the drivers, processes, and rates of past and future Antarctic ice-sheet change from models and data
3. Bipolar connections and far-field responses to Antarctic ice sheet change
4. Co-evolution of climate and life in the Antarctic & Southern Ocean
5. Emerging research priorities of societal relevance

The final day was dedicated to a science-policy session. Steven Chown, SCAR President, discussed his vision for how SCAR research can have more impact both within the Antarctic Treaty System and the United Nations frameworks. Valarie Masson-Delmotte, Co-Chair of IPCC Working Group 1, outlined the chapter structure and how the SCAR community could contribute to the next assessment report. Chuck Kennicutt & Yeadong Kim, leaders of the SCAR Horizon Scan and COMNAP ARC road map processes, talked about how international logistics and operations could be aligned to address the big science questions.

It was recognised that fundamental research questions remain that need a prioritised focus, but scientists also need to work more closely with a broad stakeholder community to enhance understanding of ice sheet change and its wider impacts on the Earth system such as interhemispheric connections and global to regional sea-level change. This is essential for assessing sea-level rise impacts, as well as for enhancing climate mitigation and adaptation measures over the short-, medium- and long-term.

http://www.scar-pais.org/index.php/conference.

2. *The PAIS Programme Approach*

The overarching goal of PAIS has been to improve confidence in predictions of ice sheet and sea-level response to future climate change and ocean warming. For this, PAIS aims to improve understanding of the sensitivity of East, West, and Antarctic Peninsula Ice Sheets to a broad range of climatic and oceanic conditions. Study intervals span a range of timescales, including past "greenhouse" climates warmer than today, and times of more recent warming and ice sheet retreat during glacial terminations. The PAIS research philosophy is based on data-data and data-model integration and intercomparison, and the development of data transects, extending from the ice sheet interior to the deep sea. The data-transect concept (Fig. 1) links ice core, continental, ice sheet-proximal, offshore, and far-field records of past ice sheet behaviour and sea level, yielding an unprecedented view of past changes in ice sheet geometry, volume, and ice sheet-ocean interactions. These integrated data sets have enabled robust testing of a new generation of coupled Glacial Isostatic Adjustment-Ice Sheet-Atmosphere-Ocean models that include new reconstructions of past and present ice bed topography and bathymetry. PAIS has accomplished its objectives by: 1) facilitating the planning of new data-acquisition missions using emerging technologies; 2) encouraging data sharing and integration of spatially targeted transect data with modelling studies; and 3) initiating/expanding cross linkages among Antarctic research communities. The PAIS Scientific Programme is led by a Steering Committee with wide knowledge of thematic issues, and appropriate regional (field), technical and logistical experience. Additionally, four subcommittees have been established to implement the scientific objectives of PAIS: 1) *Palaeoclimate Records from the Antarctic Margin and Southern Ocean (PRAMSO)*; 2) *Palaeotopographic-Palaeobathymetric Reconstructions; 3) Subglacial Geophysics*; and 4) *Ice Cores and Marine Core Synthesis*. The subcommittees provide the overall leadership, direction and management for their respective topics. Membership of these committees allows PAIS to widen involvement in the programme in terms of expertise, gender and nationality.

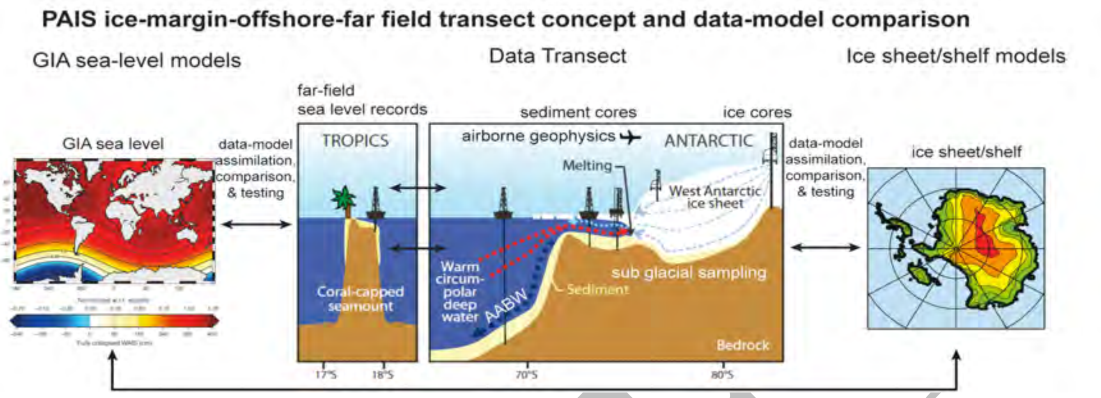

Fig. 1: *The PAIS Approach integrating – data transects with GIA and ice sheet models*

3. Research advances and highlights from the PAIS Programme: Our greatest hits!

- *Antarctic ice sheet sensitivity during past high-CO_2 world's and its contribution to global sea-level change:* Geological proxies from the Antarctic continental margin have enabled ocean and land temperatures, sea-ice extent, ice sheet extent, subglacial hydrology, carbon cycle feedbacks and paleogeography to be reconstructed for past warm climate states. This has provided improved boundary conditions for testing and developing ice sheet and climate model skill and performance, as well as evaluating model sensitivity. Significant outcomes include:
    - Reconciling southern high-latitude meridional temperature gradients and polar amplification between simulations and data (e.g *Pross et al., Nature 2012; Bjil et al., PNAS, 2012; DeConto et al., Nature 2012)*.
    - Identifying equilibrium ice volumes and contribution to global sea-level under past "warmer-than-present" climates (e.g. mid-Pliocene, mid-Miocene; *Miller et al., Geology 2012; de Boer et al., Cryosphere 2015; DeConto et al., 2012; Pollard et al., EPSL 2015; Gasson et al., PNAS 2016; Golledge et al., Climates of the Past 2017*).
    - Recognition on the importance of bedrock topography and paleobathymetry on past Antarctic ice volumes (e.g *Gasson et al., GRL 2015; building Wilson & Luyendyke, GRL, 2009)*.
    - Recognition of the sensitivity of marine-based sectors of the EAIS from models and data (e.g. *Gulick et al., Nature 2017; Cook et al., Nature Geosciences 2013; Scherer et al., Nature Comms. 2016; Levy et al., PNAS 2016; Gasson et al., PNAS 2016 Simkins et al., Nature Geoscience 2017; Golledge et al., GRL, 2017)*.
    - Identification of ~400-500ppm CO_2 as a potential threshold for marine-based ice sheet stability *(e.g. Levy et al. PNAS, 2016, Gasson et al., PNAS, 2016)*
    - Identification of 600ppm CO_2 as a potential threshold for terrestrial ice sheet stability *(Galleoti et al., Science, 2016; building on DeConto & Pollard, Nature 2003)*

    - Insights into the influence of mean climate state (CO_2) on the response of the Antarctic ice sheet to orbital forcing (e.g. *Patterson et al., Nature Geosciences 2014; building on concepts in Naish et al., Nature 2009)*.

- *Geological evidence of ocean forcing and marine ice sheet instability:* The potential for abrupt and non-linear "runaway" retreat of Antarctica's marine based ice sheets due to marine ice sheet instability (MISI) and marine ice cliff instability (MICI) up until recently had only been mathematically simulated in ice sheet models.
    - Geological observations of the last deglaciation and recent observations coupled with models have now identified MISI during the Holocene after climate forcing had stopped in the Ross Sea *(e.g. Jones et al., Nature Comms. 2015; McKay et al., Geology, 2016),* and MICI in the Amundsen Sea sector (*Wise et al., Nature, 2017*) and Antarctic Peninsula *(Rebesco et al., Science 2014)*
    - Geological and oceanographic observations of oceanic forcing of marine-based ice sheets *(e.g. Hillenbrand et al., Nature, 2017; Rintoul et al., Science Advances, 2017; Smith et al., Nature 2017)*

- *The temporal and spatial pattern of deglaciation and Antarctic contribution to global melt-water pulse 1A:* Improved geological and bathymetric constraints combined with ice sheet models have:
    - Improved understanding of the extent of the Last Glacial Maximum (LGM) ice sheet and deglaciation into the Holocene (*e.g. Hillenbrand et al., Geology, 2013; Golledge et al., QSR 2013; Mackintosh et al., QSR, 2014; Anderson et al., QSR 2014; Bentley et al., QSR 2014; Johnson et al., Science, 2014; Lee et al., Geology, 2016; McKay et al., Geology, 2016*)
    - Shown that the potential contribution of the Antarctic ice sheet to melt-water pulse 1A. This is policy relevant as most of the Antarctic contribution of about 1m/century (3-4m) came from retreat of WAIS (*e.g. Golledge et al., Nature Comms. 2014; Weber et al., Nature 2014*)

- *Antarctic ice volume influence on regional sea-level variability:* The importance of departures in regional sea-level elevation from global mean sea-level due to rotational, visco-elastic and gravitational changes as water mass is transferred between the ice sheets and the ocean has been identified in the far and near-fields of the Antarctic ice sheet from paleo-reconstructions. This has been established through models that couple ice sheet, solid Earth geodynamical and climate models constrained by both near-field and far-field geological reconstructions of sea-level and water depth changes. Important outcomes include:
    - Role of Earth deformation processes (GIA and dynamic topography) on near-field sea -level changes and ice sheet dynamics (*e.g. Gomez et al., Journal of Climate 2018; Stocchi et al., Nature Geoscience 2013; Galleoti et al., Science 2016; Austermann et al., Geology, 2015; Gomez et al., Nature Geoscience 2015; Whitehouse et al., JGR 2017; de Boer et al., QSR 2017; Gomez et al., Journal of Climate 2018; Pollard et al., JGR 2017*).
    - Improved understanding the global sea-level fingerprint of Antarctic ice sheet melt (especially rapid WAIS melt on the Northern Hemisphere) (*e.g. Raymo et al., Nature Geoscience 2012; Dutton et al., Science 2014; Kopp et al., Earth's Future 2017*)

- *Paleo-data calibrated of ice sheets models provide revised global sea-level predictions for IPCC scenarios:* A new generation of continental scale ice sheet models that simulate MISI and in one case MICI have been developed and tested by reconstructing past ice sheet volume and extent constrained by paleoclimate and paleo-ice extent data. These models have been used to simulate future Antarctic meltwater contribution to global mean sea-level for the IPCC representative concentration pathways: Implications include:

    - Better reconciliation with reconstructions of proximal ice sheet extent and far-field sea-level from geological data (e.g. closure of the mid-Pliocene warm period sea-level budget). *(e.g. Gasson et al., Geology 2016; Pollard et al., EPSL 2016; Golledge et al., GRL, 2017)*
    - That Antarctic marine based ice sheet melt may have contributed up to 5m of global sea-level rise during the Last Interglacial. (e.g. *DeConto & Pollard, Nature 2016*). This provocative implication needs testing (see below)
    - That Antarctic contribution to global sea-level rise out to year 2100 and beyond may have been under-estimated in IPCC AR5 projections especially for high emission scenarios (e.g. RCP 8.5 could be +40 to +80cm more by 2100) (*e.g. Golledge et al., Nature 2015; DeConto & Pollard, Nature 2016*)

- *Recognition of Antarctic ice sheet thresholds & commitment to future sea-level rise:* These paleo-calibrated Antarctic ice sheet model projections imply:
    - A threshold for marine ice sheet stability may exist at ~1.5-2°C global warming above pre-industrial (e.g. between RCP 2.6 and 2.4, the target of the Paris Agreement). (*Golledge et al., Nature, 2015; Clarke et al., Nature Climate Change 2015; Pollard & DeConto Nature, 2016)*
    - Above this threshold stabilising ice shelves melt, and MISI kicks in committing the world to ongoing ice sheet loss and multi-metre sea-level rise. (*Golledge et al., Nature, 2015; Clarke et al., Nature Climate Change 2015; Pollard & DeConto Nature, 2016*)
    - The Paris target maybe the threshold for major Antarctic ice sheet melt down (*to be assessed by IPCC AR6*).

- *Transferring science into the policy setting:*
    - PAIS scientists have contributed as authors to IPCC AR5 and will contribute as authors to IPCC AR6 and Special Reports (Cryosphere and Oceans, 1.5°C) [*Naish, Mackintosh, DeConto, Golledge*]
    - PAIS research (e.g. ice sheet, sensitivity, irreversibility, processes, ice sheet model predictions for future global sea-level rise) influential in AR5 report and a priority for AR6 report.
    - PAIS research is having influence within the Antarctic Treaty System as the implications of Antarctic and Southern Ocean change for the rest of the planet and humanity become better understood. [*Naish, Escutia have given SCAR Science Plenary Lecture at ATCMs*).
    - Revised sea-level scenarios based on paleo-calibrated Antarctic ice sheet model projections are being utilised in planning documents for decision-makers (*e.g. Climate Ready Boston, NOAA regional sea-level projections, California Sea-level projections, NZ Coastal Hazards Guidance*).

- *Leadership and co-ordination of IODP Antarctic margin drilling:*
    - PAIS community contributed strategic White Paper (from predecessor SCAR-ACE Programme, led by Laura DeSantis) which was highly influential in developing the 10-year IODP Science Plan including a theme on "polar ice sheets and sea-level" and "past high CO2 worlds". (Peter Barrett & Rob DeConto co-authored science plan, Tim Naish member of NSF-NRC committee to review plan and required funding).
    - Paleoclimate Records of the Antarctic Margin and Southern Ocean (PRAMSO) subcommittee of PAIS was set up to foster a community plan for future geological

    drilling priorities on the Antarctic margin and in the Southern Ocean (led by Laura DeSantis).
    - This has been highly successful and four IODP drilling expeditions have been approved within a 3 year time frame (2018-2020) to provide depth and latitudinal transects of geological data across the Antarctica's vulnerable marine-based ice sheet margins. The first expedition (IODP Exp. 374) has been carried out in the Ross Sea in early 2018 (led by Laura DeSantis & Rob McKay). Amundsen Sea drilling (led by Karsten Gohl & Julia Wellner IODP Exp. 379) and Scotia Sea drilling (led by Mike Weber & Maureen Raymo IODP Exp. 382) are scheduled for early 2019. Shallow drilling on the continental shelf using a mission specific platform (led by Carlota Escutia and Trevor Williams, IODP Exp. 373) is scheduled for 2020-2021.
    - Many members of the PAIS community served on IODP Science Evaluation Panel and Facility Boards.
    - IODP acknowledge the success of their Program is in part due to the scientific co-ordination and expertise within PAIS and its predecessor programmes (ANTOSTRAT, ACE).
    - A Southern Ocean IODP workshop led by Rob McKay in Sydney, 2017, has identified more Antarctic targets for proposal development for when the drillship returns to the Southern Ocean in 2020-2021, including a plan to drill on the Totten Glacier coast of East Antarctica where warm water incursions have been observed on the continental shelf. This includes the Sabrina Coast proposal (led by Leanne Armarnd) and the Totten shelf proposal (led by Amelia Shevennell and Sean Gulick).
    - International collaboration through PAIS using the marine facilities of many SCAR nations (Italy, Korea, USA, NZ, Germany, UK) has enabled critical site surveys to be undertaken as a basis for these drilling proposals, which have generated high priority science outcomes in their own right.
    - PRAMSO is starting a new international drilling initiative to obtain bedrock and sediment samples from a transect of subglacial drill holes across the West Antarctic Ice Sheet to reconstruct paleo sea-ways (e.g. establish the extent of WAIS during the Last Interglacial).

- *Facilitation of multidisciplinary Antarctic research.*
    - The PAIS research approach by its very nature is multi-disciplinary
    - The latest phase of PAIS has seen successful close collaboration between solid Earth dynamicists (SERCE) in order to resolve the role solid Earth deformation processes as feedbacks on ice sheet dynamics and understand their influence of regional sea-level variations.
    - While integration with non-Antarctic paleoceanography community was achieved through ACE and continues with PAIS, more focussed effort is required to integrate oceanographers with glaciologists to better represent and understand the role of ocean forcing on ice sheet dynamics.
    - Fossilised molecular biomarkers analyses have proved powerful proxies for reconstructing sea surface and land temperatures, hydroclimate, the carbon cycle and terrestrial vegetation.
    - The paleocological variability in siliceous planktonic microfossil assemblages is allowing past sea-ice variability and primary productivity turnover in the Southern Ocean as a consequence of climate change to be reconstructed.
    - The application of evolutionary biology and molecular genomic approaches in reconstructing paleogeography (e.g. paleo-seaways through West Antarctica) and past terrestrial environments is beginning to be explored, and will be a powerful tool for the future ice sheet reconstructions (see below).

    - Given the focus that PAIS Programme now places on understanding the forcings, feedbacks and processes recent and future ice sheet change it has become strongly aligned with SERCE and ANTCLIM21 aims, and is likely to be increasingly cross-disciplinary and collaborative with ANTERA and ANTECO strategic research programmes.

- *Capability development (to do)*

4. Context and motivation for a revised research strategy

SCAR's future strategic direction

SCAR is developing future research priorities that address the rapid pace of environmental change, and the growing global sustainability problems it brings. SCAR will continue to provide rigorous, defensible scientific evidence to the ATS and its Agreements - The Protocol for Environment Protection (CEP) and the Commission on the Conservation of Antarctic Marine Living Resources (CCAMLR), but in addition it aims to expand its partnerships and influence, such as its engagement with the Intergovernmental Panel on Climate Change and United Nations Framework Convention on Climate Change (UNFCCC) and IPCC. In particular, SCAR recognises the importance of the global adoption of the Sustainable Development Goals, and initiatives to give effect to them, such as Future Earth.

The Paris Climate Agreement

Towards the end of 2015 in Paris at the 21st meeting of the Conference of Parties (COP 21) to the UNFCCC, its 196 member nations agreed to keep global warming below 2° C, the "safe guardrail for dangerous climate change" identified by the IPCC and introduced by the UNFCCC at Copenhagen in 2009. This goal is to be achieved through nationally determined commitments (NDCs) aimed to reduce all anthropogenic greenhouse gas emissions to zero before the end of this century. Following pressure from vulnerable African and low-lying coastal nations, the parties further agreed to "pursue efforts" to limit temperature increase to 1.5 °C, and the IPCC was charged with producing a Special Report on what impacts would be avoided by achieving this, including possible greenhouse gas emissions pathways. The Paris Climate Agreement was subsequently signed by 194 countries in New York on Earth Day, 22 April 2016, and went into force on 7 November 2016.

The Agreement is challenging, especially since the current rate of global emissions (40 billion tonnes per year) could take Earth's surface temperature to 1.5° C in 5–10 years and 2° C in 15–20 years. The NDCs tabled in Paris, if successfully implemented, will restrict global warming to ~2.7 °C (Fig. 2). This is still above the UNFCCC safe guardrail. Current policy settings would see global temperatures stabilising closer to 3.5 °C. To be on track to meet the Paris target, collectively parties need to commit to a 40% reduction in global greenhouse gas emissions with respect to 1990 levels by 2030.

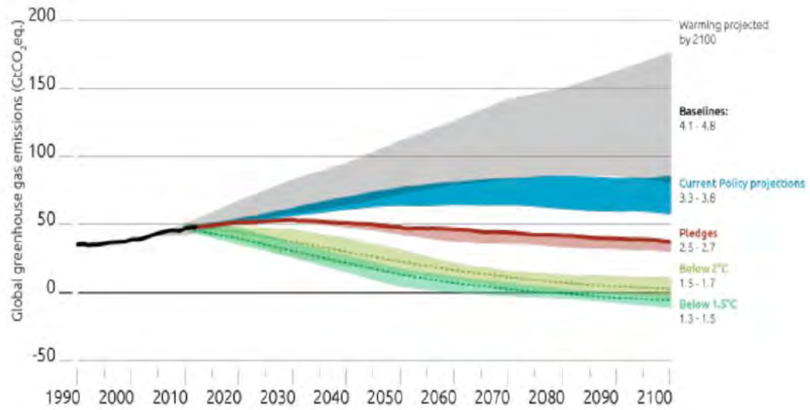

Fig 2: Global greenhouse gas emission scenarios and global average temperatures to the year 2100 for "business as usual" (baseline), an assessment of current global policy settings, the Paris Agreement pledges, and the 2 °C and 1.5 °C stabilisation scenarios. *Source: Climate Action Tracker http://climateactiontracker.org.*

How does SCAR interact with the ATS and what is its relationship with the UNFCCC and the IPCC?

While the ATS has no status within the UNFCCC, SCAR does have observer status within the IPCC through its membership of the International Council of Scientific Unions (ICSU) (Fig. 3). SCAR/ ICSU nominates participants to attend IPCC plenary sessions and meetings as well as candidates to be considered for authorship of special and assessment reports. More importantly SCAR helps mobilise the international science community to address the impact of climate change on Antarctica, and the role Antarctica plays in the global climate system. Five of the six science priorities developed in the SCAR Horizon Scan process held in New Zealand in 2014 are of direct relevance and interest to the IPCC, now preparing for its sixth integrated assessment report and two newly commissioned Special Reports – *Global Warming at 1.5° C* and *Climate Change and the Oceans and the Cryosphere*. Two of SCAR's strategic research programmes, *Past Antarctic Ice Sheet Dynamics* (PAIS) and *Antarctic Climate in the 21st Century* (AntClim21) made significant contributions to the IPCC's Fifth Assessment Report from the legacy of several large IPY research initiatives, and are positioning themselves to make even more significant contributions to the Sixth Assessment Report.

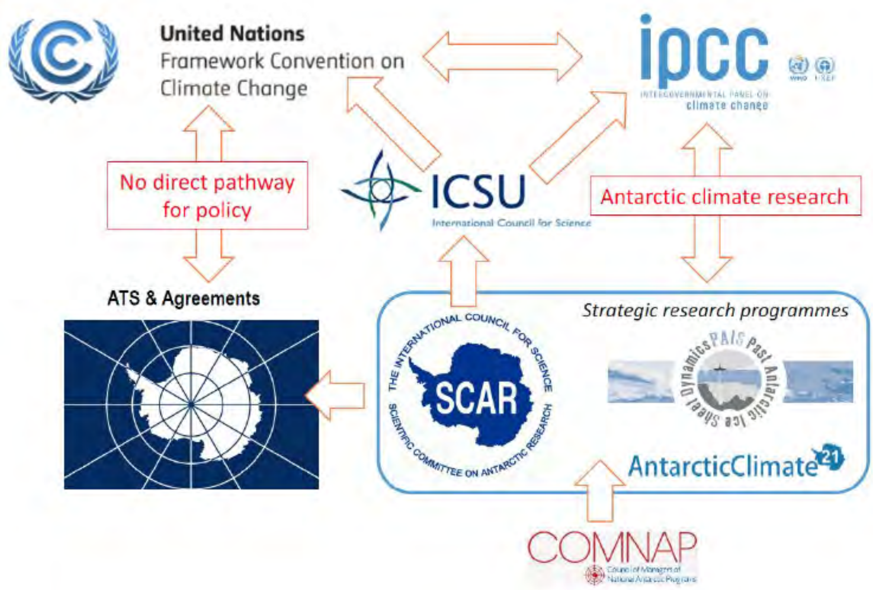

Fig 3: Relationships and interactions between the UNFCCC, IPCC, ICSU and the Antarctic Treaty System, key international governmental and scientific organisations with climate and Antarctic interests. *Source: Author.*

Antarctica's contribution to future sea-level rise?

Changes caused by natural and anthropogenic drivers (e.g. CO_2) are communicated to Antarctica by oceanic and atmospheric processes, and influence the polar atmosphere, ocean, ice sheet, sea ice, and biosphere. Likewise, changes in Antarctica and the surrounding Southern Ocean have worldwide consequences. Some consequences of Antarctica's changing climate are listed in Table 1. Sea-level rise (SLR) is the clearest planet-wide signal of human-induced climate change. So far global sea level has risen 20 centimetres in response to a 1 °C warming. So what does the IPCC predict future SLR will be by the end of the century? In its 2013 assessment report it said SLR could be 1 metre higher with no policy on emissions reductions and 0.5 metres with aggressive emissions reductions as outlined in the Paris Agreement (Fig. 4). No matter what we do from now on we have already committed the planet to 25–30 centimetres of SLR over the next 40 years from the greenhouse gas warming that has already occurred. This is heat already built into the system and is known as committed climate change.

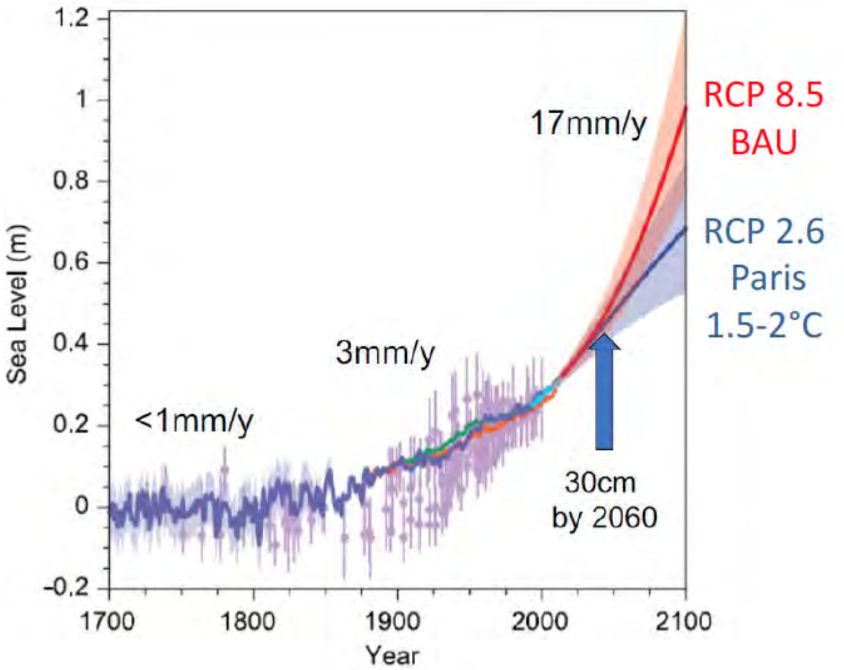

Fig 4: Historical global mean sea-level rise based on palaeoclimate reconstructions, and satellite and tide gauge measurements. This is continued on the right with projected sea-level rise for the IPCC 5th Assessment Report (2013) low (RCP 2.6) and high emission (RCP 8.5 – "Business as usual" or BAU) scenarios. *Source: IPCC*.

Arguably, the biggest uncertainty of societal and policy relevance facing climate science today is the future contribution of the Antarctic ice sheet to global SLR. After assessing the evidence, the IPCC noted the potentially large contribution from rapid retreat of unstable parts of the Antarctic ice sheet, but did not include this in their global sea-level predictions. They argued at the time of writing (2013) that the scientific evidence was not clear enough for quantifying the likelihood of a rapid and potentially non-linear response by Antarctica, but cautioned that "based on current understanding, collapse of marine-based sectors of the Antarctic ice sheets, if initiated, could cause global mean sea level to rise tens of centimetres above the *likely* range [of up to 98 centimetres] during the 21st century".

Table 1: Global and Antarctic consequences of anthropogenic warming

Global	Warming of the climate system is unequivocal, and the human influence is clear.
Global	The clearest global response is global sea-level rise (SLR). 20 cm SLR observed since 1850; 15 cm of SLR occurred in the last 30 years.
Global	Given the global reach of Antarctic and Southern Ocean processes, climate change in the region will have widespread consequences for the Earth system and for human society dependent on it.
Ice sheet	The Antarctic ice sheet holds 90% of the world's ice and if returned to the ocean would raise sea level by 58 m. East Antarctic Ice Sheet contains 54 m SLR; West Antarctic Ice Sheet contains 4 m SLR.
Ice sheet	The ice mass loss is contributing to global SLR at an accelerating rate and by mid-century may be the single biggest factor contributing to global SLR.
Sea level	The largest uncertainty in predicting global future SLR is predicting the response of the Antarctic ice sheet to continued warming in the ocean and atmosphere.
Southern Ocean	At present, the Southern Ocean takes up more anthropogenic heat and CO_2 than oceans in other latitudes, which acts to slow the pace of surface climate change around Antarctica. 95% of the heat and 25% of the CO_2 have gone into the ocean.
Atmosphere & ocean	The tug of war between ozone hole and global greenhouse gases that acts to cool Antarctica while warming the rest of the planet, steepens the pole–equator temperature gradient of the Southern Hemisphere, invigorating zonal atmospheric circulation and causing warm circumpolar deep waters to upwell along the coast of Antarctica. This increased heat flux to the marine margins of the ice sheet is causing collapse of stabilising ice shelves and rapid thinning and retreat of the ice sheet.
Atmosphere & ocean	Freshening of the surface waters from ice melt has reduced the production of cold salty Antarctic Bottom Water by 50% between 1970 and 2014, with consequential changes for heat transport via the global ocean conveyor.
Ocean productivity	By returning nutrient-rich deep water to the sea surface and exporting nutrients to lower latitudes, the Southern Ocean overturning circulation supports 75% of global marine primary production north of 30° S.

Table 2: Information from palaeoclimate archives on the sensitivity of Antarctica's ice sheets and implications for global sea level

Sensitivity	Climate reconstructions from the geological past show that the Antarctic ice sheet is highly sensitive to relatively small increases in Earth's average temperature.
Polar amplification	This sensitivity is because amplifying feedbacks and processes cause the polar regions to warm two to three times more than the global average.
2–3 °C warmer	The last time Earth experienced atmospheric CO_2 concentrations of 400 ppm (today's concentration) was three million years ago. Global temperature equilibrated at 2–3 °C warmer, polar temperatures were 6–7 °C warmer, and Antarctica lost marine-based ice from its more vulnerable subglacial basins, contributing +13 m to global sea level. Greenland melting also contributed another +7 m.
3–4 °C warmer	400–600 ppm atmospheric CO_2 (3–4 °C global warming, ~15–17 million years ago) appears to be a threshold for loss of the mostly marine-based parts of the West Antarctic Ice Sheet (+3 m SLR), and marine-based sectors of the East Antarctic Ice Sheet (+17 m SLR).
4–5 °C warmer	600–700 ppm atmospheric CO_2 (4–5 °C global warming, ~25–34 million years ago) appears to be a threshold for loss of Antarctica's land-based ice, and at 1000 ppm CO2 Antarctica has no ice.
Rates of change	After the last ice age sea level rose 120 m due to Northern Hemisphere (+100 m SLR) and Antarctic (+20 m SLR) ice melt from ~18,000 to ~8000 y BCE), a rate of 1.2 m/century or 12 mm year. For a few hundred years around 14,500 years ago the rate reached 4 m/century. Antarctica on its own contributed to SLR at between 1 and 1.5 m/century at this time.

What do the latest generation of paleo-calibrated Antarctic ice sheet models show?

New projections from computer-based Antarctic ice sheet models since the 2013 IPCC report indicate higher rates and magnitudes of future Antarctic ice mass loss for the higher-emission scenarios. These models now incorporate recently recognised processes that lead to rapid collapse of floating ice shelves and marine-based ice sheets (Fig. 5). Model skill and performance have been developed and tested within the SCAR PAIS programme on past warm climate analogues constrained by geological data. These models indicate Antarctica may contribute as much as an additional 80 centimetres 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 (Fig. 6). The models also show that if a given CO_2 threshold is passed, Antarctica's ice sheets will continue to melt for centuries to come even after CO_2 levels and atmospheric temperatures have stabilised. This commitment to ongoing multi-metre SLR is because of the heat trapped in the ice sheet and ocean system, and the longevity of CO_2 in the Earth's atmosphere (centuries to millennia).

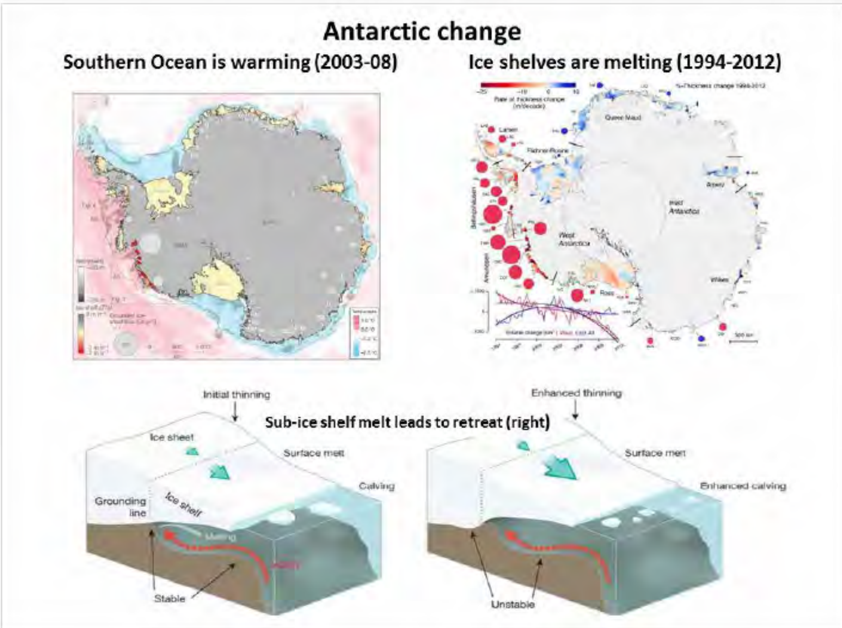

Fig 5: The two maps show the changes now taking place to the Antarctic region: on the left the warming ocean (in pink), and on the right areas where the ice shelves are thinning (red circles). In both maps changes are most marked along the Pacific coast of the West Antarctic Ice Sheet. *Sources: Pritchard et al. (2012, Nature); Paolo et al. (2015, Science).*
The two block diagrams show how warm circumpolar deep water rises up onto the continental shelf and melts the ice shelves, the diagram on the right showing the potential runaway scenario where the melting beneath leads to marine-based ice sheet retreat into deep subglacial basins. *Source: Hanna et al. (2013, Nature).*

What does the target of the Paris Climate Agreement mean for Antarctica?

The results of the new models show that stabilisation of Earth's temperature below 2 °C, the Paris Climate Agreement goal (RCP 2.6, Fig. 6), reduces 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. 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, surface melting and catastrophic collapse of ice shelves appears to occur, after which ocean heat can rapidly remove marine ice sheets grounded in deep sub-glacial basins.

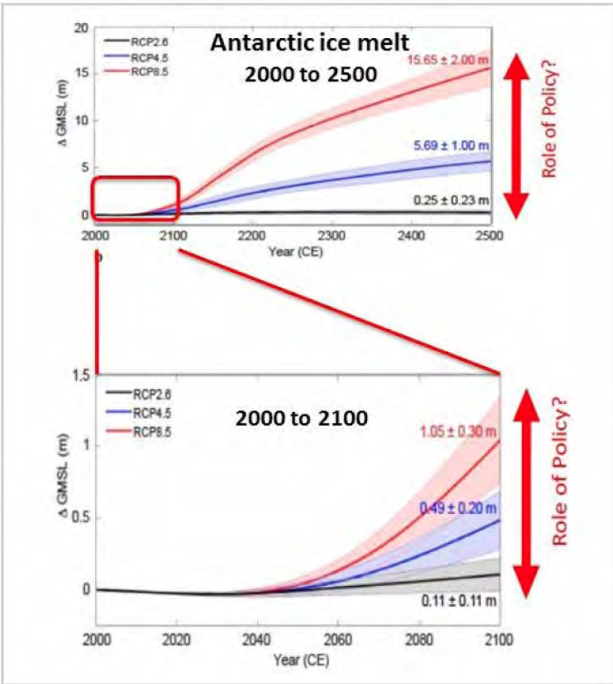

Fig 6: Antarctic contribution to global sea-level rise for high and low IPCC emission scenarios from a recent model that includes recently recognised processes of rapid ice shelf and runaway marine ice sheet retreat, and is calibrated by palaeoclimate reconstructions. The model shows that low emissions policies provide the only opportunity for preserving the ice sheets and limiting sea level rise. *Source: DeConto & Pollard (2016, Nature)*

5. *Future priorities and directions*

Less than one third of the 194 member states of the UNFCCC belong to ATS and have direct access to Antarctica for research, yet the UNFCCC, through the IPCC process, requires that scientific knowledge. The ATS and its agreements (CEP and CCAMLR) also require evidence-based policy and decision-making that includes knowledge of the impacts of climate change. Critical knowledge gaps have been identified in the IPCC's Fifth Assessment Report, and by strategic assessments carried out by national Antarctic programmes and funding agencies, and through the SCAR Horizon Scan process. There are many areas, such as conservation and environmental protection and management, where understanding the impacts of climate change on Antarctica is a priority.

However, an overarching theme of global reach continues to be understanding the response of Antarctica's ice sheet and the Southern Ocean to climate change and improving estimates of the ice sheet's contribution to global sea level rise. The urgency and scale of these strategic research priorities requires:

- Multi-disciplinary international collaboration including expertise and alignment of resource
- Access to new satellite data, autonomous vehicles, instruments and observatories that can access the ice sheet interior, the ocean, the cavity under ice shelves, the base of ice sheets, and sediments and rocks under the ocean and the ice sheet
- More access to aircraft, ships, and over-snow traverse capability
- Commitment to long-term stable funding
- Use of emerging technologies for energy and for storing and communicating data in real time
- Access to remote areas of Antarctica all year round

To meet these challenges the Council of Managers of National Antarctic Programs (COMNAP) has undertaken the Antarctic Roadmap Challenges (https://www.comnap. aq/Projects/SitePages/ARC.aspx), which identifies the resources, infrastructure, logistics, and supporting technologies needed to enable priority science objectives to be achieved over the coming decade.

Given that SCAR's future strategic direction is to take a more holistic, trans-disciplinary approach to form a large SRP focussed on the past and future of the cryosphere and its interactions with oceans, atmosphere and life, PAIS could propose to be a central organising hub for this initiative, by essentially aligning with SERCE and ANTCLIM21 and parts of ANTERA and ANTECO.

Therefore, a future SRP programme based on the PAIS approach could be focussed around:

"Understanding the response of Antarctica's ice sheet and the Southern Ocean to climate change for improving estimates of the ice sheet's contribution to global sea level rise and better prediction of other climatic and biological impacts".

- The PAIS approach has proved effective and innovative, and its mission is still current, relevant and required to address key knowledge gaps concerning the contribution of the Antarctic ice sheet to past, present and future sea-level rise, and attendant changes in the Southern Ocean.
- It undertakes fundamental policy-relevant research targeting global research priorities and seeing research through the implementation pathway to key climate assessment fora (e.g. IPCC) for uptake by policy and decision makers (e.g. UNFCCC, ATS, government and local government).
- However, the PAIS approach would be significantly strengthened by closer collaboration with biologists, oceanographers and solid Earth geophysicists and dynamicists, ice core community and Earth system modellers.
- PAIS has established a successful model-data transect integration approach. Now we need to improve understanding of key processes, rates of change on different temporal and spatial scales.
- To achieve this requires a three-pronged approach
    - Paleoclimate observations and records need to be obtained from key locations on orbital to annual (ice core and sediment drifts) with an emphasis on obtaining highest resolution records of trends and variability.
    - Observations (atmosphere, ocean, ice sheet surface, sea-ice, ice shelf and subglacial and topographic bathymetric) are required from key locations to measure recent change to understand process and improve knowledge of boundary conditions for numerical models.
    - New generation Earth system models (e.g. ice sheet-ocean/atmosphere-solid Earth) of varying complexity need to be developed and tested on present and past boundary conditions and then used for improving model predictions of future change (e.g. global and regional sea-level for IPCC emission scenarios).

Areas of emphasis and priority for a future SRP discussed at the PAIS Conference in Trieste include:

Improved understanding of atmosphere-ocean forcing processes of marine-based ice sheet dynamics

- Improved understanding of the processes of ocean and atmospheric forcing of marine-based ice sheet dynamics. Models are highly parametrised and critically need observations (e.g. ice shelf surface and subglacial melt rates, ocean temperatures, circulation, freshwater flux and stratification, surface melt) for validation and testing (both for past warm climate analogues and present observations).
- Improved surface mass balance changes (over long and short scales), ice core elevation changes, water isotopes analysis/modelling
- How do changes in atmospheric circulation influence ocean heat transport to the grounding lines? What are the important feed backs (e.g. meltwater flux and stratification, sea-ice)?
- This involves strategically-located geological drilling (such as Ross Sea Exp. 374 IODP) and ocean observations that can reconstruct and measure the outflow of Antarctic Bottom Water, the inflow of Circumpolar Polar Deep Water and along slope flow, as well as sub-ice shelf oceanographic observations and sediment cores.
- What is the role of atmospheric warming in ice shelf dynamics (e.g. hydrofracture, MICI)?
- Direct evidence of boundary conditions critical for modellers including, subglacial conditions/hydrology, ice shelf cavity, bathymetry/topography (present and past).
- Improved coupling of ice sheet and ocean dynamical models that incorporate key (missing) processes and boundary conditions critical for reducing the uncertainty of the Antarctic ice sheet contribution to global sea-level.
- Balance needed between complexity, spatial and temporal scale. Models that are fit for purpose for addressing both local/regional/continental/global scale and short term and long term questions.
- Past (last millions of years) and present regional atmospheric circulation (pathways of moisture advection, wind direction and strength) and local katabatic winds driving sea ice/polynya variability and related bottom water formation reconstructed from integration-comparison of coastal and inland ice core with sediment core data and models.

Improved understanding of solid Earth feedbacks on ice sheet dynamics and regional sea-level variations.

- 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.
- Modelling of the role of dynamic topography on ice sheet dynamics.
- Coupled GIA-ice sheet and 2- and 3-D stratigraphic erosion-sedimentation models to interpret continental margin geological records correctly in terms of ice sheet volume and sea-level variability and local uplift or subsidence of subglacial bed and sea floor.
- Geothermal heat flux measurements (also for ice sheet modellers) and ice rheology (particularly for PAIS ice sheet modellers)

Improved understanding of spatial and temporal changes in Antarctica's marine based ice sheets during the LGM and deglaciation (~24kyr to present).

- This time interval spans the last natural experiment of global warming the Earth has experienced. It provides an opportunity to evaluate both the processes and rate of ice sheet thinning and retreat on different sectors of the ice sheet margin, including evaluating the role of MISI. Age control remains an issue, but marine sediment ramped pyrolysis radiocarbon dating provides an opportunity for improvement, also with integration with cosmogenic geomorphological approaches.

- The non-linear response of Antarctica's marine sub-glacial basins and contribution to global meltwater pulses remains a policy-relevant open question.
- Addressing this theme requires an integrated modelling data acquisition approach, that combines targeted marine sediment cores, sub-ice shelf cores, sea bed mapping (swath bathymetry), and geomorphic cosmogenic isotope studies of outlet glacier thinning, integrated with (ideally) coupled ice sheet-GIA-ocean/climate models. The last deglaciation is critical for identifying and evaluating key processes, feedbacks and rates relevant to modelling IPCC scenario projections.

Improved reconstructions of Antarctic ice sheet volume and extent for past "warmer-than-present" interglacials

- What happened to the Antarctic ice sheet during the last interglacial period (~125,000 years ago), when far-field sea-level reconstructions suggest global sea-level was up to 9m higher than today. One ice sheet model suggests Antarctica was capable of providing up 6m GMSL equivalent. This is arguably one of the most important outstanding questions paleoclimate should address, as it has major implications for understanding ice sheet sensitivity to very small increases in global or hemispheric surface temperature. This is also the case for other Late Quaternary "superinterglacials" (MIS 11 and 31) and the Pliocene warm period (400ppm CO_2 world).
- Addressing this issue requires a multi-disciplinary integrated approach involving:
    - (i) drilling a transect of holes through the West Antarctic ice sheet to access bedrock and possible marine sediments that may have been ice free to reconstruct paleo seaways and ice sheet extent. PRAMSO proposes to co-ordinate this using ANDRILL-style and fast drill bed access technology to drill a transect from the Siple Coast to Amundsen Sea and to the Weddell Sea. These will compliment IODP drilling offshore of these sectors. Should also involve drilling into an EAIS subglacial basin (e.g. Wilkes).
    - (ii) use of "molecular clock" genomic evolutionary biological techniques to reconstruct timing and existence of past sea-ways through west Antarctica.
    - Use of last interglacial reconstructions from ice cores to understand ice sheet elevation changes, proximity of marine conditions (etc.).

Improved understanding of the global implications of Antarctic change

- Bi-polar-interhemispheric connections (e.g. ocean see-saw, antiphase ice sheet growth and hidden ice)
- Reconciliation of tropical-Antarctic teleconnections (e.g ENSO-SAM, influence on ITCZ)
- Reconciliation of far-field sea-level reconstructions with Antarctic ice volume change and implications for sea-level budegts.
- That new Antarctic ice sheet projections improve and are incorporated into global and regional sea-level projections (e.g. IPCC).

Capability development (to do)

Engagement (to do big discussion at Trieste Conference on both of these issues).