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SCAR Delegates Meeting 2021

Past Antarctic Ice Sheet Dynamics
Final Report

Summary

Report Authors

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Introduction/background to the programme

The Past Antarctic Ice Sheet (PAIS) program's aim is to provide geological and ice core evidence of Antarctic Ice Sheet response to a broad range of past climatic and oceanic conditions. That evidence is used to constrain paleo-simulations of regional Antarctic climate, ice sheet dynamics and sea-level models, as well as to improve the physics of climate and ice sheet models used in projections. Improved representation of processes within models has to narrower uncertainties in future Antarctic Ice Sheet contribution to global sea level changes in response to on-going and projected global climate change. PAIS has delivered above expectation with respect to the implementation plan developed 8 years ago, and is now completing final products. Extensive information will be available in book "Antarctic Ice Sheet evolution" (publication planned in 2021, ANNEX A). The book is the product of a large PAIS community's effort and represents a comprehensive synthesis of the current knowledge of Past Antarctic Ice Sheet dynamics, the legacy from previous SCAR programs, and of challenges for the future.

Major achievements and legacies.

PAIS has coordinated the scientific community to share ideas, integrate multi-disciplinary knowledge, produce a large amount of high-impact scientific publications, to submit innovative international scientific proposals, and facilitate large international research consortia (e.g. IODP). PAIS catalysed the interest and facilitated the cooperation from other scientific programs and organizations by demonstrating the advantages of optimizing the use of research infrastructures and tools and of multidisciplinary teamwork. The main scientific achievements have progressed understanding of the complexity of the Antarctic ice sheet sub-glacial, ice proximal environments and distal environmental response to past global climate changes at different time scales over the past 34 Million years and at higher atmospheric CO2 levels. The PAIS Programme outputs are many, diverse and span: (i) the production of high-impact scientific publications in the world's leading journals (ii) contributions to IPCC reports, Antarctic Treaty lectures and papers, and contributions to other international policy fora, (iii) building multi-disciplinary collaboration hosting ground-breaking community-driven international conferences (e.g. Trieste 2017), (iii) supporting student and ECR summer schools and training courses, (iv) leveraging more than USD $100M for international consortia to undertake geological drilling on the Antarctic margin, and (v) development a new generation of Antarctic ice sheet models for improved future projections of ice mass change and sea-level rise. We list below areas of major contribution:

- Fundamental new insights in Antarctic Ice Sheet sensitivity during past high-CO2 worlds and its contribution to global sea-level change.
- New knowledge on the extent and nature of major Antarctic glaciations
- Importance of evolving topography, bathymetry, erosion and pinning points in ice sheet dynamics.
- Reconstructions of Southern Ocean sea and air surface temperature gradients and implications for polar amplification
- First geological evidence of ocean forcing and marine ice sheet instability
- Improved temporal and spatial patterns of AIS retreat and its contribution to rapid sea-level rise during global Melt-Water Pulse 1A
- A better understanding of ice-sheet-ocean interactions
- Co-produced with SERCE, fundamental insights into Antarctic ice-Earth interactions and their influence on regional sea-level variability and Antarctic Ice Sheet dynamics
- Improved interpretation of subglacial processes from mapping the seabed
- Paleo-data calibrated ice sheets models provide revised global sea-level predictions for IPCC scenarios

Finally, as PAIS evolved it became more transdisciplinary working with solid Earth geodynamicists, oceanographers, climate scientists and a modellers. This lead to the development of a white paper that reflected a convergence of scientific interest across SCAR's science groups on improving the understanding of Antarctica's dynamic ice sheet contribution to global sea-level rise and lead to the development of the multi-disciplinary INSTANT Programme.

Final procedural recommendations to Delegates

SCAR continues to face some organisational challenges within its Science Groups. There is a high degree of fragmentation that leads to some inefficiencies and overlap of effort and capabilities. The SRP's have proven instrumental in helping co-ordinate and focus SCAR capabilities on high-priority scientific issues, such as those outlined in the SCAR Horizon Scan. Future SRP's need to build strong links with action and expert groups in SCAR (some rationalisation is still required), as well as external partners to ensure SCAR's scientific capability is most effectively contributing to issues of global importance.

Main report

Original rationale and objectives

The Past Antarctic Ice Sheet (PAIS) programme **aims** to improve understanding of the sensitivity of East, West, and Antarctic Peninsula Ice Sheets to a broad range of climatic conditions and to improve confidence in projections of Antarctic Ice Sheets (AIS) contributions to global sea level change in response to on-going and projected global warming.

The PAIS **research philosophy** is based on data-data and data-model integration and intercomparison, and on the development of "ice-to-abyss" paleo-environmental reconstructions**,** extending from the ice sheet interior to the deep sea. The data transect concept links ice core, terrestrial, ice sheet-proximal, offshore, and far-field records of past ice sheet and ocean circulation dynamics and sea level changes. The integration of such records yields an unprecedented view of past changes in ice sheet evolution and ice-ocean interactions. Specific drainage basins are targeted to account for different areas having different evolution. These integrated data sets enable robust testing of a new generation of coupled Glacial Isostatic Adjustment (GIA)-Ice Sheet-Atmosphere-Ocean models that include new reconstructions of past and present ice bed topography and bathymetry.

The PAIS **role in coordinating the scientific community** is in: 1) Facilitating the planning of new data-acquisition missions, using emerging technologies and targeting scientific knowledge gaps. 2) Encouraging the infrastructures and data sharing (e.g. update and use of the Antarctic Seismic Data Library System, SDLS ANNEX B) and the integration of spatially targeted transect data with modelling studies. 3) initiating/expanding cross linkages among Antarctic research communities, inside and outside SCAR. 4) Training and engaging with students and early career scientists to develop skills in multidisciplinary paleo-environmental reconstructions and be a proactive part of the scientific community

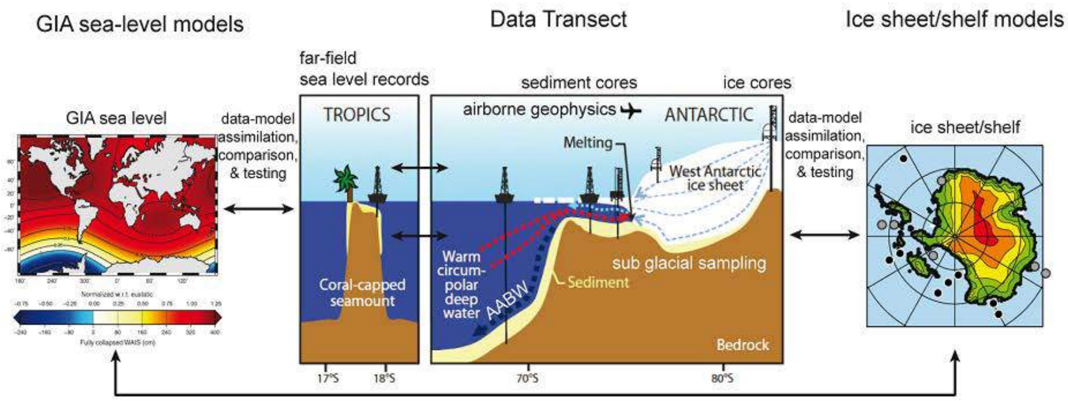

Fig. 1 *The PAIS research approach is based on data-data and data-model integration and intercomparison, and the development of "ice-to-abyss" data transects Left panel: Glacial Isostatic Adjusted sea level (from Bamber et al., 2009). Central panel is adapted from figure 2.6 of the "Illuminating Earth's Past, Present, and Future: The Science Plan for the International Ocean Discovery Program IODP 2013-2023)". Right panel: Ice sheet volume reconstruction for extreme interglacials (adapted from Pollard and De Conto 2009). Dots show the IODP transects (black dots: achieved Expeditions 318, 374, 379, 382; grey dots: to be scheduled expeditions Prop 732 and Exp 323)*

Main scientific achievements

PAIS have progressed understanding of the complexity of AIS sub-glacial, proximal and distal environments and of their response to past climate changes at different time scales. The results obtained improve our knowledge of Southern high-latitude polar amplification in the past. Polar amplification is projected to increase and the rate at which polar areas respond to ongoing and future climate changes is yet to be determined as highlighted by the IPCC SROCC (2019).
A huge international effort has been made in collecting and analysing new and legacy data with coordinated and multidisciplinary approaches in key areas where the geological record preserves fingerprints of past glacial and interglacial processes. Results of such data analysis and the integration with numerical modelling yielded: better estimates of past ocean (distal) and terrestrial temperatures (coastal and AIS plateau); improved past sea-ice extent reconstructions for some past warm periods; improved paleo-ice sheet extent for the last glacial maximum (LGM; 19-23 Ka B.P.), a better understanding of subglacial paleo-hydrology processes, new knowledge about the carbon cycle and paleogeographic reconstructions of AIS bed during key past periods. This relates to the **PAIS original objectives,** which aimed to:

- provide geological evidence and data-model reconstructions of AIS evolution during past warm periods (including recent warm interglacials and the more ancient high-CO_2 worlds), and
- Link terrestrial records of AIS change with the marine records, including far-field sea level records.

Important **scientific advances** of PAIS regarding these objectives are:

- ➢ A better understanding of the AIS sensitivity during past high-CO_2 warm paleoclimates and its contribution to past global sea-level changes;
- ➢ Finding geological evidence of ocean forcing and marine ice sheet instability associated with non-linear “runaway” retreat; and
- ➢ Improving knowledge of subglacial processes from mapping bathymetry and subglacial beds, that provided constraints on the type of ice-sheet flow during both advance and retreat stages

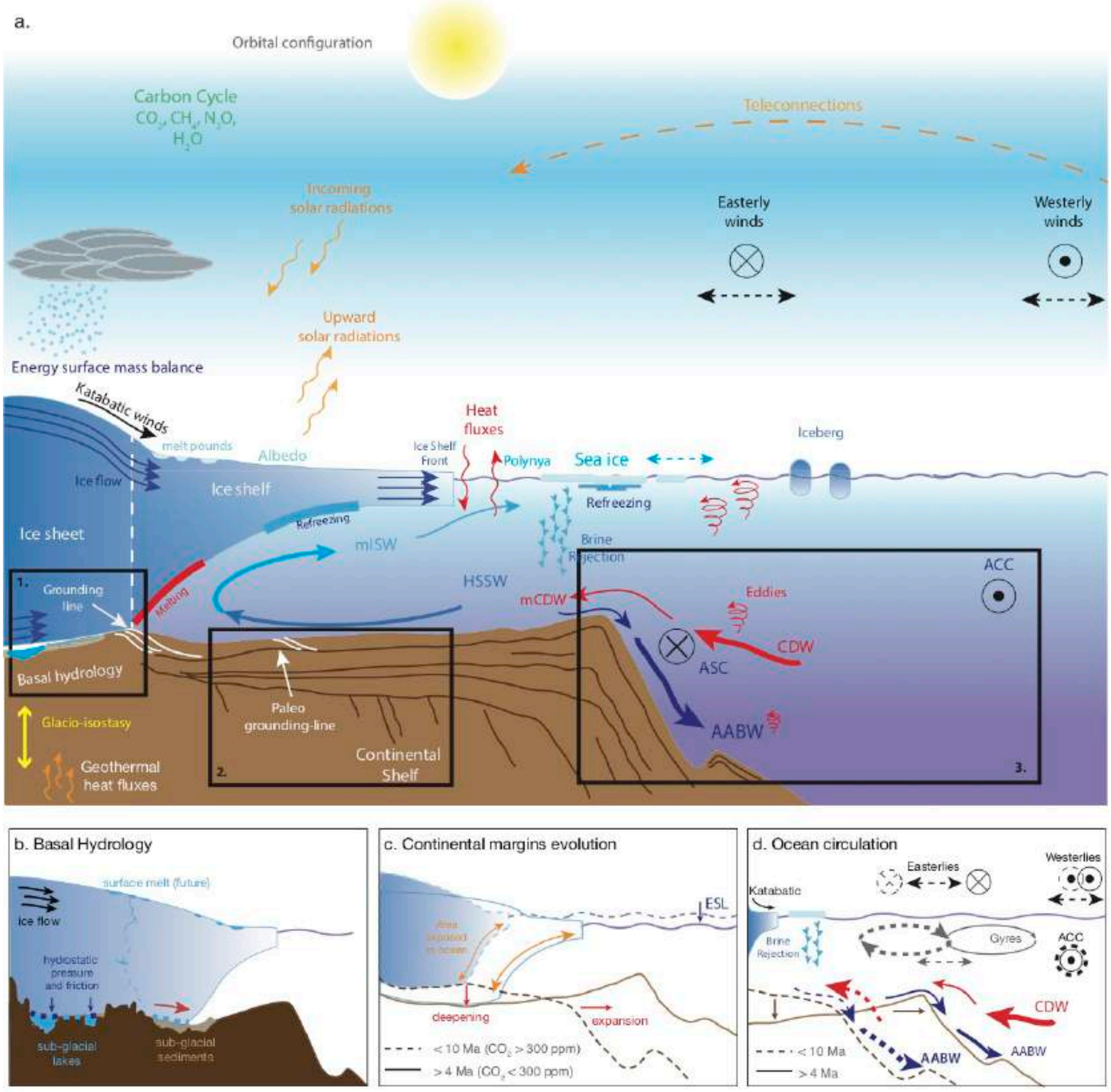

Fig. 2 main processes and environments investigated by the PAIS program (from Colleoni et al., 2018a). AABW, Antarctic Bottom Water; ACC, Antarctic Circumpolar Current; ASC, Along Slope Current; CDW, Circumpolar Deep Water; GL, Grounding line; HSSW, High Salinity Shelf Water; mCDW, modified CDW; mISW, modified Ice-Shelf Water.

More sophisticated numerical ice sheet simulations have been performed in synergy with the other SCAR Geoscience program SERCE. Paleo Ice sheet models have now been coupled with 1D and 3D glacial isostatic adjustment (GIA) models. The latter also account for dynamic topography correction. These improvements allow for testing the sensitivity of the ice sheet to different climate forcings and during different past time intervals, since the onset of continent-wide glaciations (at the transition from a greenhouse world with high atmospheric CO_2 levels over 1000 ppm, to an icehouse world with low CO_2 from 400 to 200 ppm). This relates to the **PAIS original objectives**, which specifically aimed to:

- Develop new paleotopographic/palaeobathymetric reconstructions for key intervals so as to provide more robust boundary conditions to AIS numerical simulations; and
- Integrate geologic, geophysical, oceanographic and ice core data to constrain and test a new generation of fully coupled Earth System Models.

Important **scientific advances** of PAIS regarding these objectives are:

- Improving our understanding of solid Earth responses and feedbacks in controlling ice sheet advances and retreats;
- Recognizing AIS-Earth interactions and their influence on regional sea-level variability; and
- Developing paleo-proxy calibrated ice sheet models that provide revised global sea-level predictions for IPCC scenarios.

The PAIS data-model approach provides an unprecedented level of insight on how the AIS responded to a large spectrum of atmospheric CO_2 levels. This approach revealed that a possible tipping point could be crossed at about +2° C of global warming above pre-industrial temperatures (the Paris IPCC agreement's Target) and lead to irreversible AIS loss and multi-meters of sea level rise.

Delivery against original implementation plan

PAIS has delivered a significant amount of products with respect to the implementation plan, under the coordination of the six PAIS subcommittees:

1. ***Palaeoclimate Records from the Antarctic Margin and Southern Ocean (PRAMSO)****:* i) Completion of International Ocean Discovery Program (IODP) Exp. 374 (Ross Sea, McKay et al., 2018), 379 (Amundsen Sea, Gohl et al., 2019), 382 (Scotia Sea, Weber et al., 2019) and shallow drilling (Amundsen Sea, Gohl et al., 2017). ii) Publication from previous drilling campaigns (IODP Exp 318, SHALDRIL, ANDRILL-1 and 2 and CRP-1,2,3 and older) in high impact factor journals. iii) Submission of new drilling proposals (e.g. Sabrina Coast, Weddell Sea, Antarctic Peninsula, Wilkes Land, Ekström Ice Shelf and Kamb Ice Stream)

2. ***Paleotopographic-Palaeobathymetric reconstructions*** showing changes in bedrock elevations, landforms and configuration of Antarctica over the past ~100 million years, by seismic stratigraphic mapping and sediment restoration models. The elevation change in subglacial topography of various AIS sectors from sub-aerial to marine was caused by tectonic subsidence, increasing ice sheet volume and load, and prolonged and repeated ice bed excavation, since the onset of widespread glaciations (e.g. Wilson et al., 2012; Paxman et al., 2019; Sauermilch, et al., 2019; Hochmuth et al., 2020 and references therein).

3. ***Sub-glacial geophysical*** reconstructions of ice bedrock roughness and sub-glacial drainage networks, from land to the coast to the shelf margin relied on: i) Airborne radio-echo sounding surveys like AGAP (Ferraccioli et al., 2011; Rose et al., 2013), Rosetta-ice (Tinto et al., 2019), ICECAP (Aitken et al, 2014; Wright et al., 2012). ii) Over snow geophysical surveys (e.g. Whillans subglacial lake, Horgan et al., 2012, and Kamb Ice Stream grounding zone, Horgan et al., 2017; Thwaites Glacier, Holschuh et al., 2019). iii) Ice flux modelling (e.g. Morlighem et al., 2020). iv) Multibeam surveys over the continental shelf, revealing LGM and previous subglacial and sub-ice shelf features (e.g. Davies et al., 2017; Simkins et. al. 2018; Smith et al. 2019 and reference therein; Gales et al., 2020, Hogan et al., 2020, Kuhn et al., 2017).

4. ***Integrating ice and marine sediment cores*** from: i) ultra-high resolution and expanded Holocene sediment and ice stratigraphy (e.g. Ashley et al., 2020); ii) cross-linkage of multiple datasets of Pleistocene sediment and ice core records to

reconstruct regional versus local climate forcings, processes and environmental changes (e.g. Mezgec et al. 2017, Hillenbrand et al., 2017; Wilson et al., 2018; Crosta et al., 2018; Etorneau et al., 2020).

5. ***Recent Ice Sheet extent reconstructions*** since the LGM, by integrating numerical models constrained by a large range of observations. The latter include data on past grounding-line positions and dynamics from ice proximal and offshore geophysical surveys and marine sediment cores, and on past ice-sheet thickness changes from exposure-age dating on land and constraints from ice and lake sediment cores (e.g. The RAISED Consortium, 2014; Golledge et al., 2014; Kingslake et al., 2018; Bart and Tulaczyk, 2020; Mckay et al., 2016; Jones et al., 2015; Lowry et al., 2019; Lee et al., 2017).

6. ***Deep-Time Ice Sheet reconstructions*** since the onset of glaciations by integrating numerical models with the observations providing indirect estimates of: i) ancient ice volume and sea-level histories (e.g., Clark et al., 2016; Dutton et al., 2015; DeBoer et al., 2015; Pollard et al., 2015; Pollard and DeConto, 2020: Miller et al., 2020a, 2020b); ii) ice sheet sensitivity to astronomic, atmospheric CO_2, temperature and oceanic forcings (Galeotti et al.,2016; Golledge et al., 2014; Sutter et al., 2016; Colleoni et al., 2018, Staps et al., 2019; Levy et al., 2019; Turney et al., 2020); iii) glacial/interglacial ice sheet extent amplitude, frequency and dynamics (Passchier et al., 2011; McKay et al., 2012; Cook et al., 2013; Gasson et al., 2016; Gulick et al., 2017; Patterson et al., 2014; DeBoer et al., 2017; Anderson et al., 2018; Sangiorgi et al., 2018; Grant et al., 2019); iv) AIS sensitivity to far-field and near-field sea level changes, GIA and dynamic topography (e.g. Stocchi et al., 2013; Gomez et al., 2013; Austermann et al., 2015; Pollard et al., 2017; Tigchelaar et al., 2019; Gomez et al.,2018,2020).

Outcomes of the **all six PAIS subcommittees** are publications on the Antarctic contribution to future global sea level changes based on ice sheet models calibrated to AIS reconstructions for the Pliocene, the last interglacial (LIG, 130 ka) or post-LGM deglaciation (e.g. Golledge et al., 2015; DeConto and Pollard, 2016; Edwards et al., 2019; Golledge et al., 2019; Gowan et al., 2021)

Main education, outreach and capacity building achievements

PAIS has supported and encouraged the next generation of Antarctic scientists by:

- Including early career scientists (ECS) in the leadership of sub-committees and as members of the SC (Casado and, Santibañez, selected by APECS*)*
- Encouraging ECS to take part in PAIS related meetings and workshops by offering bursaries for travel and subsistence.
- Funding graduate students every year to attend ECORD, PAIS and other related schools.
- Teaching and co-funding the IODP-PAIS school in 2019 http://www.scar-pais.org/index.php/highlights/news-highlights/76-pais-iodp-antarctic-school-2019-report). A second edition of the school is planned for the Summer of 2022.
- Providing lectures for teachers (e.g. ECORD School of Rock, 2018 and Polar Educator meeting, 2017)
- Promoting the Antarctic SDLS open-source database (ANNEX B) and other publicly available data (e.g. International Bathymetric Chart of the Southern Ocean, IBCSO, Bedmap2 and 3, IODP and National core repositories).

PAIS organized and co-chaired sessions and workshops during all SCAR-OSC and ISAES, IPC, EGU, AGU and other symposia.

A PAIS strategic planning conference took place in Italy, in 2017 http://www.scar-pais.org/index.php/highlights/past-antarctic-ice-sheet-dynamics-pais-conference-2017-trieste-italy where a large PAIS community identified priorities for future research (white paper 2017) and served as a basis for the new SCAR Scientific Research Programme (SRP), INStabilities & Thresholds in ANTarctica (INSTANT).

PAIS co-chief officers and representatives led or contributed to initiatives for international coordination within and outside SCAR (see ANNEX C).
PAIS co-chief officer (2013-16) Carlota Escutia was awarded with the SCAR medal 2020 for international scientific coordination https://www.scar.org/general-scar-news/2020-scar-medals/

Information about new cruises, projects and publication have been dispersed and shared via the PAIS portals http://www.scar-pais.org/ and https://www.scar.org/science/pais/pais/

Grids were produced by merging separately published reconstructions of palaeotopography and palaeobathymetry from two recent studies (Paxman et al., 2019; Hochmuth et al., 2020) and are a key output of the PAIS Antarctic palaeotopography and palaeobathymetry working group. The grids are freely available to download at the following link: https://doi.pangaea.de/10.1594/PANGAEA.923109

A new book “Antarctic Climate Ice Sheet Evolution” (ANNEX A) will be published in 2021 by Elsevier about PAIS scientific outcomes and highlights.

The Contribution to 50 years of ocean scientific drilling in Antarctica is summarized in Escutia, et al. (2019). *Oceanography*, *32*(1), 32–46.

A recent review about past Antarctic Ice Sheet dynamics is in: Noble, et al. (2020). The Sensitivity of the Antarctic Ice Sheet to a Changing Climate: Past, Present, and

Future. *Reviews of Geophysics*, 58(4), e2019RG000663.
https://doi.org/10.1029/2019RG000663

Several videos and other education and outreach initiatives for students, media and the general public have been carried out by PAIS representatives. These activities focused on the importance of understanding the AIS sensitivity to climate warming and its contribution to past and future sea level change (ANNEX C)

Partnerships made and support received

Within SCAR, PAIS has been very much linked to some activities carried out by the other SCAR SRPs SERCE, AntClim21 and AntEco whose representatives were invited to the PAIS conference 2017 to give key-note talks and contribute to the plenary discussion on future SCAR programs.

An AntClim21 paper led by Bracegirdle and co-authored by Colleoni (as PAIS representative) is: “Back to the Future: Using Long-Term Observational and Paleo-Proxy Reconstructions to Improve Model Projections of Antarctic Climate” Geosciences 2019, 9, 255. A brief article DeBoer B., Colleoni F., De Conto R., Golledge N. "Paleo ice sheet modelling to constrain past sea level", was published in PAGES issue May 19, 2019 (1)

Outside SCAR and the National Antarctic funding agencies, the International Ocean Discovery Program IODP http://www.iodp.org/ is the main organization providing enormous support for the PAIS drilling expeditions in Antarctica, both in terms of offshore (ca. 50x3 million US$ in 2018 and 2019 expeditions) and shore-based science and communication-outreach programs as well as for pre-cruise work and meetings. The synergy in the past 45 years between the SCAR geoscience paleoclimate projects and IODP is summarised by: i) Escutia et al., 2019 in the special issue on Scientific Ocean Drilling: looking to the future. https://doi.org/10.5670/ oceanog.2019.117. and ii) by McKay, Escutia et al. in the “Antarctic Climate and Ice Sheet Evolution book (Elsevier, 2021, *in preparation*)

The ANDRILL project has also provides budget support for future drilling initiative planning within the PAIS community.

The FP7 EU/Eurofleets 2 project funded ship time for international surveys.

PAIS is engaged with the community running modelling intercomparison exercises for paleoclimate like:

- PMIP3 and & 4: coupled climate simulations focused on mid-Holocene, the LGM, the LIG, and transient simulations of the last two deglaciations (i.e. evolving forcing).
- PLIOMIP2: coupled climate simulations focused on several timeslices along a deglaciation of the mid-Pliocene Warm Period (mPWP) between M2 and KM5 intervals.
- MIOMIP: aims at simulating several time slices of the Miocene Climatic Optimum (17 Ma and 14 Ma), and one timeslice within the late Miocene (8-5 Ma) an interval for which most proxy data are already available. The first phase synthesised global proxies (special issue of Paleoceanography, Steinthorsdottir, et al, 2020).) and climate simulations are on-going. PAIS

members proposed an ice sheet modelling comparison project during this 2nd phase, focused on AIS.

PAIS members are also contributing to WCRP-ISMIP6 (Seroussi et al., 2020), which will provide Antarctic and Greenland contributions to future sea-level rise of the IPCC AR6 Assessment report, as well as projections through the joined SCAR-IACS-WCRP ISMASS Group (Pattyn et al., 2018). PAIS and ANTCLIM21 and future SRPs are building stronger links with WCRP/CliC.

Other legacies

- The new SCAR INSTANT program is a PAIS and SERCE legacy together with the other programs and organizations
- The new ICEPRO (International Collaboration Effort for Improving Paleoclimate Research in the Southern Ocean) international initiative aimed at developing common strategies to improve proxy calibration and facilitate trans-national collaborations on paleoclimate studies in the Southern Ocean. An ICEPRO's workshop was held during the PAIS conference 2017 and ICEPRO leaders are members of the new subcommittee of the SCAR/INSTANT on paleo-proxy.
- Many scientific questions continue to require an improved understanding of the deeper sediment and tectonic environments of and around Antarctica, which frequently requires information from seismic data to answer these questions. The expensive nature of acquiring multi-channel seismic data and the general environmental awareness, especially in Antarctica, requires maximizing the use of existing data. Therefore, the Antarctic Seismic Data Library System SDLS will continue to be an important resource for the Antarctic Geoscience community in the future within SCAR/INSTANT
- The PAIS subcommittee Palaeoclimate Records from the Antarctic Margin and Southern Ocean (PRAMSO) has recently become a new SCAR ACTION GROUP. PRAMSO will keep exchanging information about new drilling expeditions, supporting the achievement of pending drilling proposals, stimulating new proposals
- Another SCAR new action group that has been recently approved is BEDMAP3 that can be considered a legacy from Geoscience and Physical science research programs and groups
- The Ross Sea Region Collaboration and Coordination https://www.scar.org/scar-news/pais-news/ross-sea-workshop-report/ is a recently established initiative into which PAIS leaders and members, as well as from AntClim21 and other programs participated. It is aimed at bringing together national Antarctic programmes operating in the Ross Sea, and leading researchers, to discuss existing research plans and emerging future priorities in the Ross Sea Region for the next decade. This understanding will provide a basis to explore opportunities for collaborative research and logistical efficiencies to increase and accelerate research priorities

Draft final Budget summary

	2018	2019	2020
	Spent	Spent	Allocated
(US$)	9,768	24,766	36,400

Please also provide a breakdown of the following:

- Total expenditure

  2018:
  - $1720 to support the CLIVASH2k meeting in Cambridge
  - $1128 for the Nottingham Dinocyst summer course
  - $1074 website annual fee
  - $900 OSC meeting costs (catering)
  - The remainder was travel claims, mainly for the OSC

  2019:
  - $23115 Travel support for ISAES (partly covered with PRAMSO income)
  - $14093 Travel support of PAIS-IODP school
  - $5560 Direct support PAIS-IODP school
  - $1074 website annual fee
  - $921 Other travel support
  - 3000 US$ for the SCAR ExCom meeting participation

- Total direct support received from other sources

  - ➢ The ANDRILL project provided support ($25,000) used in part for the participation of early career and other scientists to the PAIS/PRAMSO workshop during the ISAES in Rep. South Korea
  - ➢ The IODP US Science Support Program provided $31,600 for organizing the PAIS-IODP school in 2019
  - ➢ US ~$90M from IODP to support three Antarctic drilling expeditions.
  - ➢ US ~$250,000 from the FP7 EU/Eurofleets to support one geophysical survey in 2018 in the Ross Sea

- Total budget used to support ECRs

  - ➢ 7000 US$ for ECRs to participate to the SCAR-OSC 2018
  - ➢ 20,000 US$ for students attending the IODP-PAIS school in 2019
  - ➢ 13,657 US$ for students and ECRs to participate to the ISAES 2019
  - ➢ 20,000 US$ *is pre-allocated* for support students attending the 2nd edition of the IODP-PAIS school in 2022

- Total budget used to support **countries with developing programmes**

  - ➢ 7300 US$ to support travel/accommodation for students from Chile, Brazil, India, and Ukraine attending the PAIS conference in 2017
  - ➢ 8000 US$ to support travel/accommodation for students from Argentina, Ireland, Switzerland, India attending the IODP-PAIS school in 2019

Final future research recommendations to Delegates

Predecessors to the PAIS program, the ACE and ANTOSTRAT programs, yielded significant advances in the knowledge of processes driving the AIS dynamics, and AIS vulnerability to climate forcing. All three programmes have shown that the AIS crossed its tipping points many times over the past 34 Ma. Recent modelling efforts suggest that +2°C of global warming could be a temperature threshold for the AIS to cross one of its tipping points heralding significant ice sheet disintegration. However, rates of global sea level rise in the near future hold a large uncertainty due to the unpredictable response of the marine-based sectors of the AIS to oceanic warming. For example, ice sheet model predictions differ because of the paucity of observations required to better constrain ocean warming within ice shelf cavities.

Studies on paleo biostratigraphy, geochemistry and geomorphology led to the compilation of guidelines for interpreting past glacial and interglacial stratigraphic records. PAIS favoured the integration of these studies for facies association analysis. Such a multidisciplinary approach, shared and successfully applied to latitudinal data transects, revealed unprecedented knowledge about past AIS dynamics. However, these studies are still too sparse; we need to complete the transect approach as both proximal and distal records are still needed from various sectors. We now need to widen this approach to reproduce similar investigations in more regions around the Antarctic margin. High resolution and expanded geological records are needed, especially from warmer-than-present time intervals and from particularly vulnerable sectors of the Antarctic margin, in order to validate paleo-simulations. Despite extensive grounded ice that caused widespread sediment erosion since the onset of glaciations, millennial-scale, expanded stratigraphic records interleaved between hiatuses can provide “snapshots” of past warm time intervals as revealed by PAIS efforts that retrieved sediment cores trapped and preserved in basins (below the ice sheet, ice shelves and beneath the continental shelf). In addition, current-controlled sediment drifts, that accumulated on the continental slope and rise, preserve continuous millennial scale records of ice-sheet dynamics on land, source-to-sink and paleoceanographic changes and reflect ice sheet dynamics on the shelf.

Models predicting future sea level change trajectories need to be validated by robust paleo-simulations constrained by a larger set of observations. The challenge for future research within the new SCAR/INSTANT program will be to find such expanded paleo-records (by implementing geophysical and sediment coring/drilling surveys, both on ice and at sea) and investigate them with the multidisciplinary approach developed as part of PAIS and finally integrate the results in a regional framework.

More direct information is needed on past AIS behaviour in response to paleoclimate forcing, at short time scales (millennial) and considering a large range of different boundary conditions (e.g. bed elevation and roughness, occurrence of ice shelf, sea ice, etc). We need to improve existing and develop new proxies that will allow reliable reconstructions of important forcing mechanisms, such as deep-water temperatures, in ice-proximal settings.

Decadal instrumental observations are not enough to constrain future sea level projections, because the thermo-dynamic response of the Greenland and Antarctic ice sheets and their related instabilities has a longer-term component.

Past reconstructions from both ice (up to 1 million of years) and sediment (since the onset of glaciations, ca. 34 Ma) cores can inform long-term projections over a few millennia, but some refinements at sub-millennial timescales to investigate some abrupt events of the recent past are necessary to help explain and reconcile deviations among different projections.

Future studies should also focus on technological advances aimed at increasing core recovery percentage of paleoclimate records and in refining dating tools for increasing the resolution of the stratigraphic records. This will allow correlating short term events and long-term trends along the Antarctic margin and from its hinterland, to the coast, to the Ocean.

Final procedural recommendations

- SCAR continues to face some organisational challenges within its Science Groups. There is a high degree of fragmentation that leads to some inefficiencies and overlap of effort and capabilities. The SRP's have proven instrumental in helping co-ordinate and focus SCAR capabilities on high-priority scientific issues, such as those outlined in the SCAR Horizon Scan. Future SRP's need to build strong links with action and expert groups in SCAR (some rationalisation is still required), as well as external partners to ensure SCAR's scientific capability is most effectively contributing to issues of global importance.

- Generally SRP is made by scientists that are not necessarily able to communicate in different languages (e.g. to policy makers, to the general public). More help from SCAR will improve the capability in communicating inside and outside the results from the SRPs.

Notable Papers

The following list is not exhaustive of the huge amount of significant production in the field of PAIS, but can give a quick view of the multidisciplinary work carried out in the program's life span. Note that * indicate early-career lead authors

1. *Cook, C. P., van de Flierdt, T., Williams, T., Hemming, S. R., Iwai, M., Kobayashi, M., Jimenez-Espejo, F. J., Escutia, C., González, J. J., Khim, B.-K., McKay, R. M., Passchier, S., Bohaty, S. M., Riesselman, C. R., Tauxe, L., Sugisaki, S., Galindo, A. L., Patterson, M. O., Sangiorgi, F., … Yamane, M. (**2013**). Dynamic behaviour of the East Antarctic ice sheet during Pliocene warmth. **Nature Geoscience**, *6*(9), 765–769. https://doi.org/10.1038/ngeo1889
    - This paper present a geochemical and petrographical provenance study combined with biostratigraphic analysis of sediments recovered from site U1361 (IODP Exp 318) in the continental slope of the George V Land margin. The result documents that the Eastern Antarctic Ice Sheet retreated several hundreds of kilometers inland from the Wilkes subglacial Basin, during the Pliocene climatic warm interval between 5.3 and 3.3 Ma. Such retreat could have contributed between 3 and 10 m of global sea level rise from the East Antarctic ice sheet.

2. Bijl, P. K., Bendle, J. A. P., Bohaty, S. M., Pross, J., Schouten, S., Tauxe, L., Stickley, C. E., McKay, R. M., Röhl, U., Olney, M., Sluijs, A., Escutia, C., Brinkhuis, H., Klaus, A., Fehr, A., Williams, T., Carr, S. A., Dunbar, R. B., Gonzàlez, J. J., … Yamane, M. (**2013**). Eocene cooling linked to early flow across the Tasmanian Gateway. *Proceedings of the National Academy of Sciences*. https://doi.org/10.1073/pnas.1220872110

- This paper found direct evidence from marine microfossil and organic geochemical records from site U1356 (IODP Exp 318) of paleo sea surface temperature (2–4 °C) cooling caused by the throughflow of a westbound Antarctic Counter Current since ~49–50 Ma. This has been interpreted as evidence of a southern opening of the Tasmanian Gateway.

3. Passchier, S., Bohaty, S. M., Jiménez-Espejo, F., Pross, J., Röhl, U., Flierdt, T. van de, Escutia, C., & Brinkhuis, H. (**2013**). Early Eocene to middle Miocene cooling and aridification of East Antarctica. *Geochemistry, Geophysics, Geosystems*, *14*(5), 1399–1410. https://doi.org/10.1002/ggge.20106
   - This paper date the time of a major shift to arid conditions occurred as ice volume on the continent grew 34 million years ago, from continental weathering changes obtained by the geochemical character of sediments deposited off the coast of East Antarctica.

4. The RAISED Consortium, Bentley, M. J., Cofaigh, C. O., Anderson, J. B., Conway, H., Davies, B., Graham, A. G., ... & Mackintosh, A. (2014). A community-based geological reconstruction of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum. Quaternary Science Reviews, 100, 1-9. https://doi.org/10.1016/j.quascirev.2014.06.025.
   - This was a real community achievement within PAIS, which brought together many different researchers working on land and in the ocean, who pulled together to publish the current state of knowledge on LGM-Holocene AIS changes (despite having individually published partly contradicting reconstructions in previous papers) in a format that is useful for modellers.

5. *Patterson, M. O., McKay, R., Naish, T., Escutia, C., Jimenez-Espejo, F. J., Raymo, M. E., Meyers, S. R., Tauxe, L., Brinkhuis, H., Klaus, A., Fehr, A., Bendle, J. A. P., Bijl, P. K., Bohaty, S. M., Carr, S. A., Dunbar, R. B., Flores, J. A., Gonzalez, J. J., Hayden, T. G., … Yamane, M. (**2014**). Orbital forcing of the East Antarctic ice sheet during the Pliocene and Early Pleistocene. ***Nature Geoscience***, *7*(11), 841–847.

   This paper demonstrates that maximum iceberg debris accumulation is associated with the enhanced calving of icebergs during ice-sheet margin retreat, in the warm Pliocene, between 4.3 and 3.5 million years ago. Spectral analyses show a dominant periodicity of about 40,000 years. Subsequently, the powers of the 100,000-year and 20,000-year signals strengthen, suggesting that as the Southern Ocean cooled between 3.5 and 2.5 million years ago, the development of a perennial sea-ice field limited the oceanic forcing of the ice sheet.

6. DeConto, R. M., & Pollard, D. (**2016)**. Contribution of Antarctica to past and future sea-level rise. ***Nature, 531***(7596), 591-597.
   - This work uses past ice sheet retreat scenarios during the Last Interglacial and Pliocene to calibrate the physics in a numerical ice-sheet model, that considers the effects of 1) ice shelf loss by ocean melt and hydrofracturing caused by atmospheric warming, 2) marine ice sheet instability on reverse sloped bedrock, and 3) calving at thick marine-terminating ice margins (ice cliff instability). When applied to

worse case future warming scenarios, the paleo-calibrated model predicts the complete collapse of WAIS and major ice retreat into deep East Antarctic basins, causing more than 10 m of sea level rise within the next five hundred years.

7. *Simkins L., Anderson J. B., Greenwood S. K., Gonnermann H.M., Prothro L.O., Halberstadt A.R., Stearns L.A., Pollard D., DeConto R.M. **2017**. Anatomy of a meltwater drainage system beneath the ancestral East Antarctic ice sheet. **Nature Geoscience** DOI: 10.1038/NGEO3012.
   - This paper provides new clues into the contested deglaciation history of the Ross Sea at the end of the Last Glacial Maximum. It highlights the role of bathymetry in the details of the retreat. It also demonstrates the utility of a multidisciplinary approach (using sedimentology, geomorphology, oceanography, and modeling) to better understand rates of ice sheet retreat and the role of ocean circulation changes. This approach, fostered by PAIS, is crucially needed for robust paleo-modelling, which ultimately informs future ice sheet projections.

8. *Mezgec K., Stenni B., Crosta X., Masson-Delmotte V., Baroni C., Braida M., Ciardini V., Colizza E., Melis R., Salvatore M. C., Severi M., Scarchilli C., Traversi R., Udisti R. & Frezzotti M. **2017**. Holocene sea ice variability driven by wind and polynya efficiency in the Ross Sea. **Nature Communications** volume 8, Article number: 1334 doi:10.1038/s41467-017-01455-x
   - This work combines information from marine diatom records and sea salt sodium and water isotope ice core records, to document contrasting patterns in sea ice variations between coastal and open sea areas in the Western Ross Sea over the current interglacial period. The results point to possible future impacts on sea ice, in light of recent and future changes in the Southern Ocean winds.

9. *Graham, A.G.C., Kuhn, G., Meisel, O., Hillenbrand, C.-D., Hodgson, D.A., Ehrmann, W., Wacker, L., Wintersteller, P., dos Santos Ferreira, C., Römer, M., White, D., Bohrmann, G. **2017**. Major advance of South Georgia glaciers during the Antarctic Cold Reversal following extensive sub-Antarctic glaciation. *Nature Communications* 8, doi: 10.1038/ncomms14798.
   - This work provides data from the more distal part of Antarctica's influence on the Southern Ocean, during the last deglaciation. This was provides an important and previously missing end-member within the PAIS concept of ice proximal-to-distal transects.

10. Gulick, S.P.S., Shevenell, A.E., Montelli, A., Fernandez, R., Smith, C., Warny, S., Bohaty, S.M., Sjunneskog, C., Leventer, A., Frederick, B., Blankenship, D.D. **2017**. Initiation and long-term instability of the East Antarctic Ice Sheet. ***Nature* 552**, 225-229.
    - This work provides the first evidence of marine-terminating and grounded ice near the Sabrina Coast of East Antarctic, by the early to middle Eocene epoch. The geological and geophysical record shows that expanded polar EAIS existed in the Miocene and that the Aurora subglacial basin catchment was not particularly sensitive to Pliocene warmth.

11. Wise, M.G., Dowdeswell, J.A., Jakobsson, M. & Larter, R.D. **2017**. Evidence of marine ice-cliff instability in Pine Island Bay from iceberg-keel plough marks. **Nature 550**, 506–510. doi:10.1038/nature24458.

- This paper presents the first observational evidence of an episode of rapid ice-sheet retreat resulting from ice-cliff collapse, increasing confidence in the rapid past and future retreat scenarios modelled by DeConto & Pollard (2016).

12. Hillenbrand CD, Smith JA, Hodell DA, Greaves M, Poole CR, Kender S, Williams M, Andersen TJ, Jernas PE, Elderfield H, Klages JP, Roberts SJ, Gohl K, Larter RD, Kuhn G (**2017**) West Antarctic Ice Sheet retreat driven by Holocene warm water incursions. **Nature 547**(7661), 43-48. doi:10.1038/nature22995.
    - This work, for the first time, demonstrates warm Circumpolar Deep Water inflow variability onto the Amundsen Sea Shelf and related deglaciation forcing during the Holocene epoch. These results could increase confidence in the predictive capability of current ice-sheet models and will encourage similar analysis on core samples from past warm times.

13. *Wilson, D., Bertram, R.,Needham, E., van de Flierdt, T.,Welsh, K.,McKay, R., Mazumder, A.,Riesselman, C.,Jimenez-Espejo, F., Escutia, C. **2018**. Ice loss from the East Antarctic Ice Sheet during late Pleistocene interglacials. ***Nature 561*, **383-386.
    - This work provides evidence from marine sedimentological and geochemical records for ice margin retreat or thinning in the vicinity of the Wilkes Subglacial Basin of East Antarctica during warm late Pleistocene interglacial intervals. This has important implications for the sensitivity of the marine margins of the East Antarctic Ice Sheet as the climate continues to warm. It is yet another high profile outcome from the IODP Leg 318 drilling expedition off Wilkes Land coast, that was supported and co-ordinated by PAIS.

14. *Shakun, J.D., Corbett, L.B., Bierman, P.R., Underwood, K., Rizzo, D., Zimmerman, S.R., Caffee, M., Naish, T., Golledge, N., Hay, C., **2018**. Minimal East Antarctic Ice Sheet retreat onto land during the past 8 million. ***Nature 558****, 284-287.*
    - This paper is based on the ANDRILL 1B and shows that land-based sectors of the EAIS that drain into the Ross Sea have been stable throughout the past eight million years. These findings indicate that atmospheric warming during the past eight million years was insufficient to cause widespread or long-lasting meltback of the EAIS margin onto land. The paper shows that variations in Antarctic ice volume in response to the range of global temperatures experienced over this period—up to 2–3 degrees Celsius above preindustrial temperatures, corresponding to future scenarios involving carbon dioxide concentrations of between 400 and 500 parts per million—were instead driven mostly by the retreat of marine ice margins, in agreement with the latest models.

15. Rintoul, S.R., Chown, S.L., DeConto, R., England, M., Fricker, H., Masson-Delmotte, V**.,** Naish, T., Siegert, M., Xavier, J. C. Choosing the future of Antarctica**. 2018**. ***Nature 558****, 233-240.*
    - The Tinker Muse Fellows presents two narratives on the future of Antarctica and the Southern Ocean, from the perspective of an observer looking back from 2070. In the first scenario, greenhouse gas emissions remained unchecked, the climate continued to warm,

and the policy response was ineffective; this had large ramifications in Antarctica and the Southern Ocean, with worldwide impacts. In the second scenario, ambitious action was taken to limit greenhouse gas emissions and to establish policies that reduced anthropogenic pressure on the environment, slowing the rate of change in Antarctica. Choices made in the next decade will determine what trajectory is realized. Co-produced by all SCAR SRPs

16. *Kingslake, J., Scherer, R., Albrecht, T., Coenen, J., Powell, R., Reese, R., Stansell, N., Tulaczyk, S., Wearing, M & Whitehouse, P., **2018**. Extensive retreat and re-advance of the West Antarctic Ice Sheet during the Holocene. ***Nature 558***, https://doi.org/10.1038/s41586-018-0208-x.
    - This paper shows, that during the last 10,000 years the grounding line of the West Antarctic Ice Sheet (which marks the point at which it is no longer in contact with the ground and becomes a floating ice shelf) retreated several hundred kilometres inland of today's grounding line, before isostatic rebound caused it to re-advance to its present position. The research is based on drilling sediment cores at the grounding of the Whillans Ice Stream and integration with ice sheet and glacio-isostatic adjustment modelling, which shows a negative feedback due to bedrock rebound as ice retreats that might halt retreat and even stimulate readvance. This work was presented at the PAIS Conference in 2017, Trieste, Italy.

17. Brook, E., Buizert., C. **2018**. Antarctic and global climate history viewed from ice cores. ***Nature 558***. doi.org/10.1038/s41586-018-0172-5.
    - This paper was commissioned by Nature for an Insight volume to celebrate the SCAR 60th anniversary. It summarises the state of play of Antarctic ice core research, showing that a growing network of ice cores reveals the past 800,000 years of Antarctic climate and atmospheric composition show tight links among greenhouse gases, aerosols and global climate on many timescales, demonstrate connections between Antarctica and distant locations, and reveal the extraordinary differences between the composition of our present atmosphere and its natural range of variability as revealed in the ice core record. Further coring in extremely challenging locations is now being planned, with the goal of finding older ice and resolving the mechanisms underlying the shift of glacial cycles from 40,000-year to 100,000-year cycles about a million years ago, one of the great mysteries of climate science.

18. Colleoni, C., De Santis, L., Siddoway, C., Bergamasco, A., Golledge, N., Lohmann, G., Passchier, S., Siegert, M., **2018**, Spatio-temporal variability of processes across Antarctic ice-bed–ocean interfaces. ***Nature Communications***, DOI: 10.1038/s41467-018-04583-0.
    - This review article was commissioned by Nature at the 2107 PAIS Conference, Trieste, Italy. It summarises advances in how understanding how the Antarctic ice sheet will respond to global warming relies on knowledge of how it has behaved in the past. It discusses challenges and opportunities for future research that will be the focus of the new SCAR INSTANT Programme. The use of numerical models, the only means to quantitatively predict the future, is hindered by limitations to topographic data both now and in the past, and in knowledge of how subsurface oceanic, glaciological and hydrological processes interact. Incorporating the variety and interplay

of such processes, operating at multiple spatio-temporal scales, is critical to modeling the Antarctic's system evolution and requires direct observations in challenging locations. As these processes do not observe disciplinary boundaries neither should our future research.

19. Sangiorgi, F., Bijl, P., Passchier, S., Salzmann, U., Schouten, S., McKay, R., Cody, R., Pross, J., van de Flierdt , T., Bohaty, S., Levy, R., Williams, T., Escutia, C., Brinkhuis, H., **2018**, ***Nature Communications***, DOI: 10.1038/s41467-017-02609-7
    - This research documents paleoceanographic conditions and the (in)stability of the Wilkes Land subglacial basin (East Antarctica) during the mid-Miocene (~17–13.4 million years ago) by studying sediment cores from offshore Adélie Coast. Inland retreat of the ice sheet, temperate vegetation, and warm oligotrophic waters characterise the mid-Miocene Climatic Optimum (MCO; 17–14.8 Ma). After the MCO, expansion of a marine-based ice sheet occurs, but remains sensitive to melting upon episodic warm water incursions. The results suggest that the mid-Miocene latitudinal temperature gradient across the Southern Ocean never resembled that of the present day, and that a strong coupling of oceanic climate and Antarctic continental conditions existed and that the East Antarctic subglacial basins were highly sensitive to ocean warming. This was another outcome of the IODP Leg 318 Expedition co-ordinated by PAIS (PRAMSO).

20. Levy, R.H., Meyers, S.R., Naish, T.R., Golledge, N.R., McKay, R.M., Crampton, J.S., DeConto, R.M., De Santis, L., Florindo, F., Gasson, E.G.W., Harwood, D.M., Luyendyk, B.P., Powell, R.D., Clowes, C., Kulhanek, D.K. **2019**. Antarctic ice-sheet sensitivity to obliquity forcing enhanced through ocean connections ***Nature Geoscience*** 10.1038/s41561-018-0284-4.
    - This paper examines the strong emergence of an strong obliquity (axial tilt) control on Antarctic ice-sheet evolution during the Miocene by correlating the Antarctic margin geological records from 34 to 5 million years ago with a measure of obliquity sensitivity that compares the variance in deep sea sediment core oxygen-isotope data at obliquity timescales with variance of the calculated obliquity forcing. The analysis reveals distinct phases of ice-sheet evolution and suggests the sensitivity to obliquity forcing increases when ice-sheet margins extend into marine environments. This reconstruction of the Antarctic ice-sheet history suggests that if sea-ice cover decreases in the coming decades, ocean-driven melting at the ice-sheet margin will be amplified. This paper is an outcome of the PAIS Conference in Trieste, Italy in 2017.

21. Golledge, N., Keller, E., Gomez, N., Naughten, K., Bernales, J., Truse, L. Edwards, T., **2019**. Global environmental consequences of twenty-first-century ice-sheet melt. ***Nature* 566**, 65-71.
    - This paper shows using simulations of the Greenland and Antarctic ice sheets constrained by satellite-based measurements of recent changes in ice mass, that increasing meltwater from Greenland will lead to substantial slowing of the Atlantic overturning circulation, and that meltwater from Antarctica will trap warm water below the sea surface, creating a positive feedback that increases Antarctic ice loss. In the simulations, future ice-sheet melt enhances global temperature variability and contributes up to 25 centimetres to sea level by 2100.

However, uncertainties in the way in which future changes in ice dynamics are modelled remain, underlining the need for continued observations and comprehensive multi-model assessments. Co-produced by PAIS and ISMASS.

22. *Dziadek, R., Gohl, K., Kaul, N., and the Science Team of Expedition PS 104, **2019** Elevated geothermal surface heat flow in the Amundsen Sea Embayment, West ***Antarctica, Earth and Planetary Science Letters 506***, doi.org/10.1016/j.epsl.2018.11.003.
    - This study provides ground-truth for regional indirect geothermal heat flux (GHF) estimates in the Amundsen Sea Embayment, which is part of the West Antarctic Rift System, by presenting in situ temperature measurements in continental shelf sediments. The results are critical for correct parameterizations in ice sheet and solid Earth deformation modelling associated with ice sheet dynamics.

23. Escutia, C., DeConto, R., Dunbar, R., De Santis, L., Shevenell, A., Naish, T., **2019**, Keeping an Eye on Antarctic Ice Sheet Stability, ***Oceanography 32***, https://doi.org/10.5670/oceanog.2019.117
    - This review paper was invited as part of a special issue on the achievements and future of the Integrated Ocean Discovery Program. It summarises 40 years of ocean drilling on the continental margin of Antarctica. Many of these drilling projects (IODP, ANDRILL, CRP, SHALLDRILL) were co-ordinated within the SCAR PAIS community and its predecessors (ACE, ANTOSTRAT), and have revolutionized our understanding of Antarctic ice sheet evolution and behaviour, especially during warmer-than-present climates of the past that have provided significant insights into future change and have been used to develop and improve numerical ice sheets models.

24. *Paxman, Guy J. G., Jamieson, S. S. R., Hochmuth, K., Gohl, K., Bentley, M. J., Leitchenkov, G., & Ferraccioli, F. (**2019**). Reconstructions of Antarctic topography since the Eocene–Oligocene boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *535*, 109346. https://doi.org/10.1016/j.palaeo.2019.109346
    - This is a reconstructions of Antarctic topography for four key time slices in Antarctica's climate and glacial history: the Eocene–Oligocene boundary (ca. 34 Ma), the Oligocene–Miocene boundary (ca. 23 Ma), the mid-Miocene climate transition (ca. 14 Ma), and the mid-Pliocene warm period (ca. 3.5 Ma). The modelled topography consider ice sheet loading, volcanism, thermal subsidence, horizontal plate motion, erosion, sedimentation and flexural isostatic adjustment, and validate our models where possible using onshore and offshore geological constraints.

25. *Klages, J.P., Salzmann, U., Bickert, T., Hillenbrand, C.-D., Gohl, K., Kuhn, G., Bohaty, S., Titschack, J., Müller, J., Frederichs, T., Bauersachs, T., Ehrmann, W., van de Flierdt, T., Simões Pereira, P., Larter, R.D., Lohmann, G., Niezgodzki, I., Uenzelmann-Neben, G., Zundel, M., Spiegel, C., Mark, C., Chew, D., Francis, J.E., Nehrke, G., Schwarz, F., Smith, J.A., Freudenthal, T., Esper, O., Pälike, H., Ronge, T., Dziadek, R., and Science Team of Expedition PS104 (**2020**). Temperate rainforests near the South Pole during peak Cretaceous warmth. **Nature, 580**, 81-86, doi:10.1038/s41586-020-2148-5.

- From analysis of a sediment core collected from MeBo70 seabed drilling on the Amundsen Sea shelf, pristinely preserved forest soil from the Cretaceous, including a wealth of plant pollen and spores and a dense network of roots, is discovered. These plant remains confirm that, at about 90 Ma, the coast of West Antarctica was covered by a temperate, swampy rainforest where the annual mean temperature was about 12°C. A climate model simulation shows that the reconstructed temperate climate at this high latitude requires a combination of both atmospheric carbon dioxide concentrations of 1,120–1,680 parts per million by volume and a vegetated land surface without major Antarctic glaciation, highlighting the important cooling effect exerted by ice albedo under high levels of atmospheric carbon dioxide.

26. Etourneau J., Sgubin, G., Crosta, L., Swingedouw, D., Willmott, V., Barbara, L., Houssais, M.-N., Schouten, S., Sinninghe Damsté, J., Goose, H., Escutia, C., Crespin, J., Massé, G and Kim, J.-H. Ocean temperature impact on ice shelf extent in the eastern Antarctic Peninsula. **2020**. ***Nature Communications*** 10: 1-8. DOI: 10.1038/s41467-018-08195-6
    - The paper provide direct measurement documenting that a +0.3–1.5°C increase in subsurface ocean temperature (50–400 m) in the northeastern Antarctic Peninsula has driven to major collapse and recession of the regional ice shelf during both the instrumental period and the last 9000 years.

27. *Hochmuth, K., Paxman, G., Gohl, K., Jamieson, S., Leitchenkov, G., Bentley, M., Ferraccioli, F., Sauermilch, I., Whittaker, J., Uenzelmann-Neben, G., Davy, B., DeSantis, L. (**2020**). Combined palaeotopography and palaeobathymetry of the Antarctic continent and the Southern Ocean since 34 Ma. PANGAEA, https://doi.org/10.1594/PANGAEA.923109
    - Palaeo-bathymetric models reconstructed based on all available geophysical and geological data to form complete grids of the Southern Ocean and the Antarctic margins. They will facilitate detailed investigation of past ice sheet and ocean circulation development from land to sea, which is essential for robust reconstructions of palaeoclimate and past ice sheet and ocean dynamics

28. Post, A. L., O'Brien, P. E., Edwards, S., Carroll, A. G., Malakoff, K., & Armand, L. K. (2020). Upper slope processes and seafloor ecosystems on the Sabrina continental slope, East Antarctica. *Marine Geology*, *422*, 106091. https://doi.org/10.1016/j.margeo.2019.106091
    - A detailed analysis to understand how the sea bed morphology influences the distribution of seafloor biota on the East Antarctic margin, highlighting the importance of considering bathymetry when addressing reconstructions of biostratigraphic changes and biodiversity.

Budget

We ask to use in 2021-22 the still available budget for PAIS for:

- making a new video to be openly available on YouTube about PAIS highlights (5000 EURO)
- paying the maintenance of the PAIS and ACE web portals in 2021 (370 US$)
- the remaining budget will be allocated to co-fund the Second edition of the PAIS school in 2022, which had to be postponed due to COVID-19

Membership

Role	*First Name*	*Last Name*	*Affiliation*	*Country*	*Email*	*Date Started*	*Date Term is to End*
Co-chief officer	*Tim*	*Naish*	*Antarctic Research Centre* *Victoria University of Wellington*	*NZ*	*Timothy.Naish@vuw.ac.nz*	*January 1st 2016*	*December 31st 2020*
Co-chief officer	*Laura*	*De Santis*	*Istituto Nazionale di Oceanografia e di Geofisica Sperimentale OGS*	*Italy*	*ldesantis@inogs.it*	*January 1st 2016*	*December 31st 2020*

Other members

First Name	Last Name	Affiliation	Country	Email
Carlota	*Escutia (co-chief officer from 2013 to 2016)*	*IACT- CSIC-Univ Granada*	*Spain*	*cescutia@ugr.es*
Robert	*DeConto (co-chief officer from 2013 to 2016)*	*Univ. of Massachusetts*	*USA*	*deconto@geo.umass.edu*
Claus-Dieter	*Hillenbrand*	*British Antarctic Survey*	*UK*	*hilc@bas.ac.uk*
Louise	*Sime*	*British Antarctic Survey*	*UK*	*lsim@bas.ac.uk*
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*Early Career Scientists are indicated * in first column*

ANNEX A

Antarctic Climate and Ice Sheet Evolution – Book 2nd edition (Elsevier, 2021, *in preparation*)

Co-editors Fabio Florindo, Martin Siegert, Laura De Santis, Tim Naish

CONTENT

Title	**Lead author**
Chapter 1 Antarctic Climate and Ice Sheet Evolution – Introduction	Editors: Florindo F., Siegert M., Naish T., De Santis L.
Chapter 2 Sixty-years of Coordination and Support for Antarctic-Science - The role of SCAR -	Florindo F. Meloni A. Siegert M.
Chapter 3 Cenozoic History of Antarctic Glaciation and Climate from onshore and offshore studies	McKay R., Escutia C., De Santis L., Donda F., Duncan B., Gohl K., Gulick S., Hillenbrand C.D., Hochmuth K., Kim S., Kuhn G., Larter R., Leitchenkov G., Levy R., Naish T., O'Brien P., Perez L., Shevenell A., Williams T.
Chapter 4 Circulation and water masses.	Carter L., Bostock-Lyman H. and Bowen M.
Chapter 5 Advances in numerical modelling of the Antarctic ice sheet	Siegert M. and Golledge N.
Chapter 6 The Antarctic continent in Gondwanaland.	Talarico F., Ghezzo C., Kleinschmidt G.
Chapter 7 From Greenhouse to Icehouse - The Eocene/Oligocene in Antarctica.	Galeotti S., Bijl P., Brinkuis H., De Conto R., Escutia C., Florindo F., Francis J., Hutchinson D., Kennedy-Asser A., Sauermilch ., Sluija A.
Chapter 8 The Oligocene-Miocene boundary.	Tim Naish et al.
Chapter 9 Middle Miocene to Pliocene History of Antarctica.	Richard Levy et al.
Chapter 10 Pleistocene Antarctic Climate Variability: Ice Sheet – Ocean – Climate Interactions	Wilson D., van de Flierdt T., McKay R., Naish T.
Chapter 11 Antarctica at the Last Glacial Maximum, Deglaciation and the Holocene.	Siegert M., Hein A., White D.A., Gore D.B., Hillenbrand C.D.
Chapter 12 Past Antarctic ice sheet dynamics and implications for future sea-level change.	Colleoni F., De Santis L., Naish T., DeConto R., Escutia C., Stocchi, Uenzelmann-Neben G., Hochmuth K., Hillenbrand C.D., van Der Flierdt T., Perez L., Leitchenkov G., Sangiorgi F., Jamieson S., Bentley M., Wilson D. and the PAIS community
Chapter 13 Concluding Remarks: Recent Changes in Antarctica and Future Research	Editors Florindo F., Siegert M., Naish T., De Santis L.

ANNEX B

Antarctic Seismic Data Library (SDLS) activities during PAIS

Frank O. Nitsche, Paolo Diviacco

Introduction

The Antarctic Seismic Data Library System (SDLS) was established in 1991 under the umbrella of the Scientific Committee on Antarctic Research (SCAR) and the Antarctic Treaty (ATCM XVI-12) to provide open access, under certain conditions, to all marine multichannel seismic-reflection (MCS) data collected south of 60° S. It was established with the goal of encouraging collaboration between researchers from different countries that collect and use seismic data around Antarctica. Three steps of data submission and access were instituted to both provide access to the data and protect intellectual property rights of data collectors: (1) track coordinates and contact information must be submitted to the SDLS shortly after data collection; (2) metadata and digital SEG-Y files must be submitted to the SDLS. For the first two years these data are only accessible by third parties via agreements for collaborative research projects with the data owner; (3) data that are 8 years and older after collection are accessible by third parties but the data owner must be informed of the data usage.

Use and success of SDLS

Since its foundation over 25 years ago, the SDLS has become one of the most successful data sharing and archiving initiatives inside of SCAR. Over 80% of the acquired MCS data collected around Antarctica and the Southern Ocean have been submitted and archived in the database.

Since its beginning there has been a strong overlap of SDLS contributors and users with a series of SCAR geoscience programs such as ANTOSTRAT, the Antarctic Climate Evolution (ACE), and the Past Antarctic Ice Sheet Dynamics (PAIS) programs, for which SDLS provided core functionality.

The multichannel seismic data housed by SDLS contributed to and enabled flagship science projects such as IODP and ANDRILL drilling legs including the recent drilling in Wilkes Land (IODP-318), Ross Sea (IODP-374), Amundsen Sea (IODP-379) and Iceberg Alley (IODP-382), and accepted, but not yet scheduled drilling proposals targeting the Bellingshausen sediment drifts and the Mertz Glacier continental shelf. SDLS seismic data will continue to be instrumental in proposing future drilling legs, for example near Totten Glacier, the Weddell and the Ross Sea.

The protocols for data sharing and collaboration have led to successful collaborative projects such as Antarctic paleo-bathymetric and paleo-topographic reconstructions that are based on identifying and estimating sediment distribution and volumes around the Antarctic continent from seismic data.

Besides these large-scale projects, the data shared through as the SDLS have been used for numerous regional and local tectonic, stratigraphic, and glaciological studies. As a result, the SDLS has become a role model archive for sharing and re-using of Antarctic data that are expensive to collect and often unique.

The SDLS database currently holds 153 surveys, with over 336,000 km on seismic lines from 16 countries, which is ~87% of the known seismic data collected in Antarctica. This includes new data submissions to SDLS between 2013 and 2019 from 11 surveys with a total of 19,450 km of seismic lines.

ANNEX C

List of other education, outreach and capacity building

List of initiatives for international coordination within and outside SCAR that PAIS co-chief officers and representatives led or contributed to:

- Talks (by DeConto and Escutia) in the cryosphere pavilion of the International Cryosphere Climate Initiative (ICCI) during the 2019 United Nations Framework Convention on Climate Change (COP25)
- Co-authorship of the new IODP Science Ocean Drilling 2050 framework (by McKay)
- Antarctic Environments Portal (Escutia is editor), which now is under SCAR http://www.environments.aq). It summarises policy-relevant information of concern to the to the Committee for Environmental Protection (CEP) of the Antarctic Treaty (since 2015)
- International Ross Sea region collaboration and coordination at meetings organized by USA and NZ Polar Programs (De Santis, Naish and others participated)
- "The coupled polar climate system: global context, predictability and regional impacts". EU-PolarNet project white paper 2019 (De Santis is co-lead author)
- WCRP/CliC "Melting Ice Sheets and Global Consequences" Grand Challenge (Naish is appointed Leader). WCRP 40th and 41th Joint Scientific Committee meeting and science plan implementation workshop at WMO 2019 and 2020. WRCP co-ordinates scientific initiatives such as CMIP6 and ISMIP6 for IPCC Assessment Reports. PAIS members are contributing to joined SCAR-IACS-WCRP ISMASS Group.
- Golledge, DeConto, and Mackintosh contributed to the IPCC 6th Assessment Report and Special Report on the Ocean and the Cryosphere in a Changing Climate (SROCC, 2019)
- Casado and Colleoni took part in a group review of the IPCC SROCC (2019). A correspondence dealing with fostering early careers participation to review process of IPCC reports and other large-scale initiatives has been published by Casado in Nature: https://www.nature.com/articles/d41586-018-05956-7
- Levy, Colleoni, and other PAIS scientists participated in the Miocene MIOMIP first meeting in 2018

Books

Matsuoka, Kenichi (ed., with 15 authors, including Florence Colleoni and Laura De Santis) 2020. Life of the Antarctic ice. From deep inland to the coast. Tromsø, Norway: Norwegian Polar Institute.

Dowdeswell, Julian & Hambrey, Michael, 2018. The Continent of Antarctica. Published by Pakadakis, Newbury, UK. It is a highly illustrated book intended for a lay-readership, and featured as a "Book of the Week" in Nature soon after it came out last autumn (our hemisphere!), as well as on the SCAR website.

Public speeches:

EGU symposium talk (webcasted and still available online) "Cryosphere as the thermometer of Cenozoic Earth system evolution" Florence Colleoni, Laura De Santis, and Andrea Bergamasco
https://meetingorganizer.copernicus.org/EGU2019/orals/30246

Interview with Science journalist on exp. 389 (also in the interview Karsten Gohl, Julia Wellner and Rob DeConto) https://www.sciencemag.org/news/2019/04/newly-drilled-sediment-cores-could-reveal-how-fast-antarctic-ice-sheet-will-melt

Interview with Kelly Hogan in the middle of this BBC article about some of the first results from the ITGC program https://www.bbc.co.uk/news/science-environment-54079587

Interview with Johann Klages about his Nature paper on Amundsen Sea MeBo core results (Antarctic Cretaceous forests) in this podcast (interview starts 9:50 into the podcast) https://www.nature.com/articles/d41586-020-00985-7

Outreach event "Then and now" with public speeches by Jim Kennett, Peter Barrett, Fred Davey, Rob McKay, Laura De Santis, presented by Tim Naish and Denise Kulhanek, live-recorded in Lyttleton (NZ) on March 8th 2018 and available from the PAIS web site http://www.scar-pais.org/index.php/insights/video

Imperial College Festival 2018 http://www.imperial.ac.uk/news/185986/imperial-festival-transforms-under-12s-into-mini/

Pint of Science London Talks 2018: Understanding Antarctica (talks by Martin Siegert and Tina van de Flierdt)

Pint of Science London Talks 2019: 'The Frozen Continent' (https://pintofscience.co.uk/event/the-frozen-continent; talks by Martin Siegert and David Wilson) and 'Polar Thinking' https://pintofscience.co.uk/event/big-climate-question---small-village-answers; by Tamsin Edwards

Pint of Science Trieste talks 2019: "Iceberg in vista: come cambia il livello del mare" talk by Florence Colleoni.

Videos and other outreach material:

Video "Antarctic Scientific Deep Sea Drilling: a long history" by Kimberly Kenny. https://www.youtube.com/watch?v=GN9faSiGUZQ

Video "PAIS the sound of a community effort". Made by Giulia Massolino for the international conference PAIS https://www.youtube.com/watch?v=Fklvy0YTtk8&feature=emb_logo

Video about the PAIS conference 2017 https://www.youtube.com/watch?v=bdJdpamyAwQ&feature=emb_logo

A new Video about PAIS highlights is still under construction and will be ready for the delegate meeting 2021.

videos at https://thwaitesglacier.org/index.php/media

Outreach and educational material from the IODP exp. 379 https://iodp.tamu.edu/outreach/expeditions/amundsen_sea_ice_sheet_history.html and IODP Exp 382 https://iodp.tamu.edu/outreach/expeditions/iceberg_alley_paleoceanography.html

Blogs, videos and educational resources made during the IODP expeditions 2018-19:

- exp 374 https://joidesresolution.org/expedition/374/
- exp 379 https://joidesresolution.org/expedition/379/
- exp 382 https://joidesresolution.org/expedition/382/

The Standing Committee for Undersea Feature Name (SCUFN) has approved some new feature names for the East Antarctic continental margin. The area is seaward of

the Sabrina Coast of Wilkes Land between 114° and 122°E. The new names apply to a suite of submarine canyons and a submarine valley.
Five of the names are words provided by the Noongar People, the Australian Aboriginal group whose traditional lands would have been adjacent to the Sabrina Coast before Antarctica and Australia separated around 135 Million years ago. The sixth canyon is named after an eminent Australian marine scientist.
Geoscience Australia has produced a fly-through of a canyons available via YouTube. The canyon was mapped in 2017 by scientists on the CSIRO research vessel RV Investigator, by a team including Assoc. Prof. Leanne Armand (ANU), Dr Phil O'Brien (Macquarie University) and Dr Alix Post (Geoscience Australia). This project is supported through the Australian Government's Australian Antarctic Science Grant Program (AAS #4333) and through a grant of sea time on RV Investigator from the CSIRO Marine National Facility. The proposal for new names was greatly assisted by Ursula Harris at Australian Antarctic Division and by the Australian Hydrographic Office.

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