SCAR Scientific Research Programme

External Performance Review

PAST ANTARCTIC ICE SHEET DYNAMICS (PAIS)

http://www.scar.org/srp/pais

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Introduction

The overarching goal of PAIS is 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 will link 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 will enable 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 will accomplish 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 (**Appendix I**) 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.

Deliverables and Milestones

Antarctic greenhouse environments under >600 ppm CO_2 scenarios The early Eocene provides insights into the response of Earth's climate and biosphere to the higher range of atmospheric carbon dioxide (CO_2) levels predicted for the future as a result of relatively un-restricted anthropogenic carbon emissions. Climate during the early Eocene 'greenhouse world' are poorly constrained in Antarctica. Sediments collected off the east Antarctic Wilkes Land coast during Integrated Ocean Drilling Programme (IODP) Expedition 318, provide quantitative, seasonal temperature reconstructions for the early Eocene pointing to extremely mild frost-free winters capable of supporting the growth of diverse, near-tropical forests (*Pross et al., Nature 2012*). At around 50 Ma, a regional surface water and continental cooling (2–3 °C) (*Pross et al., Nature 2012*), coeval with earliest throughflow of a westbound Antarctic Counter Current through a southern opening of the Tasman Gateway (*Bjil et al., PNAS, 2012*), corresponds with the loss of the tropical forest in favour of temperate vegetation. This information provides critical new constraints for the validation of global climate models and for understanding the response of high-latitude terrestrial ecosystems to increased CO_2 forcing. Climate and carbon cycle modeling (*DeConto et al., Nature 2012*) points to the importance of Antarctic terrestrial ecosystems in global carbon cycle dynamics, prior to widespread Antarctic glaciation at the Eocene-Oligocene Transition (EOT, 34 Ma). It was shown that enough soil organic carbon could have been stored in Eocene Antarctic permafrost environments to trigger sudden, extreme warming events if the permafrost was lost. These Antarctic climate-

carbon dynamics provide an alternative mechanism for the cause of global events like the Paleocene-Eocene Thermal Maximum (PETM) and subsequent Eocene hyperthermals, and reinforce the importance of Antarctica in the global climate system, even before the development of its massive ice sheet-sea ice system.
The stepwise expansion of ice on Antarctica during the EOT induced crustal deformation and gravitational perturbations around the continent rising (in the order of 10s of m) sea level close to the ice sheet, despite an overall reduction in the mass of the ocean caused by the transfer of water to the ice sheet (*Stocchi et al., Nature Geosciences 2013*). Sediment cores from around Antarctica and at the vicinity of the Antarctic ice sheet, are in agreement with the spatial patterns of relative sea-level change indicated by GIA models. These results are consistent with the suggestion that near-field processes such as local sea-level change influence the equilibrium state obtained by an ice sheet grounding line.
Once the Antarctic Ice Sheet grew, the highly diverse Eocene rainforest evolved to an Oligocene cold temperate forest and an impoverished Miocene sub-Antarctic shrubland (*Salzmann et al., EGU abstract 2016*). Temperatures on the Wilkes Land margin were higher than in the Ross Sea region (i.e. Andrill, Cape Roberts) and Seymour Island (Antarctic Peninsula), implying that Wilkes Land was possibly one of the last refugia for temperate forest taxa on Antarctica during the Late Oligocene. These studies point to the need for records from other Antarctic sectors to understand regional differences and continental gradients, which PAIS will continue to support, encourage, and facilitate.

East Antarctic Ice Sheet (EAIS) stability or instability in 400-600ppm CO_2 world? The warm-Pliocene period (5-3 Ma) is recognized to be an important analogue to near-future conditions and for understanding the long-term response of the Earth System to 400pm atmospheric CO_2 (see section below on IPCC contribution). Reconciling near field records of the ice sheet with, far-field sea-level records and models has been a major challenge facing the paleoclimate research community. Work conducted under the SCAR Antarctic Climate Evolution (ACE) Programme (predecessor of PAIS) provided evidence for a complex behaviour of the Neogene EAIS. However, complete deglaciation was not demonstrated with geological data. Neither was an entirely stable EAIS defendable. A recent summary of this history and state of knowledge was produced by Barrett (*Earth and Environmental Science Transactions of the Roy. Soc. Edinburgh, 2013*), However, most climate and ice sheet models were not able to simulate significant loss EAIS required by the far-field sea-level records (*Miller et al., Geology, 2012*) given that atmospheric CO_2 levels were relatively low throughout this period. Work conducted under PAIS, has now provided geological evidence for marine EAIS retreat into the Wilkes Subglacial Basin during the early Pliocene implying that the EAIS is capable of contributing as much sea-level rise, if not more, than the West Antarctic Ice Sheet (WAIS) (*Cook et al., Nature Geosciences 2013; Patterson et al., Nature Geosciences 2014; Reinardy et al., Paleo3, 2015*). These results have triggered the revision of ice sheet models (*Dolan et al., 2011; de Boer et al., 2015; DeConto et al., 2012; Pollard and DeConto, 2012; Pollard et al., 2015*) which, when incorporating melt-driven hydrofracturing of ice shelves and ice-margin cliff failure (*Pollard et al., 2015*), now reproduce a rapid Pliocene collapse of West Antarctic ice, and retreat into East Antarctic subglacial basins. The total Antarctic ice loss corresponds to ~+17m sea-level rise, in good agreement with far-field geologic sea-level records and near-field ice extent records. Modelling studies are now ongoing to understand how the uncertainty in the Bedmap2 Antarctic topographic data set effects model derived estimates of past (and future) ice-sheet retreat (*Gasson et al., GRL 2015*). Using the warm mid-Pliocene as a test case, it is found that estimates of Pliocene sea-level rise vary from 12.6 to 17.9m, simply due to unknown topographic boundary conditions.

This study clearly points to the need for additional, targeted geophysical surveys, which PAIS will continue to support, encourage, and facilitate.
PAIS and it's focus on the Pliocene also helped spark the development of the U.S. NSF supported PlioMAX project (www.pliomax.org), with the mission of linking Pliocene sea-level indicators with GIA modelling and ice sheet modelling, to further improve constraints on the Pliocene sea-level, and hence Antarctic ice sheet sensitivity (e.g., *Raymo et al., 2011; Rovere; 2014*).
Attention is now turning to the Miocene where work conducted under PAIS, includes two important new papers based on the Antarctic Geological Drilling Program (ANDRILL) 2A record *(Levy et al., Gasson et al., PNAS 2016).* This work reveals that all the marine based ice in the EAIS (equivalent to +22m sea-level rise) was likely lost at times in the Miocene when atmospheric CO_2 approached or exceeded ~500ppm, similar to CO_2 levels that will be reached in middle of this century. The ANDRILL 2A sediment record (*Levy et al., 2016*) shows strong orbitally-paced variability of the ice margin in a Ross Sea up to 6°C in the Ross Sea, and the ice-modelling companion paper (*Gasson et al., 2016*) shows that a combination of including new ice-shelf hydrofracturing physics and climate-ice sheet feedbacks can produce ice volume changes consistent with benthic oxygen isotope records, resolving a longstanding problem of EAIS hysteresis.

The contribution of Antarctica to abrupt sea-level rise during the Last Deglaciation In recent years new geological and bathymetric constrains of the ice extent during the Last Glacial Maximum (LGM) and the patterns of retreat during the Holocene deglaciation have been provided (*Bentley et al., Quaternary Science Reviews 2014; Weber et al., Science 2014, Rebesco et al., Science 2014*). These records provide evidence for episodic mass loss of the Antarctic ice sheet between 20 and 9 kyr. Older events are related to the deglaciation of the Antarctic Peninsula Ice Sheet and the EAIS in the SE Weddell Sea, with the onset of the Antarctic-wide deglacial warming marked by an IRD peak at around 17 kyr when the Northern Hemisphere was cold during Heinrich event 1. New constraints have been provided for the Antarctic contribution Meltwater Pulse 1A from an ice sheet model *(Golledge et al., Nature Communications 2014)* and a well-dated iceberg rafted debris record in the Scotia Sea *(Weber et al., Nature, 2014)*. The agreement between these two entirely independent studies is remarkable and shows that ice mass discharge primarily from WAIS contributed at rates if up to 1m/century to sea-level rise during meltwater pulse 1A. This work points to the importance of ocean warming in the timing of ice-sheet retreat during the last deglaciation, with clear implications for possible future response to a warming ocean.

Policy relevant PAIS research informs the IPCC 5th Assessment Report A number of PAIS outputs mentioned above were influential in Assessment Report 5 of the Intergovernmental Panel on Climate Change *(IPCC, 2013),* and contributed to Chapter 5 "Information from Paleoclimate Archives" (*Masson-Delmotte et al., 2013*), Chapter 13 "Sea-level Change" (*Church et al., 2013*), the Technical Summary and Summary for Policy Makers. PAIS members also contributed as authors. PAIS researchers specifically contributed to AR5 topics, including carbon-cycle feedbacks, polar ice-sheet dynamics and contribution to sea-level rise, high-latitude temperature response to high CO2, polar amplification, and anthropogenic greenhouse gas attribution in the context of ice cores. Examples of some specific policy relevant statements from AR5 are listed below.

1. **There is *high confidence* that the volumes of the Greenland and WAIS were reduced during periods of the past few million years that were globally warmer than present.** Ice sheet model simulations and geological data suggest WAIS retreat if atmospheric CO2 concentration stays within or above the range of 350 ppm to 450 ppm for several millennia. *Chapter 5 executive summary*

2. **New temperature reconstructions and simulations of past climates show with *high confidence* polar amplification in response to changes in atmospheric CO2 concentration.** For high CO2 climates *Chapter 5 executive summary.*
3. **There is *high confidence* that global mean sea level was above present during some warm intervals of the mid-Pliocene (3.3 to 3.0 million years ago), implying reduced volume of polar ice sheets.** The best estimates from various methods imply with high confidence that sea level has not exceeded +20 m during the warmest periods of the Pliocene, due to deglaciation of the Greenland and WAIS and areas of the EAIS. *Chapter 5 executive summary.*
4. **With *very high confidence*, the current rates of CO2, CH4 and N2O rise in atmospheric concentrations and the associated radiative forcing are unprecedented with respect to the highest resolution ice core records of the last 22,000 years**. *Chapter 5 executive summary.*
5. **The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years.** *Summary for Policymakers.*

II. Primary publications in peer-reviewed journals (use appendices if necessary)

References to citations in the previous section and other selected PAIS publications are listed in **Appendix II.** In addition, PAIS has produced three special volumes and has contributed to Policy relevant reviewed publications (i.e., *Kennicutt et al., Nature and Antarctic Science, 2014*).

III. Major reports, including linkages to major SCAR activities (e.g. advice to the Treaty or IPCC)

Active involvement of members of the PAIS scientific community in international programmes and networks has provided science-based advice to: 1) SCAR activities (e.g., Antarctic Treaty, HorizonScan, Strategic Plan, etc.); 2) other major scientific programs (e.g., IODP, EU PolarNet); and 3) Policy makers (IPCC, United Nations Climate Change Conferences; Antarctic Portal). A detailed list of reports to which members of the PAIS have contributed are listed in **Appendix III**. PAIS will continue to provide reports on its activities to SCAR and contribute to reports for international and national programmes and government bodies, as required.

IV. Workshops and other key meetings organized and activities associated to major SCAR meetings (Open Science Conferences, International Symposia on Biology, Earth Sciences, etc.)

PAIS work on facilitating coordination and collaborations between different multidisciplinary and interdisciplinary international groups is largely conducted through community workshops and meetings. Some of the completed activities funded/co-funded by PAIS are listed in **Appendix IV.** In addition to these activities, PAIS convenes scientific sessions and additional meetings of the Steering Committee and subcommittees during large international meetings such as AGU and EGU, SCAR OSC (2012, 2014 and 2016), ASLO 2015, and XII ISAES 2015. PAIS plans to organize a PAIS Symposium in 2017 in Trieste (Italy). It is expected to be similar in size and format to the 1st ACE Symposium held in Granada in September 2009.

V. Capacity building and education outreach activities; detail any difficulties encountered

PAIS endeavors to support and encourage the next generation of Antarctic scientists by: 1) including young scientists in the leadership of sub-committees and the SC (see **Appendix I**); 2) encouraging young scientists to take part in PAIS meetings and workshops by offering bursaries for travel and subsistence; 3) participation and funding, when possible, of graduate students to attend the Urbino Palaeoclimate School, the Karthaus Summer School on Ice Sheets and Glaciers in the Climate System, and other training schools in topics that are relevant to PAIS. PAIS members also serve as instructors at these summer schools. **Appendix V** lists some of the activities conducted by PAIS since 2012.

VI. New data and/or meta-data (including plans for archiving)

PAIS supports continued development of the ***Antarctic Data Library System*** for Cooperative Research (SDLS) under the auspices of Scientific Committee on Antarctic Research (SCAR) and the Antarctic Treaty (ATCM XVI-12). The SDLS provides open access to all multichannel seismic-reflection data collected south of 60° S. The new website is operated and administered at the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) and provides open access to Antarctic multichannel seismic-reflection data online is http://sdls.ogs.trieste.it/
While PAIS does not directly support other data archiving infrastructure, it maximizes the effectiveness of its limited budget by encouraging responsible archiving of data and samples to established data centres and repositories. Among these databases the most relevant to the data to be generated by PAIS are: 1) PANGAEA the data Publisher for Earth & Environmental Science- http://www.pangaea.de/ which holds all ANDRILL Program data, and a wealth of data from marine sediment cores from the Southern Ocean. 2) The IODP data bases and core repositories http://www.iodp.org/access-data-and-samples holds all Antarctic and Southern Ocean cores and data obtained by the Ocean Drilling Programmes since the 70s (i.e., DSDP, ODP, IODP). 3) The IPEV IMAGES Programme Sub-Antarctic and Antarctic portal - http://gcmd.gsfc.nasa.gov/KeywordSearch/Home.do?Portal=amd_fr, which contains data from both marine and ice core records. Other databases include NOAA NCDC/NSIDC, and national programmes metadata systems.

VII. Communication activities (eg website contents and stats, social media stats, brochures, speaking engagements, etc.) and how these contribute to the promotion of SCAR and its mission.

PAIS has been involved in numerous *community service and outreach activities*. In terms of public interest in PAIS research, PAIS members have been interviewed in numerous occasions in TV and radio, disseminating research findings and information about research projects to the general public. PAIS members have been quoted in numerous articles in newspapers concerning scientific results, research plans and expert opinions. PAIS also collaborates in science museums exhibits (e.g., http://icestories.exploratorium.edu/dispatches/en-espanol-video-del-joides-resolution/). Finally, through programmes of relevance to PAIS, video journals, video animations and blogs have been produced (e.g., http://andrill.org/static/media.html; http://www.youtube.com/watch?v=uvzrK24YJyQ). In addition, PAIS leadership has been invited to provide *science policy, keynote, and public outreach talks* such as: 1) The SCAR Lecture at XXXVII Antarctic Treaty Consultative Meeting, Brasilia, Brasil, April 2014; 2) The United Nations COP19 – Day of the Cryosphere: Climate Change Today in Polar and Mountain Regions, Varsaw, November 2013, 3) The S.T. Lee Lecture series on Antarctic Studies, 4) The WAIS Initiative, Julian, CA USA, 2014; and 5) The International Conference on Paleoceanography (ICP), Barcelona, 2013.

VIII. Linkages to other SCAR groups, international programmes and other activities

PAIS is well aligned with the other SCAR SRPs, particularly with SERCE, Ant-eco and AntClim21. With SERCE we share the study of ice dynamics and sea level but they involve very different scientific communities, and different time scales (i.e., post LGM vs 60 Ma). Linkages with Ant Eco involve the study of paleoenvironments, biota evolution, land bridges, and refugia. Linkages to AntCLIM21 relates to climate variability since the LGM. PAIS also has linkages with SCAR Expert Groups such as ADMAP, ISMASS, ATHENA, IBSCO and ANTVOLC; as well as SCAR Action Groups (CGG, Multibeam Data Acquisition, SAVant). Result of these cross linkages is the SCAR-OSC 2016 Mini-Simposium "The Antarctic ice sheet from past 2 future" co-organized by PAIS, SCERCE, AntClim 21 and ISMASS. Outside SCAR, and given that the nature of PAIS science is international and global in scope, we have established partnerships with: IODP, ANDRILL, SHALDRIL (Shallow Drilling Program), ICECAP (International Climate and Environmental Change Assessment Project), AGAP (Antarctica's Gamburtsev Province Project), PLIOMAX (Pliocene Maximum Sea Level Project), PALSEA (Sea Level and Ice Sheet Evolution), and WAIS among other national Antarctic research centres and multinational research projects.

IX. Expenditure on project activities and plans for unspent funds

Expenditure to date is related to the funding of workshops; the funding of early career and senior scientists to attend SCAR conferences, PAIS meetings and proposal-writing workshops considered in the PAIS Implementation Plans; and providing support for open access to articles relevant to PAIS. In addition, PAIS has committed funding for training schools. These activities are listed in **Appendices IV and V**. Planning is ongoing for a PAIS Symposium to be held in Trieste in 2017. Therefore PAIS 2016 and 2017 funding will be largely used to support this symposium.

Future Plans

Future plans for the next 4 years (2016-2019) include (see also **Appendix VI** for updates on the programmes in the original implementation plan):

- shallow drilling project on the Amundsen Sea Embayment shelf and in Pine Island Bay with MeBo is scheduled to take place in February to March 2017 on an RV Polarstern cruise (Gohl et al.);
- Field seasons for Totten Glacier (Armand et al) seismic and coring cruise 2017 on the Australian vessel Investigator.
- Field season to the Scotia Sea-Ona Basin (Escutia et al.) seismic and coring cruise 2017 on Spanish vessel BIO Hespérides.
- Field seasons for Ross Sea (Stocchi et al) seismic and coring cruise 2017 on the Italian vessel OGS Explora (EU-Eurofleets 2 project).
- IODP-MSP expedition 831 in the George V Land margin (T. Williams and C. Escutia co-chiefs) scheduled for January-February 2018 with the NBP Palmer (USA) and the shallow Rock driller (BGS,UK).
- Provide input to IODP to schedule of the IODP expeditions in the Ross Sea (proposal 751), Amundsen Sea (prop. 839), Antarctic Peninsula (prop.732)
- Continue the coordination of the scientific community to implement active and encouraging the submission of new shallow and deep drilling proposals from the Antarctic margin and from the ice shelf (using the ANDRILL platform)

- Progress on paleobathymetric mapping and ice sheet modelling
- Involve physical oceanographic community to develop collaborative work on understanding the role of Antarctic and Southern Ocean waters in ice sheet dynamics
- Organize the PAIS 2017 meeting in Trieste, Italy, to highlight main results achieved and scientific/technical questions still to be solved
- Organize PAIS sessions workshops and business meetings in major international meetings (SCAR OSC, AGU, EGU, ISAES)
- Continue outreach activities via National/International Programmes.
- Submit a proposal to the EU - SKŁODOWSKA-CURIE INNOVATIVE TRAINING NETWORKS for organizing an advanced school on polar stratigraphy
- Work on cross-linkages with other programmes (i.e., ice-core & marine core integration, develop links with SERCE and PAIS);
- Provide input to IPCC in a coordinated action with the other SCAR programs

Appendix I - Membership

Steering Committee

Last Name, First Name	Affiliation	Country	Email	Gender	Term	Expertise
Escutia Carlota	IACT-U. Granada	Spain	cescutia@ugr.es	F	2012-2016 chief-office 2016- ex-officio PAIS proponent	Paleoclimate-glacial processes-Ice Sheets
Robert DeConto	U. Massachusetts	USA	deconto@geo.umass.edu	M	2012-2016 chief-office 2016- ex-officio PAIS co-proponent	Ice Modeling
Tim Naish	Victoria U. of Wellington	NZ	Timothy.Naish@vuw.ac.nz	M	2016- chief-officer	Cyclostratigraphy-Ice sheets and sea level
Laura De Santis	OGS	Italy	ldesantis@ogs.triestе.it	F	2012- PAIS co-proponent	Geophysics-glacial evolution
Robert Larter	British Antarctic Survey	UK	rdla@bas.ac.uk	M	2012- PAIS co-proponent	Geologyand Geophysics – paleo ice-sheets
Karsten Gohl	AWI	Germany	karsten.gohl@awi.de	M	2012- PAIS co-proponent	Geophysics-rustal and sedimentary processes
Ross Powell	Northern Illinois U	USA	r.powell@mchsi.com	M	2012- PAIS co-proponent	Sedimentology-subglacial geology and marine ending glaciers
Mike Bentley	Durham U	UK	m.j.bentley@durham.ac.uk	M	2012- PAIS co-proponent	Glacial geomorphology dating-Ice sheets and sea level
Barbara Stenni	U. Trieste	Italy	barbara.stenni@unive.it	F	2012-	Ice cores
Julia Welner	U. of Houston	USA	jswellne@Central.UH.EDU	F	2012-	Sedimentology-glacial processes
Paolo Stocchi	NIOZ	NL	Paolo.Stocchi@nioz.nl	M	2012-	GIA modelling
Jongkuk Hong	KOPRI	Korea	jkhong@kopri.re.kr	M	2014-	Seismic and radar
Yusuke Sugamuna	NIRP	Japan	suganuma.yusuke@nipr.ac.jp	M	2013-	Paleomagnetism-Geochronology
Sun Bo	Polar Research Institute of China	China	sunbo@pric.gov.cn	M	2013-	Glaciology
Marcelo Reguero	Instituo Antartico Argentino	Argentina	regui@fcnym.unlp.edu.ar	M	2015-	Paleontology Vertebrates
Marcelo Leppe	INACH	Chile	mleppe@inach.cl	M	2015-	Paleontology Botany
Peter Bjil	U. Utrecht	NL	P.K.Bijl@uu.nl	M	2015-	Paleoceanograhy dinocists
J. Abel Flores	U. Salamanca	Spain	flores@usal.es	M	2015-	Paleoceanography nannofossils
Anton Van Putte	Royal Belgium I for Nat. Sci	Belgium	antonarctica@gmail.com	M	2013-	Databases SCADM

Members

Membership of the four established subcommittees allows PAIS to widen involvement in the programme in terms of expertise, gender and nationality. The mailing list at this time includes more than 208 scientists from all SCAR countries.

Appendix II - Primary publications in peer-reviewed journals

PAIS Selected publications to illustrate the breath of Science and Programs conducted under the PAIS umbrella:

2016

- Galeotti, S., DeConto, R., Naish, T., Stocchi, P., Florindo, F., Pagani, M., Barrett P., Bohaty, S., Lanci, L., Pollard, D., Sandroni, S., Talarico, F., Zachos, J., in press, Antarctic Ice-Sheet variability across the Eocene-Oligocene boundary climate transition***. SCIENCE (in press).***
- Gasson, E., DeConto, R., Pollard, D., Levy, R., 2016, Dynamic Antarctic ice sheet during the early to mid-Miocene, **PNAS**. 10.1073/pnas.1516130113.
- Levy, R., Harwood, D., Florindo, F., Sangiorgi, F., Tripati, R., von Eynatten, H., Gasson, E., Kuhn, G., Tripati, A., DeConto, R., and Fielding, C., Field, B., Golledge, N., McKay, R., Naish, T., Olney, M., Pollard, D., Schouten, S., Talarico, F., Warny, S., Willmott, V., Acton, G., Panter, K., Paulsen, T., Taviani, Marco T., and SMS Science Team. 2016. Antarctic ice sheet sensitivity to atmospheric CO2 variations in the early to mid-Miocene. **PNAS**. 10.1073/pnas.1516030113.

2015

- Barron, J.A., Stickley, C.E., and Burkry, D., 2015. Paleoceanographic and paleoclimatic constrains on the global Eocene diatom and silicoflagellate record. Palaeogeography, Palaeoclimatology, Palaeoecology 422: 85-100.
- De Boer, B., Dolan, A., Bernales, J., Gasson, E., Goelzer, N.R., Sutter, J., Huybrechts, P., Lohmann, G., Rogozhina, I., Abe-Ouchi, A., Saito, F., Van De Wal, R.S.W., 2015. Simulating the Antarctic ice sheet in the late-Pliocene warm period: PLISMIP-ANT, an ice-sheet model intercomparison Project. Cryosphere 9 (3):881-903.
- Feakins, S., Warny, S., and DeConto, R. 2015. Snapshot of cooling and drying before onset of Antarctic Glaciation, Earth and Planetary Science Lettersmm, 404:154-166.
- Pollard, D., DeConto, R.M., Alley, R.B. 2015. Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure. Earth and Planetary Science Letters, 412: 112-121
- Gasson, E., DeConto, R. M., and Pollard, D. 2015 Antarctic bedrock topography uncertainty and ice sheet stability, Geophysical Research Letters, Vol 42: 5372-5377.
- Barrett, P.J., 2013. Resolving views on Antarctic Neogene glacial history and the Sirius debate, Earth and Environmental Science Transactions of the Royal Society of Edinburgh, 104, 31–53, 2013.
- Griener, K.W., and Warny, S., 2015. Nothofagus pollen grain size as a proxy for long-term climate change: An applied study on Eocene, Oligocene, and Miocene sediments from Antarctica. Review of Paleobotany and Palynology 221:138-143.
- Lavoie, C., Domack, E. W., Pettit, E. C., Scambos, T. A., Larter, R. D., Schenke, H.-W., Yoo, K. C., Gutt, J., Wellner, J., Canals, M., Anderson, J. B., and Amblas, D., 2015. Configuration of the Northern Antarctic Peninsula Ice Sheet at LGM based on a new synthesis of seabed imagery. The cryosphere, 9:613-619.

- Lewis, A & Ashworth, A, 2015, An early to middle Miocene record of ice-sheet and landscape evolution from the Friis Hills, Antarctica, Geological Society of America, 128, doi: 10.1130/B31319.1.
- Teitler, L., Florindo, F., Warnke, D.A., Fillippelli, G.M., and Taylor, B., 2015. Antarctic Ice Sheet response to a long warm interval across Marine Isotope Stage 31: A cross-latitudinal study of iceberg-rafted debris. Earth and Planetary Sciences, 409:109-119.
2014
- Christner, B.C., Priscu, J.C., Achberger, A.M., Barbante., C., Carter, S.P., Christianson, K., Michaud, A.B., Mikucki, J.A., Mitchell, A.C., Skidmore, M.L., Vick-Majors, T.J. and the WISSARD Science Team, 2014. A microbial ecosystem beneath the West Antarctic Ice Sheet. **Nature** 512, 310–313, doi:10.1038/nature13667.
- Cowan, E.A., Christoffersen, P., Powell, R.D. and Talarico, F.M., 2014. Dynamics of the late Plio-Pleistocene West Antarctic Ice Sheet documented in subglacial diamictites, AND-1B drill core. Global and Planetary Change, 119: 56-70. doi: 10.1016/j.gloplacha.2014.05.011.
- Escutia, C., Brinkhuis, H., and the Expedition 318 Science Party. 2014. From Greenhouse to Icehouse at the Wilkes Land Antarctic margin: IODP 318 synthesis of results. In Developments in Marine Geology 7: Earth and life processes discovered from subseafloor environment. Stein, R. (AWI/Paleoclimate), Blackman, D. (Scripps/Solid Earth), Inagaki, F. (JAMSTEC/Biosphere), and Larsen, H.-C. (IODP-MI) (Eds.): 295-328.
- Golledge, N.R., Menviel, L., Carter, L., Fogwill, C.J., England, M.H., Cortese, G. and Levy, R.H., 2014. Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning. **Nature Communications** 5: 5107. doi:10.1038/ncomms6107.
- Huang, X., Gohl, K., Jokat, W. 2014. Variability in Cenozoic sedimentation and paleo-water depths of the Weddell Sea basin related to pre-glacial and glacial conditions of Antarctica. *Global and Planetary Change,* 118, 25-41, doi:10.1016/j.gloplacha.2014.03.010.
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Appendix III: Major reports, including linkages to major SCAR activities (e.g. advice to the Treaty or IPCC)

- Lead authors for the International Ocean Drilling Program (IODP) Science Plan 2013-2023.
- Lead and contributor authors for the ERICON Science Perspective 2015-2030: Scientific Research in Polar Seas.
- Lead and Contributing Authors of 5th Assessment Report (AR5 - 2013): The Physical Science Basis. Intergovernmental Panel of Climate Change (IPCC).
- Lead and Contributing Authors of the European Science Foundation (ESF) Science Position Paper 2015 “Sailing through Changing Oceans: Ocean and Polar Life and Environmental Sciences on a Warming Planet” http://www.esf.org/publications.html
- Invited participation in the COP19 “Day of the Cryosphere: Climate Change Today in Polar and Mountain Regions” (7 November, 2013, Warsaw, Poland). A side activity to the United Nations Framework Convention on Climate Change.
- SCAR Lecture in PAIS topics to the Antarctic Treaty ATCM XXXVII-CEP XVII meetings (30 April, 2014, Brasilia, Brasil).
- Invited participants in the SCAR Horizon Scan retreat (21-23 April, 2014, Queenstown, New Zealand).
- Professors Martin Siegert and Tim Naish awarded the Martha T Muse Prize for Science and Policy in Antarctica in 2013 and 2014, respectively.
- Members of the Antarctic Portal Editorial Group since 2015.
- Members of the SCAR Structure Review Group (April 2015).
- A PAIS Whitepaper submitted to the Council of Managers of National Antarctic Programs (COMNAP) Antarctic Roadmap Challenges (ARC) Project considered during the ARC workshop in Tromso at the end of August 2015.
- Invited participation to the COMNAP ARC Workshop, 22-24 August 2015, Tromso (Norway).

- Scientific reviewer to the Ice Sheets - Awakening Giants chapter of the “Thresholds and Closing Windows – Risks of Irreversible Cryosphere Climate Change” Report of the International Cryosphere Climate Initiative (http://iccinet.org/thresholds) - ICC at COP20 Paris.
- Review of the U.S. NAS/Polar Research Board report on A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research (2015).
- PAIS membership in the EU-PolarNet External Expert Advisory Board (EEAB) (www.eu-polarnet.eu).
-Future planning for a U.S.-NERC focus on WAIS, in progress.

Appendix IV: Workshops and other key meetings organized and activities associated to major SCAR meetings (Open Science Conferences, International Symposia on Biology, Earth Sciences, etc.)

- Antarctic and Southern Ocean Drilling (PRAMSO) workshop, July 2012 (Portland, USA). Kick-off meeting for community to organize projects in the PAIS latitudinal transect strategy.
- Scotia Arc Symposium: Geodynamic Evolution and Global Implications. May, 2013 (Granada, Spain).
- Eastern Ross Sea IODP Drilling proposal writing workshop, June 2013 (St. Petersburg, USA)
- Wilkes Land Eocene Greenhouse and Greenhouse-Icehouse transition workshop, Fall 2013 (NIOZ, NL)
- MOCA Joint Model-data workshop for the Late Pleistocene evolution of the Greenland and Antarctic ice sheets LGGE, Grenoble, May 22-24, 2014
- Multiproxy approach to the reconstruction of climate of the Pliocene Workshop, Barcelona, Spain, September 2014.
- PAIS Subcommittee meetings during the SCAR OSC, Auckland, New Zealand, 2014. PRAMSO and SDLS (23 August, 2014).
- PAIS open community and Steering Committee meetings during the SCAR OSC, Auckland, New Zealand, 25 and 27 August 2014, respectively.
- PAIS Subcommittee (PRAMSO) and Town Hall meetings during the XII ISAES, Goa, India, July 2015.
- Wilkes Land & Ross Sea Oligocene ice sheet dynamics, April 2015 (NIOZ, NL).

Appendix V: Capacity building and education outreach activities; detail any difficulties encountered

- Participation in the Association of Polar Early Career Scientists (APECS) Networking Cruise for early career researchers. 26 de August 2014, Auckland, New Zealand.
- Participation in the Smart Talk speaker panel of the IceFest: Bringing Antarctica to the World. Auckland, New Zeland, 27 de Agosto 2014.
- PAIS support and participation in the “Polar Marine Diatom Workshop” Salamanca, Spain, 19th-24th July 2015. This is a training course for PhD and Master students. The workshop was attended by 45 persons of which 25 were PhD students and five were early career researchers with no permanent position. The participants represented 15 countries, with 26 from European institutions and 19 others from Australia, Japan, Republic of Korea and the USA.
- PAIS contributed funding for students and early career researchers to attend the SCAR OSC 2014 in Auckland, New Zealand.
- PAIS provided US$10,000 funding for four students and two keynote speakers to attend the XII International Symposium on Antarctic Earth Sciences. In addition, PAIS provided US$6000 to the XII ISAES organizers for student travel support.

- PAIS contributed co-funding and participated in the “Advanced course in organic-walled dinoflagellate cysts”, September 13-19, 2015 in Heidelberg, Germany.
- Members of the Scientific Committee for the SCAR Open Science Conference (OSC) in Auckland (NZ) 2014 and SCAR-OSC in Kuala Lumpur, Malaysia, 2016; and the XII International Symposium on Antarctic Earth Sciences ISAES 2015, Goa, India.
- Chair of the Science Support and Advisory Committee of ECORD □(the European Consortium of Ocean Research Drilling) (October 2010- December 2013) and Vice-chair of ESSAC (2014).
- Co-chair of the Scientific Committee for the SCAR Open Science Conference in Buenos Aires, Argentina, 3-6 August 2010.
- Chairs of the First Antarctic Climate Evolution (ACE) Symposium, Granada, Spain, 2009.
- The Urbino Summer School for Paleoclimatology (USSP), where Antarctic climate and ice sheet dynamics has become a major segment of this highly competitive and renowned graduate-training workshop.

Appendix VI – Updated PAIS Implementation Plan. This table is updated from the original Implementation Plan.

Projects	***Location***	***Objectives***	***Year***	***Implementation Since 2013***
Current				
ANDRILL SMS & MIS	Ross Sea	Pleistocene-Miocene glacial history	2007-2008	Continue review of sedimentary cores from SMS & MIS programmes. Comparison-integration with Exp 318, ODP Legs & CRP, and available onshore data. Provide data to numerical GIA-ice sheet modelling community. 2 new papers in PNAS (Feb 2016) on Miocene ice sheet response to 400-600 ppm CO2.
IODP Leg 318	Wilkes Land	Holocene to Eocene Greenhouse palaeoclimate and glacial history	2010	Continue review of sedimentary cores from Exp 318. Comparison-integration with ANDRILL, CRP, ODP Legs, and available onshore data. Work on Holocene ice-core and marine-core integration. Provide data to numerical GIA-ice sheet modeling community.
Subglacial WISSARD (LISSARD & RAGES) Drilling	Whillans Ice Stream	Marine Ice Sheet Stability and Subglacial Life Habitats in West Antarctica	2009-2015	Analyze water, sediment and geophysical data and samples collected during the 2012-2013and 2013-2014 field seasons. Papers being submitted and others still in the pipeline (e.g.

				we have one just recently accepted for EPSL).
WAIS Divide	WAIS ice flow divide	Climate, ice sheet history and cryobiology	2010-2013	2013 field season ended: Ice cores record of past climate and greenhouse gases in the atmosphere that extends back 68,000 years. Current planning for future proposal
AGAP	Gamburtsev Mountains	Initial ice sheet formation, subglacial hydrological processes	2008-2009	Continue review of data obtained and provide data to numerical ice sheet modeling community.
Approved				
Amundsen Sea shelf - MeBo	Amundsen Sea Embayment shelf	Basic shelf stratigraphy, glacial onset, LGM retreat ages	Scheduled for early 2017	Implementation of MeBo drilling in the Amundsen Sea
Totten Glacier seismic and coring cruises (US, Italy, Spain, Australia)	Totten Glacier	Basic shelf stratigraphy, Pleistocene ice sheet dynamics, LGM retreat.	NSF cruise achieved in early 2015 Australian cruise Scheduled for early 2017	Analysis of data collected during the NSF cruise from eastern Wilkes Land dredging & Totten Glacier surveys Planning and implementation of Australian led international coring and seismic cruise to the Totten Glacier
Ross Sea seismic and coring cruises (NL, UK, Italy, NZ, South Korea) – EU/EUROFLEETS 2	eastern Ross Sea slope and rise	Basic slope and rise stratigraphy, Miocene-Pleistocene ice sheet dynamics, LGM retreat, Ross Sea Gyre along slope current, and Antarctic Bottom Water present and past dynamics.	Approved 2014 Scheduled for early 2017	Planning and implementation of the cruise to collect seismic data for IODP prop. 751 site survey
IODP 813-Full	Eastern Wilkes Land; Adélie Land & George V Land shelf	Greenhouse to Icehouse Antarctic paleoclimate and ice history from George V Land and Adélie Land shelf sediments	Scheduled for 2018 by ECORD FB	Planning and implementation of the IODP expedition
IODP 732-Full2	West of Antarctic Peninsula and Bellingshausen Sea	Sediment drifts off the Antarctic Peninsula and West Antarctica; Late Miocene to Quaternary paleoceanography & ice sheet history	At JR-FB to be scheduled	Continue fostering IODP proposal for Bellingshausen Sea drift drilling. New site survey data were collected by BAS (UK) in early 2015
IODP 751-Full2	Western-central Ross Sea	Ocean-ice sheet interactions and West Antarctic Ice Sheet vulnerability: clues from the Neogene and Quaternary record of the outer Ross Sea continental margin	At JR-FB to be scheduled	Continue fostering IODP proposal for western-central Ross Sea IODP drilling. New site survey data were collected by PNRA (Italy) and KOPRI (S. Korea) in 2014 and 2015. A new cruise is scheduled in 2016-17 with EU-Eurofleets funds. .
IODP 839-Full	Amundsen Sea Embayment	Development and sensitivity of the West Antarctic Ice Sheet tested from drill records of the Amundsen Sea Embayment	At JR-FB to be scheduled	Continue fostering IODP proposals for Amundsen Sea Embayment.
Proposed				
IODP 812-Pre	Eastern Ross Sea continental shelf	"Shallow drilling in the far southeastern Ross Sea Antarctica for records of the early West Antarctic Ice Sheet".	After review of the pre proposal, SEP has requested a full proposal to be submitted.	Continue fostering IODP proposal for Eastern Ross Sea shelf
ANDRILL Coulman High	Central-southern Ross Sea	Palaeogene to lower Miocene ice sheet behaviour &	Coulman High	Investigating other future sites

		environments during greenhouse gas levels	proposal rejected by NSF, but supported by ICDP And deactivated by IODP	to employ the ANDRILL platform (Siple Coast, Neumayer Station) Current status is that the Coulman High drilling project has been abandoned. ANDRILL Program has been closed down.
IODP 847-Full	Drake Passage	Plio-Pleistocene reconstruction of ocean, atmosphere and ice-sheet interactions through the Drake Passage	submitted Oct. 2013; deactivated by SEP in July 2015 but with strong encouragement to resubmit	Continue fostering IODP proposal for Drake Passage/Scotia Sea
IODP 848-Full	Weddell Sea	Late Neogene ice-sheet and sea-level history of the Weddell Sea	Submitted Oct. 2015 – SEP recommended revision	Continue fostering IODP proposal for Weddell Sea
IODP 861-Pre	W Antarctic Peninsula	Cenozoic formation of the Antarctic glacial landscape investigated by low-temperature thermochronometry (W Antarctic Peninsula)	deactivated by SEP in June 2014 but with encouragement to resubmit	Continue fostering IODP proposal for West AntarcticPeninsula
IODP 873-Pre	SE Pacific & southern Chilean margin	Plio-Pleistocene paleoceanography of the Subantarctic Southeast Pacific linked to Drake Passage throughflow	deactivated by SEP in Jan 2015 but with strong encouragement to resubmit	Continue fostering IODP proposal for SE Pacific; new site survey data are collected in early 2016
Planned				
IPICS “Beyond Epica: oldest ice"	Dome C, Dronning Maud Land	Deep ice core drilling to obtain the oldest ice climate record from the Antarctic Ice Sheet	-2016	A new proposal for co-funding site surveys for identifying future new drilling sites to sample oldest ice (> 1 Ma) is going to be submitted to the EU H2020 in 2016
IODP southern Indian Ocean (former IODP 824-Pre)	Conrad Rise, Del Caño Rise, South Indian Ocean	Antarctic Cryosphere and Southern Ocean Responses to Glacial-Interglacial Climate Change: Transect drilling across the Indian Ocean sector of the (ACC)	Re-submission planning	Discussion on resubmission plan will be held in Kuala Lumpur (SCAR-OSC) during the PRAMSO meeting
Rapid Access Ice Drill (RAID)	Antarctic Ice Sheet	Development of rapid access ice drill for deep drilling of basal ice sheets and sub-ice bedrock in Antarctica	First tests in 2015; expected scientific projects from 2017/18	Moving forward with testing in 2016-17. If successful it may be funded to carry on with the first scientific drilling