VICTORIA UNIVERSITY OF WELLINGTON
TE HERENGA WAKA

Te Puna Pātiotio Antarctic Research Centre

Annual Review 2021

CAPITAL THINKING. GLOBALLY MINDED.
MAI I TE IHO KI TE PAE

IMPROVING UNDERSTANDING OF ANTARCTIC CLIMATE AND ICE SHEET PROCESSES, AND THEIR IMPACT ON NEW ZEALAND AND THE EARTH SYSTEM

Tasman Glacier lake - Photo: Huw Horgan

Contents

Designed and edited by: Michelle Dow
Contributions from: Brian Anderson, Michelle Dow, Nick Golledge, Richard Levy, Darcy Mandeno, Rob McKay, Tim Naish, and Lauren Vargo.

Cover images:
Kamb Ice Stream, Antarctica - Photo: Gavin Dunbar
Brewster Glacier, New Zealand - Photo: Lauren Vargo

HIGHLIGHTS
BY THE NUMBERS

1 decade

to tip an Antarctic ice sheet system into rapid mass loss according to paper in *Nature Communications* (page 8).

170 metre

sediment core highlights climate changes will have a significant impact on Antarctica's coastal biological system (page 9).

6th IPCC report

confirms that changes are happening in Earth's climate across every continent and every ocean. ARC's Nick Golledge was a lead author (page 20).

6 authors

from the ARC involved in writing chapters for the new book, *Antarctic Climate Evolution* (page 21).

50x30 coalition

The ARC is a founding member of a worldwide movement to press governments to reduce greenhouse gas emissions to 50% by 2030 (page 10).

60 metres

of sea-level change from ice loss in Antarctica's deep past (page 11).

COP26

ARC researchers, Nick Golledge and Lauren Vargo, presented at the 2021 United Nations Climate Change Conference of the Parties (page 23).

104 years

ago, our resident mummified penguin "Ralph" died in the dry valleys of Antarctica according to radiocarbon dating (page 25).

$4.6 million

project SWAIS 2C (Sensitivity of the West Antarctic Ice Sheet to global warming of 2°C) is an international effort led by Richard Levy (page 12).

1200 kilometre

traverse across the Ross Ice Shelf to the Kamb Ice Stream (KIS-2) drill site this field season (page 13).

$5.5 million

in revenue obtained by the ARC in 2021 (page 26).

2 Marsdens

awarded to Ruzica Dadic and Holly Winton in 2021 for research into different aspects of sea ice (page 28).

15,000 km

of New Zealand coastline has had sea-level projections mapped at 2 km intervals (page 14).

31% ice loss

from New Zealand's glaciers since 1978 (page 15).

47 publications

in 2021 with ARC staff and student authorship, including five in *Nature* and one in *Science* (page 30).

42 talks

given to scientists, politicians, stakeholders, schools and community groups by ARC staff and students (page 32 & 35).

5 theses

completed in 2021 by ARC supervised PhD and MSc students (page 17).

1st all female

research team from the ARC headed to the Ice this 2021/22 season (page 19).

65 interviews

given by ARC staff and students on Antarctic and climate related issues (page 33).

Icons from www.flaticon.com

DIRECTOR'S SUMMARY

Associate Professor Rob McKay
Director, Antarctic Research Centre

It goes without saying that this was another year of constant adaptation to challenges related to the ongoing pandemic. However, the year did start to see a return to some form of normality for our researchers, albeit a new normal. Although curveballs were thrown at us on a near weekly basis in terms of planning and undertaking our research, the year continued to emphasize just how resilient and dedicated the Antarctic community as a whole are. It was fantastic to have a full season on the Ice this year, after limited operations last year. For those who went to Antarctica this season, requirements for pre-departure quarantine and other logistical bottlenecks resulted in several weeks being added to their already very long seasons. This was also on the back of a hectic year of preparation in order to get equipment to the ice on time, with critical equipment for our events arriving in the country with only a few days to spare. Due to the exhaustive and dedicated efforts across our entire support team and by Antarctica New Zealand, it all came together. As I write this, our Te Puna Pātiotio—Antarctic Research Centre field teams have all returned from a remarkably successful season on the ice.

This year's field events saw a team of all female, early career researchers deploy into the field on an event to understand seasonal flow of the Ross Sea. We were also successful in obtaining unique sub-ice shelf geophysical, geological and oceanographic datasets collected at the grounding line of the Kamb Ice Stream in West Antarctica. These data will inform on oceanic processes that influence ice sheet melt rates in this critical region where the grounded ice sheet meets the oceanic waters that flow beneath the Ross Ice Shelf. The success of this event was only made possible by the hard work of our staff in the Science Drilling Office, who successfully made two access holes through approximately 500 metres of the Ross Ice Shelf using our hot water drill system, and kept these holes open for several weeks.

While the science at the Kamb Ice Stream was an outstanding success this year, it was also a critical season for testing our hot water drill system. This provided important preparation work for what will be a much larger and even more ambitious undertaking over coming years, where we will lead drilling operations for the international SWAIS 2C project (Sensitivity of the West Antarctic Ice Sheet to global warming of 2°C). For the past two years, Alex Pyne and Darcy Mandeno, in collaboration with long-time partners GNS Science and Webster Drilling and Exploration Ltd., have been designing and building a light weight drilling system capable of retrieving ~200 metres of sediment from the sea floor beneath ice shelves in remotely located regions of Antarctica. The aim is to see how the West Antarctic Ice Sheet responded to global warming in the past, when it was at least as warm as that expected in the coming decades. Originally envisioned as a flagship initiative of the New Zealand Antarctic Science Platform, the International Continental Scientific Drilling Programme has now also awarded the project a USD$1.2 million grant, making it the first Antarctic drilling project in that programme. The global relevance of this project is further emphasized by substantial funding and science contributions from Australia, Germany, Italy, Japan, Republic of Korea, the United Kingdom, and the United States. We are truly excited to be playing such a critical role in this international project.

As usual, life was not any less busy for those who did not deploy to Antarctica this year, with a number of impressive publications led by our students and early career researchers. We also oversaw important contributions that will directly inform policymakers, both in New Zealand and around the globe. Nick Golledge was a lead author on the Intergovernmental Panel on Climate Change Sixth Assessment Report, which is an exhaustive and impressive undertaking in its own right. However, it was also his ice sheet models, that are informed by the results of our field campaigns to understand ice sheet processes and past climates, that were central to informing the sea-level projections in that report. While this work highlights the global relevance of our research programmes, our team also continued to customise these projections to investigate regional impacts on sea-level rise in Aotearoa New Zealand through the MBIE-funded NZ SeaRise programme. Lauren Vargo and Nick Golledge also presented at the 26th UN Climate Change Conference of the Parties (COP26), with Lauren presenting on the state of New Zealand glaciers, and Nick an overview of the Australasian regional summary in the IPCC Sixth Assessment Report.

In the build-up to COP26, the Antarctic Research Centre was invited to be one of the ten founding members of the newly launched 50x30 coalition. This coalition consisted of 10 leading international scientific institutions pressing governments, including New Zealand's, to commit to the necessary actions to prevent catastrophic damage to the Earth's snow and ice regions. Prior to COP26, most governments had pledged carbon neutrality by 2050 and even declared a "planetary emergency", but it was apparent to us and the members of this coalition that almost none were taking meaningful steps to truly achieve the Paris Agreement goal of its preference to limit warming to 1.5°C. As a consortium of experts in cryosphere science, we highlighted that overshooting these goals is an extremely risky proposition from a future sea-level rise perspective. This is because 1.5 to 2°C appears to be close to the threshold for which the melting of polar ice sheets starts to greatly accelerate. In order to restrict warming to these values and minimise ice loss, the IPCC have indicated global emissions should be reduced by 50% by 2030. Following COP26, we were pleased to see the leadership of several leading nations, including New Zealand, in pledging to achieve this far more ambitious target. Given we are now only eight years out from this deadline, and the significant impacts that projected sea-level rise would have on New Zealand's coastal infrastructure and communities, we continue to emphasize it is increasingly urgent that meaningful action is taken to ensure these pledges are met.

Kamb Ice Steam field team, Antarctica - Photo: Huw Horgan

RESEARCH OUTCOMES

Our research approach

Rationale

We are rapidly heading towards a climate that is 2-4ºC warmer than present. Ice sheets and oceans take centuries to millennia to fully adjust to climate forcing, and the fundamental changes that we are observing today may be irreversible on human timescales. In order to provide reliable, policy-relevant projections of future climate and sea level, scientists are increasingly relying on computer models. Our Centre has undergone a numerical revolution over the last few decades, and around half of our staff now routinely carry out physics-based computer simulations of past, present and future climate.

We develop confidence in future climate projections if models show skill at simulating present and past climate. Because direct climate and ice sheet observations span the last century at best, reconstructions of past climate conditions provide the only means to assess climate and ice sheet models on their relevant timescales. Furthermore, past climate observations provide insight into the long term "endgame" (equilibrium response), that we will commit our planet to this century based on current warming scenarios. Past climate records also provide insight into the rates and magnitudes of climate and ice sheet changes that may be possible in the near future, and allow the fingerprint of human influences to be identified in the context of natural variability in the climate system.

Outcome-based research

Our research approach is policy-relevant and outcome focused. We aim to improve forecasts of future climate change including their global and New Zealand impacts, for the benefit of humanity. By reducing the uncertainties around future climate and sea-level rise predictions, our cutting-edge research is informing the International Panel on Climate Change (IPCC). Improved understanding of climate change impacts including sea-level rise impacts in the southwest Pacific region provide tangible benefits to all New Zealanders. Our research is leveraged by strong national and international collaborations and partnerships, and world-leading in-house polar drilling technology provided by the Science Drilling Office. We are funded and supported through a range of MBIE, Marsden, and Rutherford programmes, Antarctica New Zealand and private donations.

In summary, our approach involves:

a. Improving our physical understanding and observation of modern climate, ocean, glacier and ice sheet systems.

b. Acquiring past observations of surface temperature, precipitation, atmospheric composition (greenhouse gases and aerosols), ice sheet, glacier, and sea-ice variability, and oceanic conditions from terrestrial, marine, lacustrine and ice core archives.

c. Developing and improving numerical models of climate-ocean-glacier and ice sheet systems, by advancing the physics, and then carrying out sound evaluation of models against modern observations and past climate reconstructions.

d. Using our models to improve future climate simulations, and projections of glacier and ice sheet contribution to sea-level rise, river flows and other changes in the Earth System.

e. We disseminate our research findings through publications in the world's leading scientific journals, and through education, communication and engagement with the public, practitioners and policymakers.

Emily Moore, Levan Tielidze and Lisa Dowling working in the Ahuriri River valley, Southern Alps, New Zealand - Photo: Shaun Eaves

Sea ice, Antarctica - Photo: Nick Golledge

Antarctic ice sheet may have reached a tipping point

A study more than a decade in the making has shown ice loss from the Antarctic ice sheet is accelerating and may mark an irreversible progression towards a rise in global sea levels.

In the context of the historical patterns, the ice sheet is nearing a "tipping point" beyond which its degradation would be inevitable.

The study, published in *Nature Communications* (Weber *et al*., 2021) and involving ARC researcher Nick Golledge, reveals that during times in the past when the ice sheet retreated, periods of rapid mass loss 'switched on' very abruptly, within only a decade or two. Once destabilised, the ice sheet continued to retreat for several hundred years before it quickly 'switched off' again, also taking only a couple of decades.

Analysis of mud on the Antarctic sea floor showed layers of gritty sediments released by melting icebergs from eight phases of retreat and reinstatement of the ice sheet, across more than ten thousand years from the end of the ice age, each of which was accompanied by substantial global sea-level rise.

Nick said, "Up until 15 to 20 years ago the ice sheet had been in a "state of balance", where it had not significantly changed for several thousand years. Humanity added a change in the temperature that the ice sheet is unable to withstand. As a result it has reached a tipping point where, as in the past, the ice sheet has deteriorated very quickly."

After the collection of high-resolution sediment cores from the Antarctic sea floor in 2007 by lead author Mike Weber (University of Bonn), Nick's team brought in ice sheet modelling simulations applied to the same periods as the sediment samples captured.

Study co-author Dr Zoë Thomas (University of New South Wales), applied statistical methods to the model outputs that confirmed early warning signs could be detected for tipping points in the ice sheet system.

"If it just takes one decade to tip a system like this, that's actually quite scary because if the Antarctic ice sheet behaves in future like it did in the past, we must be experiencing the tipping right now," Zoë said.

While the research indicated that a certain amount of sea-level rise was inevitable, reducing emissions as quickly as possible could still limit how much and how quickly it occurred (see page 10).

Nick commented that, the research showed there was even more of an imperative to act against emissions.

"Governments have to do something and big business has to do something, but I really want to encourage individuals to do anything they can to reduce emissions. It can all have that cumulative effect."

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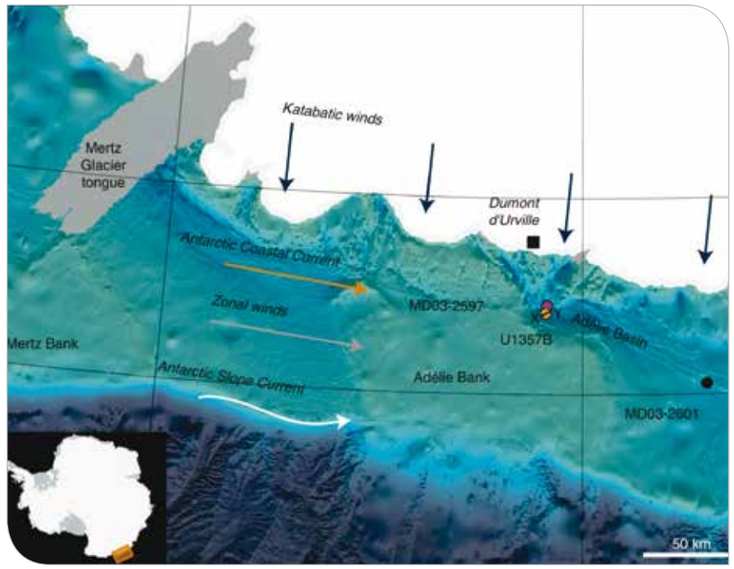
Future of Antarctic plankton linked to sea ice

Climate changes will have a significant impact on Antarctica's coastal biological system.



Study area from Johnson et al. 2021, Nature Geoscience

In a study published in *Nature Geoscience*, a team led by former ARC PhD student Katelyn Johnson (now GNS Science), and involving the ARC's Rob McKay, Nancy Bertler and Huw Horgan, showed that Antarctic sea ice had a tight connection to both Southern Ocean algae blooms and El Niño-linked weather events in the geological past. Investigating a unique 170 metre-long sediment core collected by the Integrated Ocean Drilling Programme in 2010, the research team provided the first ever reconstruction of annual to sub decadal changes in biological primary productivity along the Antarctic marine margin over the entire Holocene epoch (past 12,000 years). Funded by the Royal Society Marsden Fund, the team found Antarctic winds strongly affect the breakout and melting of sea ice, which in turn has an effect on the amount of microscopic algae that grow in surface waters.

The study used techniques such as CT (computed tomography) scan-imaging and analysis of microfossils and organic biomarkers to examine the relationship between sea ice and large algae bloom events at annual timescales. The researchers found algal bloom events occurred nearly every year prior to 4500 years ago. However, coinciding with a shift towards increased sea ice presence they then became less frequent, occurring every two to five years—a frequency similar to El Niño Southern Oscillation (ENSO) climate events. This provided evidence that ENSO and other climate modes influence multi year sea ice breakout events, which in turn directly affects biological bloom occurrences.

The results of this new paper suggest such changes will have a significant impact on Antarctica's coastal biological system because sea ice amplifies the connection between equatorial processes like ENSO and polar biology, but when sea ice is absent this connection is weakened. With rapid declines in Antarctic sea ice since 2017, and more loss projected over coming future decades, the consequences for polar biology, food webs and polar carbon cycling could be profound.

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Melting ice, Antarctica - Photo: Nick Golledge

We can limit the rate of future melting of the world's ice, as long as we act now

If global warming is limited to 1.5°C, predicted sea-level rise by 2100 could be cut almost in half.

The results of more than five years of ice sheet and glacier modelling by researchers from the ARC and 80 other scientists from around the world were published in a landmark paper in *Nature*. The study, led by Dr Tamsin Edwards of King's College London, included ARC's Nick Golledge and Brian Anderson, and ARC alumni and adjunct research fellow, Dan Lowry (also GNS Science). It used outputs from computer simulations to first train a statistical emulator—a tool that identifies relationships in the data and allows them to be reproduced more quickly than from the original models. Then, the emulator was used to investigate socio-economic scenarios or model parameter combinations that weren't part of the original simulations. The flexibility and speed of this approach make it a powerful tool for making predictions, and by running tens of thousands of 'emulated' scenarios, it also allows the uncertainty around future forecasts to be better defined.

The key finding of the research was that if global warming is limited to 1.5°C, rather than the 2.5°C that global governmental emissions pledges currently commit us to, the contribution to sea-level rise from melting ice could be cut from around 25 cm to 13 cm by 2100. This would greatly reduce the costs and impacts of coastal flooding around the world, including in New Zealand. The study underlines the importance of making swift and decisive climate action at all scales, and highlights that we still have a chance to limit the future melting of the world's glaciers and ice sheets, as long as we act now.

The results informed the United Nations Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report, and helped underscore the central message of a new global initiative, the '50x30 coalition' (www.50x30.net). This international effort, of which the ARC is a founding member, aims to press governments around the world to take more decisive action on climate change. The coalition is part of a worldwide movement to reduce all greenhouse gas emissions to 50% by 2030, in line with IPCC recommendations for staying within the 1.5°C Paris Agreement limit by the end of the century. This also requires net carbon neutrality by 2050. Currently, the New Zealand government is committed to reducing CO_2 emissions to net zero by 2050, but other greenhouse gases such as methane and nitrous oxide are not yet included in this target.

Contact: Nicholas.Golledge@vuw.ac.nz

Antarctic ice's deep past shows large contributions to sea-level change

Marine-based Antarctic ice sheet could raise sea level significantly as planet warms.

Insights into how the West Antarctic Ice Sheet responded to a warmer climate millions of years ago could improve predictions of its future, according to a paper published in *Nature* (Marschalek *et al*., 2021). An international team including ARC and GNS Science researchers has found there was significantly more ice on Antarctica during the Early Miocene—around 16-18 million years ago—than was previously thought.

The paper is a flagship output from the International Ocean Discovery Program Expedition 374, on which ARC co-author Robert McKay was co-chief scientist. It concludes the West Antarctic Ice Sheet was at times much larger than today during the early Miocene epoch—a time in the past when atmospheric carbon dioxide levels were similar to those we expect in the coming decades under low to mid-range emissions pathways.

Previously, scientists had assumed climate in the early Miocene was too warm to support a large West Antarctic Ice Sheet and struggled to understand how changes in the East Antarctic Ice Sheet could have contributed to the 60-metre variations in sea level revealed in geological records from around the world.

The research team drilled into sediments in the Ross Sea, Antarctica, to find layers that corresponded to the coldest and warmest periods of the Miocene. They found evidence of material deposited by the West Antarctic Ice Sheet at locations that are presently covered by ocean, showing the ice sheet grew much larger than it is today during the coldest periods and it retreated again during warm episodes.

This was only possible as more of the land surface beneath the West Antarctic Ice Sheet was above sea level in the past, and it is easier to grow ice sheets on mountains on land than to grow ice sheets that sit below sea level. Over millions of years, glaciers subsequently eroded the West Antarctic below sea level, making ice sheets in this region more vulnerable to melting caused by oceanic warming.

This study confirms the West Antarctic Ice Sheet today is very vulnerable to oceanic and atmospheric warming and cooling, and could raise sea level a significant amount in the future as our planet warms.

"Our observations from the past help inform predictions of how the West Antarctic Ice Sheet, which is considered particularly vulnerable to rapid ice mass loss today, will respond under various future warming scenarios," said lead author Jim Marschalek (Imperial College London).

"The good news here is that prior to our study, we were concerned that ice sheet models were underestimating loss of ice on land and associated sea-level rise in these warmer climates, and therefore could also be under-representing ice loss in the projections for future warming," said Rob.

"The geological information now matches the modelling, and gives us more confidence that the models are accurately capturing the response of both the East Antarctic Ice Sheet and West Antarctic Ice Sheet in the past."

"One of the key ice sheet models used for our Miocene experiments is also used to project future ice sheet contribution to global sea level," co-author Richard Levy (GNS Science and ARC) said.

"This particular model reveals a critical 'tipping point' that we are rapidly approaching if we don't reduce emissions, causing sea level to rise well over a metre by 2100 and much more in the centuries to come.

"Keeping future warming below 2°C, and ideally to 1.5°C, is the target to aim for to prevent this," Richard said.

Contact: Robert.McKay@vuw.ac.nz

Frazil ice, Terra Nova Bay, Antarctica - Photo: Rob Dunbar

Testing the new drill rig at Belmont Quarry, Lower Hutt - Photo: Kerry Leith

Large international effort to drill into Antarctica's past to inform our future

While COP26 focused on science and innovation's role in combating climate change, our team were preparing to drill into the ocean floor below the Ross Ice Shelf.

The team are drilling under the Ross Ice Shelf to assess what level of greenhouse gas emissions are likely to avoid catastrophic melt of the icy continent, based on the sensitivity of the West Antarctic Ice Sheet to global warming of 2°C (SWAIS 2C) in past climates. They will achieve this by retrieving sediment cores to reveal if 2°C is a tipping point in our climate system when large amounts of land-based ice melts in these climates, causing oceans to rise many metres—if it has happened before, it could happen again.

The SWAIS 2C team, led by Richard Levy (GNS Science and ARC) and ARC alumni Molly Patterson (now Binghamton University, USA), is an international effort supported by an anticipated ~USD$4.6 million in funds from New Zealand, Australia, Germany, Italy, Japan, the Republic of Korea, the United Kingdom, and the United States. The International Continental Scientific Drilling Programme also awarded the project a USD$1.2 million grant, the first for an Antarctic drilling expedition in that programme.

"We have formed a team of drillers, engineers, field experts and scientists who are up to the task. Discoveries will show us how much the West Antarctic Ice Sheet could melt if we miss Paris Agreement targets," Richard said.

SWAIS 2C's preparation team departed from Scott Base in November for a 1200 km traverse across the Ross Ice Shelf to the Kamb Ice Stream, where land ice meets the ocean and starts to float. Once the drilling camp was established, the wider science team joined the group and worked through Antarctica's summer. SWAIS 2C field campaigns are planned for the coming years. No one has ever drilled into the Antarctic seabed at a location so far from a major base, or so close to the centre of the West Antarctic Ice Sheet.

The ARC's Science Drilling Office have spent four years developing 'world-first' technology capable of hot water drilling through ~800 metres of ice before taking sediment samples from up to 200 metres beneath the ice sheet. ARC Director, Rob McKay, said it is a massively ambitious undertaking, but New Zealand engineers such as the ARC's Alex Pyne and Darcy Mandeno are recognised world-leaders in designing and building such innovative technology.

"The fact that so many countries are joining us in this effort highlights the urgency to understand more about the West Antarctic Ice Sheet, which remains the largest uncertainty for sea-level rise projections."

This knowledge will help scientists predict what might happen in the future if global temperatures continue their current trajectory towards 2.7°C above pre-industrial levels, and if we are approaching a climatic threshold for West Antarctic Ice Sheet collapse in the near future. This is important to know because Antarctic ice melt raises sea levels around the globe. The West Antarctic Ice Sheet is considered vulnerable to climate change because much of the ice, which rests on bedrock thousands of metres below sea level, is exposed to the warming Southern Ocean.

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Successful season for Science Drilling Office

The ARC's Science Drilling Office (SDO) finished another successful year, culminating with the field season at the Kamb Ice Stream.

The SDO supported the Kamb Ice Stream site two (KIS-2) hot water drilling project this field season. The SDO hot water drill (HWD) system continues to prove its capabilty gaining access to the ocean cavity close to the modern day grounding line beneath 500 metres of ice.

The season for all south bound Antarcticans started two weeks earlier this year due to Antarctica New Zealand's managed isolation requirement in Methven, New Zealand. Darcy Mandeno, the first of the southbound ARC cohort, departed for the ice mid-October to complete annual maintenance tasks for the HWD before it departed Scott Base, to traverse 1200 km, to the KIS site in mid-November. The rest of the drilling team, who joined Darcy in late November, saw the return of Hedley Berge (Senior HWD Electrician-Driller), and Sean Heaphy (HWD Mechanic-Driller), with Stephen Stretch (HWD Electrician-Driller) embarking on his first Antarctic season. Further institutional support from Katelyn Johnson (GNS Science) and Stefan Jendersie (ARC), who put aside their own scientific work to become drillers for a season, were valuable additions to the drilling team.

Among the many COVID-19 impacts during 2021, the Okeanus winch ordered at the end of 2020, and scheduled to arrive into New Zealand during the first quarter of 2021, was delayed. Okeanus, themselves having COVID induced supplier constraints, only completed the build late in 2021. The delay meant that to ensure it successfully made it for its journey to Kamb Ice Stream it had to be flown from Los Angeles to Auckland rather than shipped. It arrived at Scott Base just four days before the traverse departed! The winch made it in time due to the superb logistical support at every stage of its journey from the factory in Houston to the Kamb Ice Stream. Despite these challenges and an abbreviated commissioning and test at Scott Base the winch proved its ability to support drilling operations and a significant improvement on the capacity and safety of the various scientific operations over the previous winch system.

Back in warmer climes, the SDO continued work preparing for a seafloor sediment drilling season at Kamb Ice Stream site three (KIS-3) that integrates the HWD system with the recently developed Antarctic Intermediate Depth Drill (AIDD) rig and associated drill string handling systems.

AIDD work began in earnest in April 2021 after its arrival into New Zealand from Canada late 2019 starting with the assembly and function test of the new MP1000 rig and hydraulic power systems carried out by Darcy at Webster Drilling and Exploration Ltd., in Porirua. Further drilling tests where completed in November at Belmont Quarry by Webster Drilling operating the rig under the supervision of ARC's Antarctic Drilling Advisor, Alex Pyne. They successfully recovered 30 metres of good quality NQ core (45 mm diameter), proving that the MP1000 could provide the drilling control required. The bore hole also advantageously allowed GNS Science scientists to evaluate a bore hole dilameter tool in the Greywacke proximal to the Wellington Fault. With the continued pandemic adding uncertainties to uncertainties, work to provide the equipment for a seafloor sampling season will continue into 2022.

The significant SDO effort to support complex and remote operations such as KIS-2 and KIS-3 over several seasons has highlighted constraints on capacity within the ARC and SDO, especially since the retirement of Alex in 2019. Therefore, in August, Darcy was appointed into the new role of SDO Engineering Manager leading to a replacement required for his previous Operations and Field Engineer role to enhance the capacity of the SDO. The position is expected to be filled in the second quarter of 2022.

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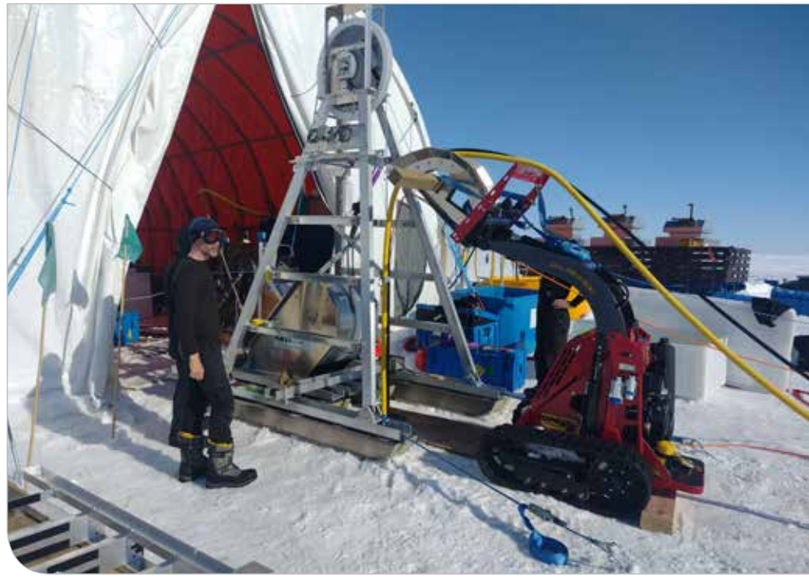


Installing the HWD well pump with the "Dingo" digger - Photo: Darcy Mandeno

Olya Albot collecting salt marsh cores, Rangaunu Harbour, New Zealand - Photo: Olya Albot

NZ SeaRise programme release new sea-level projections

New sea-level projections offer estimates of future sea-level rise around New Zealand's coastline.

Our NZ SeaRise Te tai pari o Aotearoa team have completed the fourth year of a five-year MBIE-funded Endeavour research programme. We have focused our efforts over the past 12 months on preparing data, visualisations, and communication materials to support the release of new sea-level projections. These projections offer estimates of future sea-level rise under the range of greenhouse gas emissions scenarios for locations spaced every 2 km around our 15,000 plus kilometres of coastline. Importantly, these projections include local estimates of vertical land movement that have been determined using satellite-based Global Positioning and Synthetic Aperture Radar (GPS and SAR) data. Publication of a paper led by team member Ian Hamling (GNS Science) underpins these estimates and offers critical peer review of our approach.

Greg Garner and Bob Kopp (Rutgers University, USA) have incorporated these deformation estimates into the 'FACTS' sea-level projections framework used by the IPCC. We have now incorporated the most up-to-date climate projections, as vetted through the IPCC Sixth Assessment Report, with our vertical land movement data to offer location specific relative sea-level rise projections for New Zealanders to use. Our partners at Takiwa Data Analytics have produced an interactive map to display the projections using dynamic graphs. Rebecca Priestley, Zoe Heine, and Ceridwyn Roberts have worked diligently to write stories and develop visualisations that augment the scientific data and help convey the need, value, and implications of the projections. Judy Lawrence (VUW), Rob Bell (Bell Adapt) and Ryan Paulik (NIWA) are developing information for stakeholders and are working with MfE to provide guidance around using the new projections. We plan to 'go public' on the 2 May, 2022.

Our PhD students have made great progress. Dan King has nearly completed his excellent work reconstructing sea level over the past several decades and centuries. Zoe Heine has developed her approach to 'story tell sea level' and enhance public engagement and understanding of this challenging climate change issue. Jesse Kearse continues to make advances that improve InSAR-based spatial measurements and understanding of processes that drive vertical land movement along our coast. Leana Barriball's project on Mātauranga Māori, sea-level rise in estuaries, and its impact on inanga is developing well. Olya Albot joined our team in 2021 and has pushed hard through a challenging year of COVID-19 field delays to complete her field work in Northland where she collected sediment cores from salt marsh wetlands in Rangaunu Harbour. Olya's goal is to better quantify the carbon sequestration potential of our coastal wetlands and examine the effect of sea-level rise on these blue carbon systems.

Contact: R.Levy@gns.cri.nz

Glaciers under stress

Glaciers in New Zealand, and around the world, continue to retreat as the climate warms.

The year 2021 was the hottest on record for New Zealand, and our glaciers are showing the strain. The three glaciers that we measure the length of directly (and report to the World Glacier Monitoring Service) are all the shortest since measurements began (WGMS, 2021), and continue to retreat as they respond to the most extreme ice loss year in 2017/2018. To appreciate the wider loss of glacier ice in New Zealand, Sabine Baumann, who visited the ARC in 2017, has mapped each of the 2,918 New Zealand glaciers in detail based on 2016 satellite data. While that may seem like a lot of glaciers, it is about 600 fewer than were mapped in 1978, and the area of ice in New Zealand has reduced from 1158 km^2 to 794 km^2 over that period, a loss of 31% (Baumann *et al.*, 2021).

Our field measurements of New Zealand glaciers over many years, funded by the Royal Society Marsden Fund and NIWA-MBIE funding, have led to a detailed understanding of how these glaciers respond to climate change, what has driven this ice loss, and allowed us to create and test models of the present-day behaviour of glaciers. Many of our glaciers are rather extraordinary, being amongst the most sensitive (i.e. a small temperature change has a big impact) and responsive (i.e that change results in very rapid changes in glacier length and area) on Earth. We have tested our models by using observed climate over the 20th century as input, and compared the output against what the glaciers have actually done. The match is close, which gives us confidence to consider what may happen in the future as the climate continues to warm.

Lyell Glacier lake continues to grow as the glacier retreats - Photo: Huw Horgan

As might be expected, given the sensitivity and responsiveness of our glaciers, they will continue to lose mass but, compared to other regions in the world, a relatively small proportion of the mass loss is already committed (as the glaciers respond quickly enough to only lag climate by a few years, or decades at most). If the climate remained at its 1980-2010 mean, 19% of 2006 ice would be lost by 2100 – that is how much loss is already committed. These results mean that future greenhouse gas emissions are crucial to the future existance of our glaciers. The contrast is stark, with a ~1°C warming resulting in a 50% loss, while ~4°C warming, results in a 92% loss by 2100 (Anderson et al., 2021).

The future of our glaciers is not yet decided. The benefits that they bring, with their own unique ecology, supporting recreation and tourism, regulating river flows in summer, and being an important cultural part of our landscape, can still be enjoyed by future generations, if we can meet our obligations to reduce greenhouse gas emissions.

Contact: Brian.Anderson@vuw.ac.nz

WGMS 2021. *Global Glacier Change Bulletin No. 4* (2018-2019). Zemp, M., Nussbaumer, S. U., Gärtner-Roer, I., Bannwart, J., Paul, F., and Hoelzle, M. (eds.), ISC(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 278 pp., publication based on database version. doi:10.5904/wgms-fog-2021-05.

TEACHING AND SUPERVISION

Our staff support a wide range of courses being taught within the School of Geography, Environment and Earth Sciences, as well as provide graduate student supervision. In 2021, our staff supervised 12 PhD and 8 MSc students.

Courses ARC staff taught in

ESCI111	The Earth System: An Introduction to Physical Geography and Earth Sciences
ESCI132	Antarctica: Unfreezing the Continent
ESCI201*	Climate Change and New Zealand's Future
ESCI204	Petrology and Microscopy
GEOG220	Hydrology and Climate
ESCI241	Introductory Field Geology
ESCI301*	Global Change: Earth Processes and History
GEOG318	Quaternary Environmental Change
ESCI412*	Paleoclimatology
ESCI452*	Earth History
GISC424*	Introduction to Remote Sensing
ENVI520	Environmental Management

* An ARC staff member was the course co-ordinator

Graduate completions

Florence Isaacs (PhD)
Sea ice and large-scale atmospheric variability in East Antarctica.
Supervised by James Renwick (SGEES) and Ruzica Dadic (ARC).

Wei Ji Leong (PhD)
The subglacial landscape and hydrology of Antarctica mapped from space.
Supervised by Huw Horgan (ARC/SGEES) and Brian Anderson (ARC).

Joanna Borzecki (MSc)
The long-term impacts of glacier retreat on runoff in the Waitaki Catchment, New Zealand.
Supervised by Lauren Vargo (ARC) and Ruzica Dadic (ARC).

Theo Calkin (MSc)
Sedimentology of the grounding zone of the Kamb Ice Stream, Siple Coast, West Antarctica.
Supervised by Gavin Dunbar (ARC) and Cliff Atkins (SGEES).

Emily Moore (MSc)
The glacial history of Rocky Top cirque, southeast Fiordland, New Zealand.
Supervised by Shaun Eaves (ARC/SGEES) and Kevin Norton (SGEES).

Linda Balfoort and Sam Thorpe-Loversuch explore a crevasse, Antarctica - Photo: Regine Morgenstern

SIGNIFICANT EVENTS

The Antarctic Research Centre's first all-women research team in Antarctica

Te Herenga Waka—Victoria University of Wellington have been sending staff and students to the Ice since 1957, but 2021 saw our first all-women team head south.

Team leader Alanna Alevropoulos-Borrill, who is in the final stages of completing her PhD in glaciology, was joined by ARC research fellow, Alexandra Gossart and fellow PhD student Francesca Baldacchino. The team collected data on ice flow at the Ross Ice Shelf to inform climate change models.

The Ross Ice Shelf plays a key role in limiting ice loss from Antarctica so it's important we understand how sensitive the shelf is to changes in climate. The data collected will help predict future ice loss and how much the Ross Sea catchment will contribute to sea-level rise. Collapse of the entire catchment has the potential to raise global sea levels by about 12 metres.

The research team visited six locations on the Ross Ice Shelf as part of a Rutherford Discovery Fellowship and Antarctic Science Platform funded project led by Nick Golledge. At two sites, GPS units have been collecting ice flow data since January 2020. This data will be downloaded for use in the computer models. Instruments were installed at the other four sites.

Alanna said it was "a huge privilege" to led the first all-women crew from the Centre.

"While our polar science teams are becoming more diverse, there is still a long way to go. We hope to change the dominant image of the 'polar explorer' and tell more stories about the women who work in the harsh conditions of the Antarctic continent."

The team flew to Scott Base in late November 2021 after spending 14 days in quarantine to comply with COVID-19 requirements.

It's a far cry from 1970, when Rosemary Askin, the first female Victoria University student to undertake her own research programme in Antarctica, joined the University's summer expedition to the ice. Professor Peter Barrett, who served as Antarctic Research Centre director from 1972 to 2007, had to push hard to get her on the expedition. The US Navy refused to fly Rosemary into the field without her father's permission!

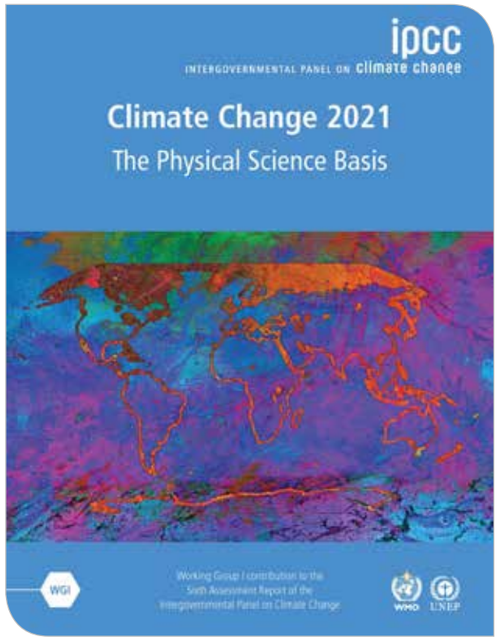
Much has changed since Rosemary's days, over the past two decades, the ARC field teams have achieved a 50/50 split between male and female students going to Antarctica.

Nancy Bertler, who has led 13 Victoria University field expeditions to the Antarctic, said we weren't deliberately trying to put together our first all-female research team.

"It's wonderful to see we have reached a critical mass where a talented and capable all-female team is deploying to conduct critical scientific work in one of the most challenging environments on the planet," she said.

"The treasure in this, for me, is that we're now at a time where we have enough female talent in our Centre that it just happened naturally."

The all-women team, Francesca Baldacchino, Alexandra Gossart and Alanna Alevropoulos-Borrill in Antarctica
Photo: Alanna Alevropoulos-Borrill



ARC's science informs latest IPCC report

ARC researcher Nick Golledge was a lead author in the latest Intergovernmental Panel on Climate Change report.

The Sixth Assessment Report (AR6) of the IPCC (Intergovernmental Panel on Climate Change), which confirms that changes are happening in Earth's climate across every continent and every ocean, took three years of writing and two weeks of virtual negotiations to approve. Nick Golledge was a lead author on the 'Ocean, Cryosphere and Sea Level Change' chapter. AR6 shows the ocean surface has warmed by about 0.9 °C as a global average since 1850, but about two-thirds of the ocean warming has taken place during the last 50 years. The report concluded that it is virtually certain the heat content of the ocean will continue to increase for the rest of the current century, and will likely continue until at least 2300, even under low-emissions scenarios.

The researchers also state very high confidence that the amount of ice lost from West Antarctica in recent decades has exceeded any gain in mass from snowfall. The authors were also confident this loss has largely been due to increased melting of ice below sea level, driven by warming ocean water. This melting has allowed the acceleration and thinning of grounded ice further inland—and this is what contributes to sea-level rise.

On the other side of the world, the Greenland ice sheet has also been losing mass over recent decades, but in Greenland this is principally due to warmer air, rather than warming ocean water.

The report notes it is *virtually certain* that the melting of the two great ice sheets, in Greenland and Antarctica, as well as the many thousands of glaciers around the world, will continue to raise sea levels globally for the rest of the current century.

James Renwick, Head of Te Kura Tātai Aro Whenua—School of Geography, Environment and Earth Sciences was a coordinating lead author on a chapter on the global water-cycle.

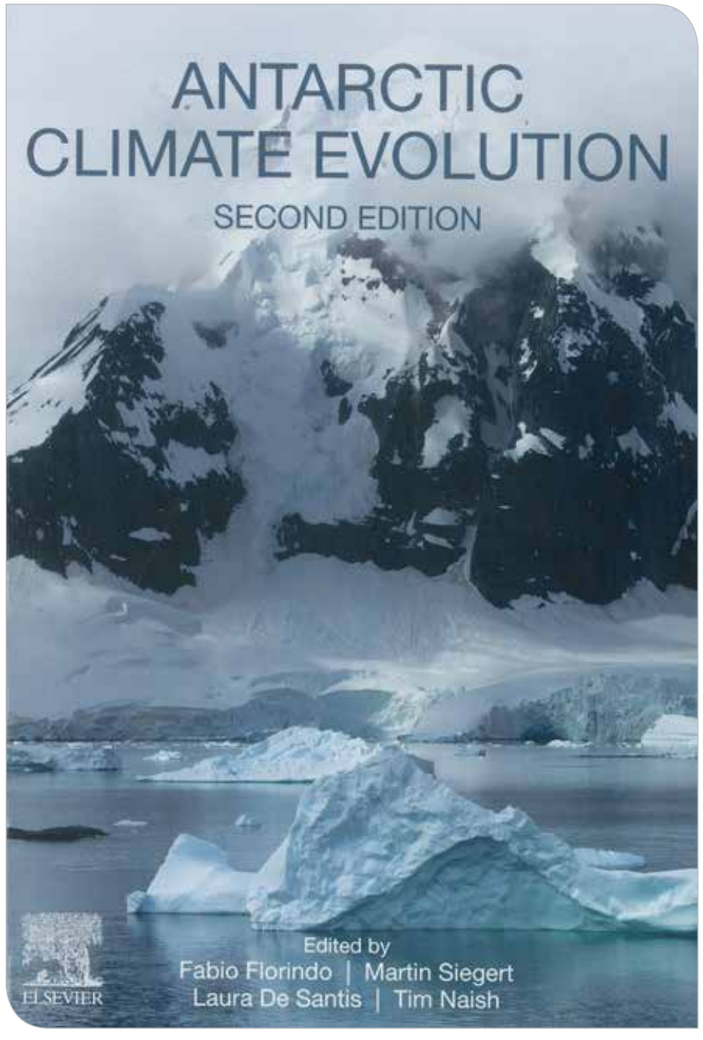
As the climate warms, the water cycle has to respond. One of the main reasons is that the amount of moisture in the air is a function of temperature—warmer air holds more moisture (water vapour)—about 7% more for each 1 °C of warming. So, when it rains, the rainfall amount will likely be larger, just because there is more water to condense and fall out of the air. At the same time, in a warmer climate, evaporation works more effectively, so land surfaces dry out faster, allowing droughts to develop more quickly and to last longer. Variability and extremes in precipitation are increasing faster than changes in averages.

Also as the climate warms, the tracks of storms move towards the poles in many regions, notably across the Southern Hemisphere. At the same time, the high-pressure regions in the subtropics are expand polewards. The net effects for New Zealand are that the west and south will see increases in precipitation in winter and spring, while the north and east will see reductions. Conversely, in the summer, the east is likely to see increases in rainfall while the west dries out a bit. And like elsewhere across the planet, ARC science indicates New Zealand glaciers will keep retreating (see page 15).

New book on Antarctic Climate Evolution

Two years of effort by the world's leading Antarctic researchers, including several from the ARC, has culminated in the release of a new 800 page book.

Antarctic Climate Evolution, will be a "go-to" reference for postgraduate students and researchers in Antarctic glaciology, climate change, paleoclimatology, and oceanography. Titled as a second edition, the book focuses on the last ten years of scientific advances since the first edition was published by SCAR's Antarctic Climate Evolution (ACE) programme. It really is staggering to see the breadth of collaboration and discovery from, ship-based drilling expeditions to the latest generation of ice sheet models. The book contains a series of state of the art reviews (chapters) on the evolution and behaviour of the Antarctic ice sheet with implications for its future response to global warming. It is a legacy product of SCAR's Past Antarctic Ice Sheet (PAIS) dynamics programme that comprehensively summarises the science advances made under its co-ordination. Co-Editors Tim Naish (NZ), Laura DeSantis (Italy), Martin Siegert (UK) and Fabio Florindo (Italy) are former leaders of PAIS and its predecessor programme ACE.



Along with Tim, fellow ARC researchers, Richard Levy, Rob McKay, Lionel Carter, Nick Golledge, and Bella Duncan took leading roles in writing a number of the chapters, and the book represents a major output for SCAR and the Antarctic Science Platform.

The prize for longest chapter and most comprehensive figures went to Richard Levy (134 pages) who covered the Miocene and Pliocene, narrowly beating Rob McKay's chapter which covered the entire Cenozoic history of Antarctic glaciation (124 pages).

While the book can be purchased online (https://www.elsevier.com/books/antarctic-climate-evolution/florindo/978-0-12-819109-5), pdfs of individual chapters are available from the lead authors upon request.

S.T. Lee Lecture in Antarctic Studies

Our annual lecture was given by a leading international speaker locked down in New Zealand when borders closed.

Terry Wilson presenting her lecture in the Hunter Council Chamber - Photo: VUW Image Services

The 18th Annual S.T. Lee Lecture in Antarctic Studies was presented by Professor Emerita Terry Wilson, from The Byrd Polar and Climate Research Center, The Ohio State University, USA on the 15 April.

Terry's lecture, 'Weighing the Antarctic ice sheet: A decade of geophysical imaging', explained a novel approach to understanding the loss of Antarctic ice by measuring the rate and pattern of bedrock deformation as the melting ice sheet 'loses weight', a process called 'glacial isostatic adjustment'. Measuring the solid Earth motions as it deforms using geodesy, and scanning the deep earth underlying the ice using seismology, provides a geophysical 'scale' to monitor weight change in the Antarctic ice sheets. It is now recognised that the changing shape of the deforming bedrock can alter how the ice sheets flow and how much ice is discharged to the surrounding oceans. Under certain conditions, these 'negative feedbacks' can stabilise ice sheet retreat and slow sea-level rise.

Terry Wilson, Coachella Valley, California, USA

Terry was a pioneer in using GPS to measure bedrock motion in Antarctica and has led over 25 field expeditions to Antarctica. She has been influential in training the next generation of polar scientists, mentoring over 40 students in Antarctic research, and organising multiple international training schools on polar science. Terry has held several high-profile leadership positions in polar science and is currently the delegate to SCAR (Scientific Committee on Antarctic Research) for the International Union of Geological Sciences.

Whilst in Wellington, as well as giving the public S.T. Lee Lecture, Terry also presented specialised lectures at GNS Science and to the School of Geography, Environment and Earth Sciences, she spoke with media, and participated in fieldtrips to Matiu/Somes Island and the Whanganui coast as part of a third year course.

New Modelling Hub Winter School

The Antarctic Science Platform National Modelling Hub recently held its inaugural "Winter School".

The National Modelling Hub Winter School - Photo: Alexandra Gossart

The National Modelling Hub Winter School was held on 18-19 October at Victoria University of Wellington's Pipitea campus after having to be postponed due to the COVID-19 lockdown in August. The two-day workshop consisted of a mix of lectures and hands-on interactive sessions focused on numerical modelling, data analysis, and computational techniques for Earth and climate sciences. Aimed at postgraduate students as well as ARC staff wishing to update and diversify their skill sets, it was an opportunity to learn practical skills not taught as part of the standard geoscience curriculum and to meet colleagues working in different subject areas. The workshop covered general principles of coding, climate models, time-series analysis, plotting in 3D, writing in Latex, and workflow and version control. Despite having a wide range of existing skills, from beginner to advanced, all participants indicated that they learned something new that they hope to be able to use in their future research. With a successful first run, plans are in place to hold the school again next winter.

ARC participation in COP26

ARC researchers were invited to speak at the 26th UN Climate Change Conference of the Parties (COP26).

In November 2021, the UN climate change conference, COP26, was held in Glasgow. This summit brings together politicians, scientists, and concerned citizens from around the world to work towards Paris Agreement goals of limiting global warming to 1.5°C above pre-industrial temperatures. Two researchers from the ARC gave remote presentations. As part of the IPCC suite of presentations at COP26, Nick Golledge presented the latest findings from AR6 regarding likely futures for the Antarctic climate, sea ice, and ice sheet. This overview was part of the 'Australasia' regional summary, but also went into some of the science behind the uncertainties of future Antarctic contributions to sea level. In the presentation, Nick showed figures from the report, including data from the AR6 Interactive Atlas. Following the presentation, Nick chaired a Q&A session on this theme, providing more detail on key areas of interest.

In a session focused on Southern Hemisphere glaciers, Lauren Vargo presented on the current state of New Zealand glaciers, which are melting at one of the fastest rates of any region in the world. Lauren included modelling results from Brian Anderson, showing that under different future warming scenarios, New Zealand will likely lose ~50-80% of glacier volume by 2100. Finally, Lauren highlighted the importance of New Zealand glaciers, including for water resources, hazards, tourism, snow sports, and culturally, and that our future emissions and policy will decide how much the ice melts over future decades.

Master's scholarship awarded in memory of Roger Cooper

In 2020, Victoria University alumni, Professor Emeritus James Kennett, gave a donation to the ARC in memory of his friend and colleague Dr Roger Cooper.

Life-long friends James Kennett (right) and Roger Cooper (left) - Photo: James Kennett

Roger Cooper and James Kennett were classmates at Victoria University of Wellington in the 1960's, Roger had conducted field work in Antarctica, and convinced James he should go the following year. In James's own words,

"It changed my life. Roger continued to inspire and encourage me in years to follow."

Roger was one of New Zealand's pre-eminent paleontologists. His contributions to our understanding of Zealandia's rich geological and paleontological histories are enormous. Roger, passed away on 2 March 2020.

The ARC decided to use the funds to support the next generation of paleoscientists, awarding the "Roger Cooper Masters Scholarship" to Emma de Jong. Emma's MSc project, starting in 2022, will use ancient molecular fossils called biomarkers, to look at phytoplankton in the Ross Sea. Using marine sediments and ice core samples to create a spatial distribution, this project will hopefully help extend the short, sparse records of past phytoplankton community composition and abundance. The scholarship will support Emma with her studies by providing full fees and a stipend and has increased her confidence pursuing an environmental science degree. In her thank you letter to James, Emma said,

"You have inspired me to continue in academia, and I hope that one day I can give back to the community like you have." — a fitting sentiment given the inspiration provided to James.

Roger Cooper Masters Scholarship recipient, Emma de Jong - Photo: Emma de Jong

Solving the mystery of our resident penguin

Ralph, the ARC's mummified penguin - Photo: Jeff Brass, GNS Science

For 15 years the ARC's mummified penguin has been visiting schools throughout the Wellington region, but when it died had always been a mystery, until now.

In 2007, a mummified Adélie penguin was rediscovered in a cupboard at Victoria University of Wellington and passed on to the ARC. Nicknamed Ralph, after Victoria University lecturer Ralph Wheeler who found the penguin in 1960 in Miers Valley, in the Dry Valleys of Antarctica, 35 km from open water and 450 m above sea level.

It's one of many mummified penguins and seals that have been found in the Ross Sea region and are thought to become lost and disorientated, and smelling water in the Dry Valleys, started upon a long journey in the wrong direction to eventually die of starvation. The cold, dry climate in Antarctica facilitates the preservation of the animals as it's too cold for bacteria or fungi to break down organic matter. Instead, the bodies eventually mummify and only break down due to physical erosion from wind and sand. Ralph was sheltered from these harsh conditions and as a result is relatively well-preserved, only missing a few feathers and the colouration in its feathers. The ARC sent Ralph to a local artist to be installed into its current display box home and has been taken to outreach events for kids ever since.

But one question remained—how long ago did Ralph die? So, in August, Ralph was sent off to the Rafter Radiocarbon Laboratory at GNS Science in hopes of finding out. To do this, the Rafter Radiocarbon team carefully sampled Ralph's feathers. These feathers were chemically treated to remove any contaminants, combusted to CO_2, then converted into graphite, which was measured in the Accelerator Mass Spectrometer to measure the ^{14}C atoms. Only then, did we finally know when Ralph met its unfortunate fate.

The answer—results indicated Ralph died about 104 years ago in 1917. Interestingly this is the same year Sir Ernest Shackleton finally arrived back in England after his heroic expedition on the *Endurance*!

(Article modified from New Zealand Antarctic Society publication by Nikita Turton, GNS Science)

Awards and appointments

In 2021 ARC staff and students were awarded the following:

Awards

Hayden Young — Runner-up in the VUW 3 Minute Thesis Competition masters category.

Appointments

Nancy Bertler — Re-appointed as the Antarctic Science Platform Director for another four years.

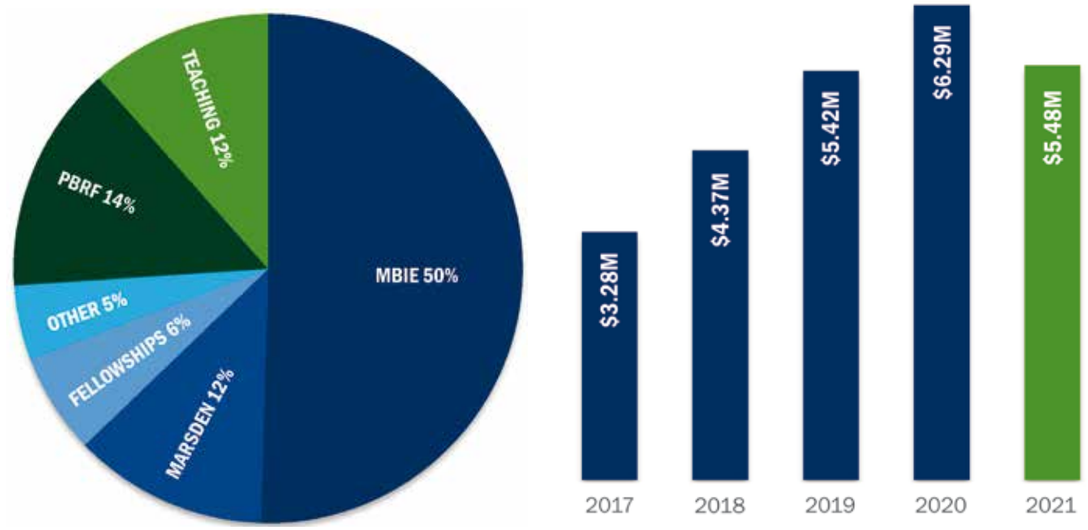
Darcy Mandeno — Appointed as Science Drilling Office Engineering Manager.

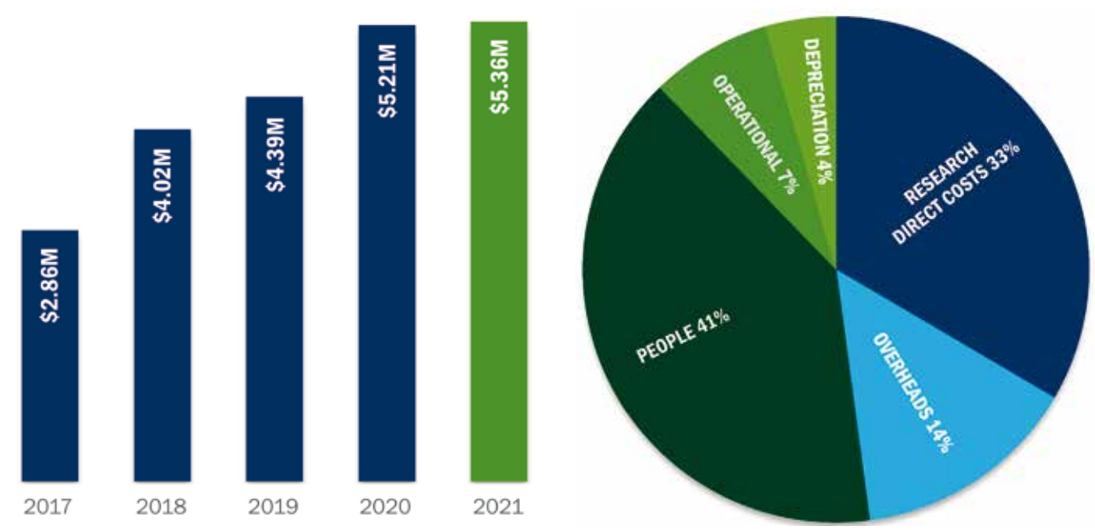
Tim Naish — Re-appointed as the Antarctic Science Platform Programme Leader: Physical Sciences for another four years.

FINANCIAL SUMMARY

In 2021, the ARC generated $5.5M in revenue, with a corresponding expenditure of $5.4M, contributed $756K of overheads to the University, and generated a $683K surplus.

The ARC finances include both a Centre budget and 49 grants held by the Research Trust of Victoria University of Wellington (RTV). Our consolidated revenue sources and expenditure areas as well as five year summaries are summarized in the charts below (all figures are exclusive of GST). These charts combine the Centre budget that operates over the University financial year (January-December) and RTV budgets which operate over the life of the projects, as such, the year-end balances for revenue versus expenditure are often out-of-phase.





Revenue

Although 2021 revenue was down on the previous year it would have been similar had 2020 not have had six months ($800K) of backdated funding for the Antarctic Science Platform.

In 2021, 73% of ARC revenue came from external funding. The majority (50%; $2.7M) was from Ministry of Business, Innovation, and Employment (MBIE) contracts direct to VUW or via subcontracts with our research partners. Our other external funding came from three active Marsden grants (12%; $672K), five Rutherford Fellowships (6%; $348K), and 'Other' national and international sources (5%; $296K) such as, the New Zealand Antarctic Research Institute, Royal Society Te Apārangi Catalyst Fund, and private donations held by the Victoria University of Wellington Foundation, and transferred to the Centre for the ARC Endowed Development Fund and Arnold Heine Antarctic Research awards.

The remaining revenue comes from other sources. PBRF (Performance-Based Research Fund) accounted for 14% ($788K) up by $200K from the previous year. The ARC received 12% ($628K) from Teaching by way of EFTS (Equivalent Full-Time Student) for teaching and coordinating School of Geography, Environment and Earth Sciences courses and tuition fees for supervising postgraduate students.

Expenditure

Our expenditure is divided between costs incurred directly within the RTV grants, and those from the Centre budget.

Research Direct Costs (33%; $1.75M) includes $891K of subcontracts to our research partners; $489K to support student fees and stipends; and $86K towards analytical costs. The remaining $289K supported costs such as fieldwork, consumables, and domestic travel.

The overhead contribution to the Research Office and University was 14%; $756K.

The Centre direct costs include people related costs associated with salaries, annual leave and superannuation (41%; $2.21M).

The Centre's operational costs (7%; $399K) were $65K less than the previous year and included; $211K to cover office and workshop space charges, $77K for research related costs that were either reimbursed from external organisations or transferred to grants, and $40K for IT related costs, leaving $71K for general operational costs such as office supplies, catering, printing, training courses, and domestic travel.

The final 4% ($237K) of expenditure is for depreciation of CAPEX equipment, this increased by $73K from the previous year due to new equipment associated with the Antarctic Intermediate Depth Drill.

Overall, 2021 expenditure was slightly higher than the previous year, and less than our revenue for the same period.

Marsden success for ARC researchers

The ARC had two successfully funded Marsden grants in the 2021 round awarded by the Royal Society Te Apārangi.

Holly Winton's project *"How did changing sea ice conditions impact primary production in the Ross Sea over the past 200 years?"* was awarded a $360K Marsden Fast-Start to assess the impacts of changing sea ice conditions on Ross Sea primary production over the past 200 years. Dramatic and unexplained changes in sea ice conditions in the Ross Sea have been observed over the last decade. Sea ice is one of the major factors driving seasonal phytoplankton blooms which play a crucial role in modulating climate through marine carbon sequestration and the radiation budget. Combining biogenic aerosol observations, phytoplankton biomarker records from ice cores and biogeochemical modelling, this project will extend the short observational records of primary production and sea ice to quantify sea ice-primary production relationships.

The team includes biogeochemical modeller Angela Bahamondes Dominguez from the Antarctic Science Platform National Modelling Hub and NIWA. The team is also made up of atmospheric chemists, atmospheric physicists and paleoclimatologists from the University of Waikato, the British Antarctic Survey, the University of Cambridge and the Spanish Institute of Marine Science.

Holly Winton in the National Ice Core Facility, GNS Science - Photo: VUW Image Services

Our other success *"Can snow change the fate of Antarctic sea ice?"* was a $913K Standard Marsden awarded to Ruzica Dadic to investigate the role of snow cover on the evolution of Antarctic sea ice to test the hypothesis that a persistent snow cover could prevent, or slow, a decline of Antarctic sea ice in response to a warming climate. Because of its highly insulating and reflective properties, snow cover on sea ice dominates the energy fluxes between the ocean and the atmosphere, yet data on the physical properties of snow and its effects on sea ice are limited. This lack of data leads to significant biases in model representation of sea ice variables and large uncertainties in how sea ice influences global climate.

This Marsden project will combine field and laboratory measurements with multi-scale modelling to improve the representation of snow processes in predictive models of sea ice evolution in the context of climate change. This project will also help publish a children's picture book that combines Māturanga Māori and Antarctic snow/ice science.

Ruzica Dadic in the Arctic - Photo: Lianna Nixon

Arnold Heine Antarctic Research Award

The 2021 Arnold Heine Antarctic Research Award recipient was recent MSc graduate Emily Moore.

Emily used the funds to write and eventually publish an academic paper based on her MSc thesis. Her thesis, titled 'The glacial history of Rocky Top cirque, southeast Fiordland, New Zealand', studied Rocky Top cirque, a presently non-glaciated site that has evidence of past glaciation in the form of moraine sequences. Moraines are ridges of glacier debris that form at ice margins. As mountain glaciers are sensitive to climate, changes in climate are expressed in glacier length fluctuations recorded by moraine deposits. These moraine records offer the potential to reconstruct past climates in order to extend existing instrumental climate records, which are especially limited in the Southern Hemisphere. The aims of Emily's thesis were (i) to constrain the timing and magnitude of past glacier length changes at Rocky Top cirque, and (ii) to derive a quantitative estimate of paleoclimate. She achieved these aims by utilisation of a combination of geomorphic mapping, cosmogenic ^{10}Be surface exposure dating and modelling of the former glacier surface (equilibrium-line altitude reconstruction).

Emily Moore taking measurements at Rocky Top cirque, New Zealand - Photo: Emily Moore

Emily's research demonstrated that the Rocky Top cirque glacier exhibited periods of re-advance or standstills within an overall pattern of glacier retreat between ~19,000 and 17,000 years ago. These insights are significant for determining the dominant drivers of climate and glacier length changes during the pre-industrial era, providing an important baseline for assessing present-day anthropogenic climate change.

The Arnold Heine Antarctic Research Award was established in 2018 with a generous donation from glaciologist Arnold Heine to support future generations of Antarctic researchers.

ARC Endowed Development Fund awards

The ARC Endowed Development Fund awards small grants of up to $4,000 to postgraduate students with research links to Antarctica.

The awards provide students with opportunities that would not have otherwise been possible. Examples include; participation in international summer schools, the opportunity to work with collaborators in world-class analytical facilities, and the ability to travel to international conferences and workshops to present their scientific discoveries on a world-stage.

Due to COVID-19 travel restrictions, only two awards were funded. The 2021 recipients were:

Theo Calkin (MSc, ARC/SGEES) to write-up a paper on his research for submission to a journal.

Jacqui Stuart (PhD, School of Biological Sciences) to support DNA metabarcoding/sequencing analyses.

PUBLICATIONS AND PRESENTATIONS

Peer-reviewed publications

Anderson, B., Mackintosh, A.N., **Dadic**, R., Oerlemans, J., Zammit, C., Doughty, A., Sood, A., Mullan, B. (2021). Modelled response of debris-covered and lake-calving glaciers to climate change, Kā Tiritiri o te Moana/Southern Alps, New Zealand. *Global and Planetary Change* 205: doi. org/10.1016/j.gloplacha.2021.103593

Ashley, K.E., **McKay**, R., Etourneau, J., Jimenez-Espejo, F.J., Condron, A., **Albot**, A., Crosta, X., Riesselman, C., Seki, O., Massé, G., **Golledge**, N.R., Gasson, E., Lowry, D.P., Barrand, N.E., **Johnson**, K., **Bertler**, N., Escutia, C.,Dunbar, R., Bendle, J.A. (2021). Mid-Holocene Antarctic sea-ice increase driven by marine ice sheet retreat. *Climate of the Past* 17: 1-19. doi: /10.5194/cp-17-1-2021

Baumann, S., **Anderson**, B., Chinn, T., Mackintosh, A., Collier, C., Lorrey, A.M., Rack, W., Purdie, H., **Eaves**, S. (2021). Updated inventory of glacier ice in New Zealand based on 2016 satellite imagery. *Journal of Glaciology* 67(261): 13-26. doi: 10.1017/jog.2020.78

Bradwell, T, Small, D., Fabel, D., Clark, C.D., Chiverrell, R.C., Saher, M.H., Dove, D., Callard, S.L., Burke, M.J., Moreton, S.G., Medialdea, A., Bateman, M.D., Roberts, D.H., **Golledge**, N.R., Finlayson, A., Morgan, S., Cofaigh, C. (2021). Pattern, style and timing of British–Irish Ice Sheet retreat: Shetland and northern North Sea sector. *Journal of Quaternary Science* 36(5): 681-722. doi: 10.1002/JQS.3163

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Invited presentations

Eaves, S. (2021). Climate reconstruction from New Zealand glaciers: A 10-year tenure (Keynote). *Australasian Quaternary Association* Conference, virtual, 9 July 2021.

Golledge, N. (2021). Latest findings from IPCC regarding Antarctic climate, sea ice and ice sheets. *COP26*, virtual, 8 November 2021.

McKay, R. (2021). History and future of the Antarctic Research Centre. *Polar Educators International, Equinox Share-a-thon*, virtual, 22-23 September 2021.

Naish, T. (2021). Climate and the cryosphere (CLiC) annual report and new strategic plan. *42nd Meeting of the Joint Scientific Commission of the World Climate Research Programme*, virtual, 27 June 2021.

Vargo, L. (2021). Climate change, New Zealand glaciers and implications. *Cryosphere Pavilion at COP 26*, virtual, 8 November 2021.

Student oral presentations

Alevropoulos-Borrill, A., **Golledge**, N., and Cornford, S. (2021). Mitigating future sea level rise through regrowth of the Amundsen Sea glaciers: Is it possible and what will it take? *New Zealand Antarctic Science Conference*, Christchurch, New Zealand, 9-13 February 2021.

Borzecki, J., **Vargo**, L., **Dadic**, R., **Anderson**, B., Zammit, C. (2021). The impact of glacier retreat on long-term water availability in the Waitaki Catchment, New Zealand. *The Snow and Ice Research Group Workshop*, Christchurch, New Zealand, 9-13 February 2021.

Calkin, T., **Dunbar**, G., Lawrence, J., Schmidt, B., Harwood, D., Martin, A., Ginnane, C., Turnbull, J., Meister, M., Washam, P., Hurwitz, B., Quartini, E., Dichek, D., Mullen, A., Spears, A., Atkins, C. (2021). Past and present sedimentation at Kamb Ice Stream Grounding Zone, Siple Coast, West Antarctica. *New Zealand Antarctic Science Conference*, Christchurch, New Zealand, 9-13 February 2021.

Henson, K., **Winton**, H., Clem, K., Frey, M., Mulvaney, R. (2021). Simulating size-resolved atmospheric dust transport to Dronning Maud Land, Antarctica. *Blowing South: Southern Hemisphere Dust Symposium*, virtual, 8-10 November 2021.

Tankersley, M., Caratori Tontini, F., **Horgan**, H., Tinto, K., Siddoway, C. (2021). Sediment thickness and basement depths beneath the Ross Ice Shelf from aeromagnetic data. *New Zealand Antarctic Science Conference*, Christchurch, New Zealand, 9-13 February 2021.

Tielidze, L., **Eaves**, S., Norton, K., Mackintosh, A. (2021). Glacial geomorphology of the Ahuriri River valley, New Zealand. *15th International Young Geomorphologists' Meeting*, virtual, 24-25 June 2021.

Tielidze, L., **Eaves**, S., Norton, K., Mackintosh, A. (2021). Timing and extent of Late Quaternary glaciation in the Ahuriri River valley, Southern Alps, New Zealand. *EGU General Assembly*, virtual, 29 April 2021.

Tielidze, L., Nossenko, G., and Khromova, T. (2021). The new Caucasus Glacier Inventory. Alpine Glaciology Meeting, virtual, 25-26 March 2021.

Whiteford, A. and **Horgan**, H. (2021). Observations of a deep basal channel at the Kamb Ice Stream. *New Zealand Antarctic Science Conference*, Christchurch, New Zealand, 9-13 February 2021.

Student poster presentations

Baldacchino, F., **Golledge**, N., **Horgan**, H., **Jendersie**, S., Christoffersen, P., Bromirski, P. (2021). Investigating the seasonal dynamics of the Ross Ice Shelf, Antarctica using remote sensing data. *New Zealand Antarctic Science Conference*, Christchurch, New Zealand, 9-13 February 2021.

Henson, K., **Winton**, H., Clem, K., Frey, M., Mulvaney, R., Renwick, J., **Bertler**, N. (2021). Dusty 20-21st century Antarctica: Change in Southern Hemisphere extratropical climate? *New Zealand Antarctic Science Conference*, Christchurch, New Zealand, 9-13 February 2021.

Leong, W. and **Horgan**, H. (2021). Spatiotemporal variability of active subglacial lakes in Antarctica from 2018-2020 using ICESat-2 laser altimetry. *New Zealand Antarctic Science Conference*, Christchurch, New Zealand, 9-13 February 2021.

Tankersley, M., Siddoway, C., **Horgan**, H., Caratori-Tontini, F., Tinto, K. (2021). New contribution to Ross Ice Shelf (Antarctica) boundary conditions: Basement depths and sediment thickness determined from aeromagnetic data. *American Geophysics Union Fall Meeting*, virtual, New Orleans, USA, 13-17 December, 2021.

MEDIA AND COMMUNITY ENGAGEMENT

TV interviews

Newsroom — 30 January, Nick Golledge, *"Science leaves no wiggle room for climate 'balance'."* https://www.newsroom.co.nz/science-leaves-no-wiggle-room-for-climate-balance

Swiss TV — 1 April, Ruzica Dadic, *"Expedition Arktis."*

Newsroom — 18 April, Holly Winton, *"What marine algae means for our climate emergency."* https://www.newsroom.co.nz/ideasroom/what-marine-algae-means-for-our-climate-emergency

TVNZ 'Breakfast' — 1 July, Tim Naish, *"World can expect 50 cm sea-level rise by 2100, even if warming stays under 2 °C."* https://www.tvnz.co.nz/shows/breakfast/clips/world-can-expect-50cm-sea-level-rise-by-2100-even-if-warming-stays-under-2-c

Newshub — 9 August, Nick Golledge, *"United Nations sounds clarion call over 'irreversible' climate impacts by humans."* https://www.newshub.co.nz/home/world/2021/08/united-nations-sounds-clarion-call-over-irreversible-climate-impacts-by-humans.html

Newshub — 10 August, Lauren Vargo, *"Climate change: What the new IPCC report says is in store for New Zealand."* https://www.newshub.co.nz/home/new-zealand/2021/08/climate-change-what-the-new-ipcc-report-says-is-in-store-for-new-zealand.html

Newshub — 10 August, Nick Golledge, *"Opinion: The longer we wait, the more devastating the consequences - why action on climate is needed now."* https://www.newshub.co.nz/home/world/2021/08/opinion-the-longer-we-wait-the-more-devastating-the-consequences-why-action-on-climate-is-needed-now.html

TVNZ 'Breakfast' — 12 August, Nick Golledge, on IPCC AR6: Sea-level rise projections.

Newshub — 9 November, Richard Levy, Tim Naish & Rob McKay, *"Climate change: Why scientists are about to drill a kilometre-deep hole into the Antarctic ice."* https://www.newshub.co.nz/home/new-zealand/2021/11/climate-change-why-scientists-are-about-to-drill-a-kilometre-deep-hole-into-the-antarctic-ice.html

Newsroom — 10 November, Tim Naish, *"NZ goes from innovator to handwringer on climate."* https://www.newsroom.co.nz/climate-change/nz-goes-from-innovator-to-handwringer-on-climate

TVNZ 'One News' — 18 November, Alanna Alevropoulos-Borrill & Nancy Bertler, *"All-women team of scientists head to Antarctica from NZ for the first time."* https://www.1news.co.nz/2021/11/18/all-women-team-of-scientists-head-to-antarctica-from-nz-for-first-time/

Newshub — 20 December, Nancy Bertler, "Importance of sea ice and relevance of EM-bird measurements."

Stuff Play 'Water' — Tim Naish, "Sea level rise." https://play.stuff.co.nz/details/_6234749360001

Radio interviews

RadioNZ 'Our Changing World' — 4 March, Shaun Eaves, *"Glaciers as barometers of climate change."* https://www.rnz.co.nz/national/programmes/ourchangingworld/audio/2018783809/glaciers-as-barometers-of-climate-change

RadioNZ 'Saturday Morning' — 17 April, Terry Wilson, S.T. Lee Lecturer, *"Antarctica's bedrock rising as ice melts."* https://www.rnz.co.nz/national/programmes/saturday/audio/2018791965/terry-wilson-antarctica-s-bedrock-rising-as-ice-melts

RadioNZ 'In brief: News from around the Pacific' — 28 April, Rob McKay, *"Academic wants bigger emissions cuts."*

RadioNZ 'Morning Report' — 29 April, Lauren Vargo, *"Accelerated global glacier mass loss in the early twenty-first century."* https://www.rnz.co.nz/national/programmes/morningreport/audio/2018793420/nz-losing-glaciers-at-record-speeds

NewstalkZB — 21 May, Nancy Bertler, *"Budget 2021: Scott Base investment 'welcome news'."* https://www.newstalkzb.co.nz/on-air/early-edition/audio/nancy-bertler-scott-base-investment-in-budget-welcome-news/

RadioNZ 'Nights'— 22 June, Lauren Vargo, *"Snow and our changing climate."* https://www.rnz.co.nz/national/programmes/nights/audio/2018800872/snow-and-our-changing-climate

RadioNZ 'News' — 10 August, Nick Golledge, *"Rising seas and melting glaciers: Changes now irreversible but we have to act to slow them down."* https://www.rnz.co.nz/news/on-the-inside/448840/rising-seas-and-melting-glaciers-changes-now-irreversible-but-we-have-to-act-to-slow-them-down

RadioNZ 'Morning Report'— 8 October, Holly Winton, *"Researchers link 700-year-old soot found in Antarctica to fires set by early Māori."* https://www.rnz.co.nz/news/te-manu-korihi/453171/researchers-link-700-year-old-soot-found-in-antarctica-to-fires-set-by-early-maori

RadioNZ 'Midday Report'— 19 November, Nick Golledge, *"Antarctica ice melt reaches a tipping point."* https://www.rnz.co.nz/national/programmes/middayreport/audio/2018821233/antarctica-ice-melt-reaches-a-tipping-point

Newspaper/magazine articles

Stuff — 13 February, Theo Calkin, *"More plants could begin to 'invade the Antarctic Peninsula' as the frozen continent warms."* https://www.stuff.co.nz/national/education/124176857/more-plants-could-begin-to-invade-the-antarctic-peninsula-as-the-frozen-continent-warms

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Olya Albot	PhD	Coastal modelling	*thesis submitted for examination in 2021
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James Renwick	School of Geography, Environment and Earth Sciences	Atmospheric circulation
Tim Stern	School of Geography, Environment and Earth Sciences	Transantarctic Mountains geophysics

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Robert Dunbar	Stanford University	Ocean chemistry
Katelyn Johnson	GNS Science	Paleoenvironmental reconstruction
Daleen Koch	GNS Science	Project Management
Mario Krapp	GNS Science	Data scientist
Dave Lowe	LoweNZ Ltd	Atmospheric chemistry
Dan Lowry	GNS Science	Numerical modeller
Andrew Mackintosh	Monash University	Glaciology and modelling
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Mike Williams	NIWA	Physical oceanography
Terry Wilson	The Ohio State University	Tectonics and Antarctic geology
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Return flight home, Antarctica - Photo: Matt Tankersley

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