Proceedings of the

New Zealand Snow and Ice Research Group

2019 Workshop
Kurow Holiday Park, Otago
20 – 22 February

Trevor Chinn on his final end of season snowline survey flight.
Photo credit: Andrew Lorrey, 2018.

Foreword

The 2019 New Zealand Snow and Ice Research Group workshop was held at:

Kurow Holiday Park, Kurow
On: 20 – 22 February, 2019

Organising Committee:

Shona Mackie
Inga Smith
Pat Langhorne
Kelly Gragg
Greg Leonard

Student Judging Panel:

Jono Conway
Oliver Marsh
Dave Prior

First Aiders:

Gemma Brett
Eamon Frazer
Kelly Gragg
Greg Leonard

The annual meeting of the New Zealand Snow and Ice Research Group provides an opportunity to meet and discuss our common interest in snow and ice research.
The New Zealand Snow and Ice Research Group (SIRG) are those people who have registered on the "SIRG" email group at: https://lists.vuw.otago.ac.nz/mailman/listinfo/sirg. SIRG maintains a website at: http://sirg.org.nz/.
SIRG is the New Zealand branch of the International Glaciological Society: http://www.igsoc.org/.
SIRG maintains an on-line bibliography of New Zealand snow and ice research publications: https://www.zotero.org/groups/sirg/items.

SIRG 2019 Programme

Wednesday, 20 February 2018

13:30	*Accommodation allocations*	
14:00	Welcome	Shona Mackie (UO)

Session 1: Snow and Volcanic Processes Chair: Jessie Lindsay Co-Chair: Brian Anderson

14:15	Potential climate change impacts on snow in New Zealand	Christian Zammit (NIWA)	Page 1
14:30	Assessing climate change impacts on New Zealand's frozen water resources	Jono Conway (BS)	Page 2
14:45	The influence of atmospheric circulations on snowfall in the Southern Alps	Rasool Porhemmat (UC)	Page 3
15:00	What can a drone tell us about snow depth?	Todd Redpath (UO)	Page 4
15:15	HMRF-based snow mapping with MODIS observations	Hongxing Liu (UAT)	Page 5
15:30	*Afternoon coffee break*		

Session 2: New Zealand Glaciers Chair: Gemma Brett Co-Chair: Christian Zammit

16:15	Projected 21st Century glacier change in New Zealand	Brian Anderson (VUW)	Page 6
16:30	The development and calibration of a distributed glacier mass balance model for Brewster Glacier	Hamish Prince (UO)	Page 7
16:45	Attribution of New Zealand glacier mass loss to natural and anthropogenic forcings	Lauren Vargo (VUW)	Page 8
17:00	Processes and feedbacks associated with near-terminus calving and subaqueous terminus morphology, Tasman Glacier, New Zealand	Jessie Lindsay (UC)	Page 9
17:15	A finite-element approach for investigating basal friction during episodes of accelerated sliding at Haupapa/Tasman Glacier	Clarrie Macklin (VUW)	Page 10

18:30	*Dinner preparations – please help*
19:30	*Dinner – please help clean up after*

Thursday, 21 February 2018

07:30	*Breakfast – please help with preparation and clean up*

Session 3: Antarctic Sea Ice and Glaciers Chair: Lauren Vargo Co-Chair: Tim Kerr

09:00	Influence of Southern Hemisphere atmospheric variability on recent sea ice concentration in East Antarctica	Florence Isaacs (VUW)	Page 11
09:15	Variability in the distribution of fast ice and the sub-ice platelet layer near an Antarctic ice shelf	Gemma Brett (UC)	Page 12
09:30	Sea ice thickness distribution in the Ross Sea: airborne EM sounding and earth system modelling	Pat Langhorne (UO)	Page 13
09:45	Winter sea ice and sub-ice platelet layer growth rates from a sea ice mass balance station	Greg Leonard (UO)	Page 14
10:00	Characterising frazil ice populations using acoustic techniques	Eamon Frazer (UO)	Page 15
10:15	Seismology of an active shear margin: Priestley Glacier, Antarctica	Dave Prior (UO)	Page 16
10:30	*Morning coffee break*		

Session 4: Antarctic Ice Shelves and Glaciers Chair: Todd Redpath Co-Chair: Stefan Jendersie

11:00	Understanding the Amery: effects of marine ice on ice shelf dynamics and stability	Lisa Craw (UT)	Page 17
11:15	Replicating RIS Rifts (RRR)	Martin Forbes (UO)	Page 18
11:30	Glaciological context of the HWD-2 borehole on the Ross Ice Shelf	Kelly Gragg (UO)	Page 19
11:45	Stress, strain and fracture on the Brunt Ice Shelf	Oliver Marsh (BAS)	Page 20
12:00	Tidal variability of ice dynamics in the grounding zone of the Priestley Glacier, Antarctica, based on observation and modeling	Christian Wild (UC)	Page 21
12:15	Patterns and lake formation on a flat-bedded model ice sheet	Arran Whiteford (VUW)	Page 22
12:30	*Lunch – please help with preparation and clean up*		

Session 5: Sea Ice, Climate and Geoparks Chair: Christian Wild Co-Chair: Dan Price

14:00	Climate change and sea ice linkages	Inga Smith (UO)	Page 23
14:15	Effects of increasing mass loss from Antarctica on ocean and sea ice properties	Shona Mackie (UO)	Page 24
14:30	Representing sea ice form drag more accurately in climate models	Ben Craven (UO)	Page 25
14:45	Gearing up New Zealand's Ocean and Sea Ice Modelling	Stefan Jendersie (VUW)	Page 26
15:00	Should the New Zealand dairy industry care about climate change?	Alice Hill (U Colorado)	Page 27
15:15	Waitaki Whitestone Geopark: UNESCO global geopark in the making	Sophie Briggs (UO / Geopark)	Page 28
15:30	*Afternoon coffee break*		

Trevor Chinn tribute, Chair: Inga Smith

16:00	Trevor Chinn tribute	Andrew Lorrey, Brian Anderson and Tim Kerr	Page 29

Student prize giving, SIRG 2020 + field trip briefing, Chair: Inga Smith

17:00	Student prize giving + SIRG 2020 planning
17:30	*Briefing for Friday field trip*
18:15	*Conference dinner at Waitaki Braids*

Friday, 22 February 2018

07:00	*Breakfast – please help with preparation and clean up*
08:00 – 15:00	*Field trip, finishing at Round Bush Campsite*
15:30	*Vans depart for Otago and Canterbury*

ABSTRACTS

POTENTIAL CLIMATE CHANGE IMPACTS ON SNOW IN NEW ZEALAND

Zammit, C.[1], Conway, J. P.[1,2,3], Anderson, B.[4], Cullen, N. J.[3], Dadić, R.[4], Kerr, T.[5], Mackintosh, A.[4], Purdie, H.[6], Redpath, T.[3], Sirguey, P.[3]
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Mountain ranges are the world's natural water towers and provide water resources across many sectors of activities in New Zealand (e.g. hydropower, primary sector for irrigation, water supply). Over the 21st century, New Zealand is projected to warm by 1-4°C by 2100, while corresponding precipitation change are more variable. As part of the Deep South Hydrology project, climate change impact on Cryosphere are explored.

Potential future climate was modelled with six different global climate models (GCMs), which have been dynamically downscaled to the New Zealand region. Four different possible futures (characterized as representative concentration pathways or RCPs) were modelled with each GCM over the period 1971-2100 to drive the catchment scale distributed hydrological model TopNet, which includes a catchment scale snow model.

In this talk we report on progress towards assessing potential climate change impact on different hydrological and snow signatures across spatial and temporal scales.

ASSESSING CLIMATE CHANGE IMPACTS ON NEW ZEALAND'S FROZEN WATER RESOURCES

Conway, J. P.[1,2,3], Anderson, B.[4], Cullen, N. J.[3], Dadic, R.[4], Kerr, T.[5], Mackintosh, A.[4], Purdie, H.[6], Redpath, T.[3], Sirguey, P.[3], Zammit, C.[2]
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Glaciers and seasonal snow are major reservoirs in the hydrological cycle, and make a significant contribution to river flows in the North and South Islands of New Zealand. Mountain rivers feed our largest hydro-electric power schemes, and provide critical water for irrigation, especially during drought. Rain-on-snow can also cause increased flood intensity. New Zealand is projected to warm by 1-4°C during the 21st Century. While warming will lead to loss of frozen water resources, the magnitude, timing, and distribution of changes in meltwater is unclear. The Deep South 'Icey' project aims to make improved future projections of glacier and snow melt from New Zealand's alpine regions. In this talk we report on progress towards developing and testing an enhanced temperature index snow model that will be used to model future snow melt. Point scale evaluation using the detailed metrological and glaciological measurements available at Brewster Glacier have allowed baseline parameters to be selected and parameter sensitivity to be investigated. Regional-scale evaluation against remotely-sensed fractional snow-covered area retrieved from MODIS measurements been performed in the Clutha catchment. This evaluation has shown the quality of these snow simulations is very sensitive to the climate model inputs and historical climate data used to train the models.

THE INFLUENCE OF ATMOSPHERIC CIRCULATIONS ON SNOWFALL IN THE SOUTHERN ALPS

Porhemmat, R.[1], Purdie, H.[1], Zawar-Reza, P.[1], Zammit, C.[2], Kerr, T.[3]
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Atmospheric circulations largely control snowfall events and their associated conditions such as temperature, precipitation, and cloudiness (Bednorz and Wibig, 2016). Synoptic classification that identifies relationships between the larger scale atmospheric circulation and the smaller scale surface environment has been found a useful tool to study the hydrometeorology of the mountain catchments (Yarnal *et al*., 2001). However, our knowledge of the atmospheric patterns leading to large snowfall events in the Southern Alps is limited. This study makes an endeavor to investigate the synoptic conditions of snow accumulation across the Southern Alps. The Snow and Ice Monitoring Network (SIN) was used to obtain snow observations at three sites, namely Mueller Hut, Mt Larkins and Mahanga. The meteorological fields including 500 and 850 hPa geopotential heights and temperature and sea level pressure, retrieved from the ECMWF ERA-Interim dataset, were used to construct composite maps for sea level pressure, 500 hPa geopotential and temperature and 850 hPa temperature during the heavy snowfall events.

The results indicate that snowfall events are associated with negative anomalies of sea level pressure and positive anomalies of geopotential at 500 hPa over the Southern Alps. Anomalies of air temperature at the isobaric level of 850 hPa show that days of heavy snowfall are related to positive anomalies which can be explained by cyclonic activities. These findings accompanied by data from automated weather stations and snow observations in mountainous terrains of the Southern Alps can be used to understand the relationship between atmospheric circulation and topographic controls leading to heavy snowfall.

WHAT CAN A DRONE TELL US ABOUT SNOW DEPTH?

Redpath, T.[1], Sirguey, P.[1], Cullen, N. J.[2], Fitzsimons, S. J.[2]
[1]*National School of Surveying, University of Otago, Dunedin, New Zealand*
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Dynamic in time and space, seasonal snow represents a difficult target for ongoing *in situ* measurement and characterisation, which in turn hampers efforts to accurately model seasonal snow and associated processes. This study exploits high resolution snow depth data, captured by a remotely piloted aircraft system (RPAS) to resolve patterns of spatial variability in snow depth, and asses the role of associated topographic controls. The Trimble UX5 RPAS was flown repeatedly over a small (0.4 km^2) alpine basin in the Pisa Range, Central Otago, during the winter and spring seasons of 2016 and 2017. Photogrammetric processing of imagery delivered high resolution ortho-mosaics (0.05 m GSD) and digital surface models (DSMs, 0.15 m GSD). Maps of snow depth (SD) were obtained by DSM differencing, whereby a reference (snow-free, captured in autumn) DSM was subtracted from a snow-covered DSM for each epoch. The spatial variability of snow depth within the basin was characterised by computing semi-variograms for snow depth at each epoch. Topographic controls were assessed via regression analysis between snow depth and popular terrain indices, including the topographic position index (TPI), relative solar exposure (RSE), and $S\bar{x}$ (upwind shelter or exposure of terrain). RPAS derived snow depth maps resolved the spatial distribution of snow well under both mid-winter and spring melt conditions. The range of spatial-autocorrelation for snow depth was comparable for both years at 20 – 30 m, despite greater observed spatial variability in snow depth for 2017. No significant direct relationships were found between snow depth and topographic controls, possibly an effect of the sampling scale and associated high variability in observed snow depth. Regression tree modelling, driven by TPI, RSE and $S\bar{x}$, however, performed well at reproducing the spatial distribution of snow depth. These results demonstrate the utility of high resolution snow depth mapping, and highlight the complex interactions between competing processes, such as wind redistribution and radiative forcings, on the evolution of seasonal snow cover in the Pisa Range.

HMRF-BASED SNOW MAPPING WITH MODIS OBSERVATIONS

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The snow cover products derived from Terra/Aqua MODIS images have been widely used for regional hydrological modelling, particularly for mountainous regions in the world. However, frequent clouds often lead to serious data gaps in snow products. We present a spatio-temporal modeling technique for filling up data gaps in daily snow cover estimates, based on time series of Terra/Aqua MODIS images. This technique exploits spectral, spatial and temporal contextual information within a Hidden Markov Random Field (HMRF) framework. We derived the extent, onset date, end date, and duration of snow cover in the Upper Rio Grande basin from 2002 to 2017 using MODIS daily snow products. Our HMRF technique reduced cloud-cover related data gaps from 32% to less than 1% and achieved a snow-mapping accuracy of 88.0% for the gap-filled areas. Our HMRF-based technique increased the snow product accuracy by 4.2% during the whole transition periods, and by 6.2% in March during snow melt. Seasonal pattern and interannual variation of snow cover during 2002-2007 are examined. The analysis results from this study would be useful for improving regional water resources management and understanding regional climate changes.

PROJECTED 21ST CENTURY GLACIER CHANGE IN NEW ZEALAND

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The changes in glacier volumes expected in coming decades will have profound impacts on alpine regions around the globe, with downstream impacts on water resources, sea-level rise and tourism. The Glacier Model Intercomparison Project (GlacierMIP) provides a framework for a coordinated intercomparison of global-scale glacier mass change models to foster model improvements and reduce uncertainties in global glacier projections. A number of recent global studies have used models of differing complexity to estimate rates of future glacier loss, but none take into account the processes of ice flow, debris-covered ice, and lake calving. A regional assessment of glacier change over the period 2005-2099 is carried out for the New Zealand Southern Alps/Kā Tiritiri o te Moana, using the GlacierMIP framework. The Randolph Glacier Inventory includes 3537 ice masses for the region, all of which are covered by 3135 glacier domains. A calibration procedure is used to match the mass balance in each glacier domain to the regional average mass balance for present-day conditions. Data from 16 global circulation models (GCMs) are downscaled using local climate data, and the anomalies from present day used to drive the glacier model using representative concentration pathways (RCP) 2.6, 4.5 and 8.5. The wide range of GCM output amongst the 16 models for each RCP means that there is overlap between glacier model output for different RCPs, but the glacier model volume means per RCP are significantly different from each other. The results show that mean ice loss is 20 % for RCP2.6, 50 % for RCP4.5 and 84 % for RCP8.5. This wide range of outcomes reflects the high sensitivity of Southern Alps glaciers to temperature warming. The results are compared to output from a number of different GlacierMIP models.

THE DEVELOPMENT AND CALIBRATION OF A DISTRIBUTED GLACIER MASS BALANCE MODEL FOR BREWSTER GLACIER

Prince, H. D.[1], Cullen, N. J.[1], Conway, J. P.[1], Sirguey, P.[1]
[1]*University of Otago, Dunedin, New Zealand*

The accurate assessment of glacier mass balance is fundamental to comprehend the ongoing changes in New Zealand's frozen water resource. Snow and ice form a major hydrological reservoir and provide an important contribution to New Zealand's fresh water consumption. The aim of this study is to develop and optimise a new distributed temperature index mass balance model for Brewster Glacier, a representative glacier in the Southern Alps of New Zealand. The performance of the model to reconstruct mass balance is considered by comparing the seasonal mass balance calculations to distributed *in-situ* glaciological measurements between 2004 and 2018.

An iterative least squares method is used to calibrate empirical components of the mass balance model to a point-based record of mass balance. Calibrated accumulation and ablation models produce Nash-Sutcliffe values of 0.82 and 0.75, respectively, calculating a cumulative mass balance to within 200 mm w.e. of the observed point-based mass balance over a two-year period (2010-2012). Calculated extraterrestrial irradiance allows an enhanced temperature-index ablation component to be forced with air temperature as the sole input variable without reducing the predictive power of the mass balance model. Modelled daily glacier wide mass balance indicates that net ablation may extend up to a month after the end-of-summer glaciological observations are made, underestimating seasonal ablation by a mean 565 mm w.e.

The spatial distribution of parameters calibrated at the point scale produces significant uncertainty, resulting in annual ablation at the lowest elevations of the glacier being underestimated by about 2000 mm w.e., while underestimating accumulation at the highest elevations of the glacier by at least 1000 mm w.e. Altitudinal variation due to a temperature lapse rate and shaded topography does not capture the observed variation in mass balance. The application of such a model at the national scale may not be suitable if empirical factors calculated at the point scale are unable to capture the variance in glacier wide mass balance.

ATTRIBUTION OF NEW ZEALAND GLACIER MASS LOSS TO NATURAL AND ANTHROPOGENIC FORCINGS

Vargo, L.[1], Anderson, B.[1], Horgan, H.[1], Mackintosh, A.[1], Dadić, R.[1], King, A.[1], Lorrey, A.[2]
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New Zealand glacier mass balance is directly measured for two glaciers and is monitored indirectly for 50 glaciers throughout the Southern Alps through the end-of-summer-snowline (EoSS) elevation. Measurements at Brewster and Rolleston Glaciers began in 2005 and 2011, respectively, and EoSS elevations have been monitored using aerial photography since 1978. These direct and indirect measurements show high interannual variability, with both positive and negative mass-balance years. However, in the past decade there have been two especially negative mass-balance years, 2011 and 2018, identified through measured negative balances and high EoSS elevations. The negative 2011 year is also highlighted by the retreat of Fox Glacier/Te Moeka o Tuawe and Franz Josef Glacier/K¯a Roimata o Hine Hukatere over the following 3 – 5 years.

We investigate the natural and anthropogenic influences contributing to the 2011 and 2018 negative mass-balance years. We use a degree-day model driven with a suite of existing general circulation model (GCM) output to simulate glacier mass balance. For multiple New Zealand glaciers, we compare the probability of negative mass balances, similar to those observed in 2011 and 2018, occurring in GCM simulations with a) natural forcings only, and b) both natural and anthropogenic forcings. Our results show that, for all glaciers, these negative mass-balance years are more likely to occur in a climate with anthropogenic forcing.

PROCESSES AND FEEDBACKS ASSOCIATED WITH NEAR-TERMINUS CALVING AND SUBAQUEOUS TERMINUS MORPHOLOGY, TASMAN GLACIER, NEW ZEALAND

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Global deglaciation is increasing the number and size of proglacial lakes, resulting in more glaciers losing mass via iceberg calving. In order to better estimate future ice volume change, we need to understand processes driving calving in fresh water environments. Some calving glaciers form subaqueous ice ramps or 'ice feet' due in part to differences in the rates of subaerial and subaqueous calving. Spatial and temporal variation of these subaqueous features indicate that other processes also exert control. Here we use photographic and satellite imagery combined with bathymetric and limnological surveys from Tasman Glacier (2013-2018) to explore the processes that drive spatial and temporal variability in ice berg calving and subaqueous terminus morphology, the relationships between near-terminus surface velocity, ice berg calving and subaqueous morphology; and the relationship between the spatial and temporal patterns of supraglacial ponds on the lower glacier terminus and near terminus velocity and subaqueous morphology.

To explore relationships between near-terminus surface velocity and calving processes Sentinel 2A and 2B images (n=36) were processed using the feature-tracking software Cosi-Cor to create maps of surface velocity from 2015 to 2018. Mean velocity values calculated for 3 regions, low, medium and high (~0.2, 1.0 and 2.5 km), from the calving face. The highest average velocity for the low, medium and high areas was 0.43, 0.41 and 0.47 $mday^{-1}$. Signal to Noise Ratio analysis of all images showed minimal to zero noise across Tasman Glacier, poor co-registration of pixels was consistent with clouded areas of the images and water bodies. An absolute minimum ice ramp melt rate (using the assumption that no subaqueous calving event took place for the ramps) ranged between 0.02 and 0.06 $mday^{-1}$ for the 2013-2014 ramps and 0.19 $mday^{-1}$ for a ramp identified over the 2015-2016 period. Other ice ramps identified from the surveys between 2014-2018 had increased in length between survey periods indicating the aerial calving rate was faster than the subaqueous melt and calving rates.

A FINITE-ELEMENT APPROACH FOR INVESTIGATING BASAL FRICTION DURING EPISODES OF ACCELERATED SLIDING AT HAUPAPA/TASMAN GLACIER

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The combined rate of ice loss from glaciers, ice caps, and ice sheets is a significant uncertainty in predicting sea level rise out to 2100. Short-term and long-term variability in glacial ice discharge contributes to this uncertainty because they are controlled by poorly constrained processes acting at the glacier's base. One such process is the interplay of subglacial water pressure and friction between ice and bedrock (which in models of ice flow is described through a sliding law). The rapid collection of water beneath a glacier is thought to elevate basal water pressure, reduce basal friction, and trigger episodes of enhanced sliding. Here, we present Global Positioning System (GPS) data from instruments on Tasman Glacier, South Island, New Zealand that record speed-up events following periods of heavy rainfall. During speed-ups, the correlation between horizontal and vertical GPS velocity indicates that peak sliding speed is coincident with the maximum rate of surface uplift. By removing uplift associated with the glacier's strain field, the remaining vertical motion is that generated by the expansion of water-filled subglacial cavities. However, the component of motion generated by the physical growth or collapse of cavities is not accounted for in commonly used sliding laws. Using a finite-element model to simulate the internal deformation and basal sliding of Tasman Glacier, we assess whether existing sliding laws are sufficient for reproducing observed surface motion or if a correction for the rate of change in cavity volume is required during rain-induced acceleration. Due to its pronounced speed-ups, Tasman Glacier is a useful case study for investigating the processes that govern the sliding rate of large glaciers prone to dynamic changes in basal conditions.

INFLUENCE OF SOUTHERN HEMISPHERE ATMOSPHERIC VARIABILITY ON RECENT SEA ICE CONCENTRATION IN EAST ANTARCTICA

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Antarctica's highly seasonal sea ice cover exerts substantial influence on the global climate system, however its recent variability and trends are not being accurately reproduced by models. This is in part because the processes that determine sea ice distribution are not yet well understood, particularly in the East Antarctic region. The aim of this study is to investigate the role that climate variability plays in determining sea ice concentration around East Antarctica, through an examination of the nearly 40-year satellite sea ice record, and climate reanalysis data. Satellite-derived HadISST2.0 monthly average sea ice concentration was compared to ERA-Interim climate reanalysis, including sea surface temperature and 500hPa geopotential height fields, and to the indices of prominent modes of climate variability, including El Nino Southern Oscillation (ENSO), the Southern Annular Mode (SAM), Zonal Wave 3 (ZW3), and the Indian Ocean Dipole (IOD), over the period 1979-2017. Time series analysis, trend analysis, and correlation mapping were used to unpick the sea ice-atmosphere relationship and how it varied both spatially and seasonally. Preliminary results indicate some moderate correlations between seasonally-averaged sea ice concentration and indices of each of the four climate modes (the strongest correlation coefficient being 0.5, with the Nino3.4 index), and that this experiences substantial seasonal and spatial variation around East Antarctica. It is hoped that the results of this study will allow greater understanding of the influence of atmospheric variability on sea ice concentration in East Antarctica, and will inform more accurate modelling of sea ice extent in the Southern Ocean.

VARIABILITY IN THE DISTRIBUTION OF FAST ICE AND THE SUB-ICE PLATELET LAYER NEAR AN ANTARCTIC ICE SHELF

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Interannual variability in the distribution and thickness of ice shelf influenced land-fast sea ice and the sub-ice platelet layer was investigated in McMurdo Sound in 2011, 2013, 2016 and 2017 with single-frequency ground-based electromagnetic induction (EM) and drill-hole surveys. EM surveying provided high-resolution measurements of thicker fast ice and a substantial sub-ice platelet layer in proximity to the ice shelf margin. Interannual variability was observed with a considerably thicker sub-ice platelet layer measured in 2011 and 2017. Fast ice formation during the winters of both 2011 and 2017 was influenced by a higher frequency of strong southerly wind events and resultant openings of the Ross Sea polynya. In contrast, calmer conditions in 2016 led to largely undisturbed thermodynamic sea ice growth and anomalously extensive fast ice coverage. A thinner sub-ice platelet layer was also observed in 2016. On shorter timescales, diurnal variability was observed in the thickness and distribution of the sub-ice platelet layer in 2011 and 2017 in a known region of exchange of water masses from the Ross Sea and the ice shelf cavity, which was not observed in 2013 or 2016. We hypothesize that variability of the winds, resultant polynya-activity and High Salinity Shelf Water production during winter could modify basal melting of the nearby McMurdo-Ross ice-shelf and thus the volume of supercooled Ice Shelf Water outflow and platelet ice formation in McMurdo Sound for a given year. On shorter timescales, changes in the sub-ice platelet layer could be driven by strong southerly wind events, polynya-induced circulation and the tides in McMurdo Sound.

SEA ICE THICKNESS DISTRIBUTION IN THE ROSS SEA: AIRBORNE EM SOUNDING AND EARTH SYSTEM MODELLING

Langhorne, P. J.[1], Leonard, G. H. [1], Frazer, E. [1], Williams, M. J. M. [2], Robinson, N. J. [2], Malyarenko, A.[1,2], Rack. W.[3], Brett, G. M.[3], Price, D.[3], Haas, C.[4], Cravens, B. [1], Smith, I. J. [1], Mackie, S.[1], Ridley, J. K.[5]
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There is increasing evidence that meltwater from the base of ice shelves influences sea ice extent. This process can drive seawater temperatures below the surface freezing point, when it is called Ice Shelf Water (ISW). Ice crystals then persist in the supercooled water and add to the mass of the coastal sea ice cover. The crystals may form a porous, friable layer, called the sub-ice platelet layer, which can be several metres thick beneath the two-metres of sea ice. Consequently platelet ice formation not only causes sea ice to be thicker, but it also alters the hydrostatic relationship between sea ice elevation and thickness, influencing satellite altimeter determination of sea ice thickness.

We focus on the SW Ross Sea in a location affected by an ISW outflow at the ocean surface, where we have conducted airborne sea ice thickness surveys using electromagnetic (EM) induction sounding. For a number of years these regional surveys have been supported over smaller geographic areas by detailed on-ice sea ice and snow thickness measurements, by on-ice EM induction transects of sea ice thickness, and by under-ice oceanographic observations that track the heat deficit and mixing in the upper ocean at selected sites. Thicknesses are compared with the output from a fully-coupled climate model, HadGEM3-GC3.1, in which various parameterizations of the roughness of the upper and lower ice boundaries are tested.

WINTER SEA ICE AND SUB-ICE PLATELET LAYER GROWTH RATES FROM A SEA ICE MASS BALANCE STATION

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[2]*Gateway Antarctica, University of Canterbury, Christchurch, New Zealand*
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Predicting the response of Antarctic sea ice to a warming world is a complex undertaking as the linkages between enhanced basal melt from cold cavity ice shelves and the thickness and extent of proximal sea ice are not fully understood. The relatively buoyant meltwater is known to flow out from beneath ice shelves at shallow depths where it interacts with a thickening sea ice cover over the winter growth season. The meltwater is supercooled and can sustain populations of frazil crystals that are deposited at the sea ice / water interface, thus acting as a conveyor belt that transfers mass from the base of an ice shelf to the surrounding sea ice. The path of the meltwater is influenced by the basal slope of the ice shelf, the stratification of the mixed layer and ambient currents. Hence the distribution of frazil crystals is not uniform and is known to vary substantially over scales of tens of kilometres.

Our team has developed a first-of-its-kind sea ice mass balance station to monitor winter sea ice and sub-ice platelet layer thickness changes. The station integrates standard sea ice mass balance componentry (sea ice thermistor string and ultrasonic snow sensor) with a Geonics EM31 electromagnetic sensor that measures the apparent conductivity of the sea ice and underlying sub-ice platelet layer. Apparent conductivity is converted to sea ice and sub-ice platelet layer thickness via a model. Data are collected by a Campbell Scientific datalogger and relayed back to New Zealand in near real-time where it is displayed on the University of Otago's sea ice mass balance station website (seaice.otago.ac.nz).

CHARACTERISING FRAZIL ICE POPULATIONS USING ACOUSTIC TECHNIQUES

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There is a demand for quantitative frazil ice size observations in order to fully model an Ice Shelf Water (ISW) plume describing the outflow of supercooled melt water from underneath ice shelves. These outflows have significant impacts on the growth of the sea ice surrounding ice shelves. Here, we develop a method to fully characterise a frazil population size distribution using acoustic techniques. Previous work in the field has thus far almost entirely been focused on frazil ice in rivers and lakes using spherical scattering in an equivalent sphere assumption, and often using only one or two acoustic frequencies. In this thesis, an oblate spheroid model is combined with a log-normal size distribution for the diameters of frazil crystals to create an analytic formula for the total scattering of a frazil population. Acoustic observations were collected across four deployments in November 2016 and November 2017 from McMurdo Sound, all of which are believed to be on the path of the northwards flowing ISW plume from the McMurdo/Ross Ice Shelf cavity. The optimisation approach was successfully applied to these four-frequency data, producing time series of believable population characteristics. A deployment from 4 – 9 Nov 2017 is analysed in detail, with median sizes (e) of the population spanning 0.16 mm to 0.50 mm, and number densities N of 320 m^{-3} to 32 000 m^{-3}. Most interesting is the optimised spread parameter, which returned higher values than expected (~1.3) for one of the two favoured solutions of the optimisation process. Unlike smaller equivalent sphere assumptions that cannot accurately measure larger sizes, the broad dimensions of the parameter optimisation have plausibility for the inclusion of rarer, large particles as have occasionally been qualitatively observed in photographs and videos under the sea ice in the McMurdo Sound ISW outflow. Supporting oceanographic evidence showed strong positive correlations between the fractional ice volume calculated from the optimised parameters and supercooling in the water column.

SEISMOLOGY OF AN ACTIVE SHEAR MARGIN: PRIESTLEY GLACIER, ANTARCTICA

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Laboratory experiments provide quantitative constitutive equations (flow laws) that describe the deformation of ice. However, most laboratory experiments are conducted at strain rates several orders of magnitude faster than the strain rates that occur in glaciers and ice sheets. Thus finding naturally deforming systems that can be considered as a low strain-rate experiment, to test the extrapolations of laboratory data, are crucial to developing robust flow laws to use in ice sheet modeling.

Lateral shear margins of glaciers and ice streams potentially provide a scenario that can be parameterized as an experiment, with constraints on stress, strain rate, temperature and the structural state of the ice (grain size, crystallographic preferred orientation etc). We will present the initial work on the true left shear margin of the Priestley Glacier in Antarctica. In January 2019 we conducted an active source seismic experiment. Explosive sources were recorded on 27 three-component geophones, measuring vibration in vertical and two horizontal directions, and 24 single-component (vertical) geophones. Direct P and S-wave arrivals are clear for all shots and geophones and preliminary analysis of wave velocities as a function of ray-path orientation show a pattern that is consistent with the crystallographic preferred orientations from simple shear laboratory experiments. This gives us a first clear indication that this site provides a good low strain-rate "experimental" site to link to kinematically equivalent laboratory experiments.

UNDERSTANDING THE AMERY: EFFECTS OF MARINE ICE ON ICE SHELF DYNAMICS AND STABILITY

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Layers of marine accreted ice form at the base of many Antarctic ice shelves, and can account for a significant proportion of the overall shelf thickness. These layers contain a considerable amount of soluble and in-soluble impurities, resulting in differing rheological properties to meteoric ice, and therefore fundamentally influence the mechanical and thermal properties of the ice shelf. However, their influence on ice shelf behaviour is not well understood. We describe a series of deformation experiments on both marine and meteoric ice from the Amery Ice Shelf that will quantify differences in rheological behaviour, and relate those differences to the chemical composition and microstructural characteristics of the ice. A numerical description of the ice flow properties derived from the experimental data will be implemented in an ice shelf model, and the effects of variations in marine ice distribution will be examined. We will then be able to assess the effects of marine ice, its rheology and its distribution on ice shelf flow.

REPLICATING RIS RIFTS (RRR)

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Tabular icebergs separate from ice shelves at long, through-cutting rifts that form transverse to ice flow near the seaward fronts of the shelves. The formation and propagation of rifts transpires over time scales from days to decades, making observational studies rare. Thus, while ice shelf rifts represent a critical component in understanding and making projections of future Antarctic mass-balance they are not well understood or represented in models, beyond idealised cases.

This work describes and demonstrates a method for modeling the horizontal propagation of through-cutting rifts in shelves. The extended finite element method is used to place rift geometries digitized from satellite imagery into a solvable FEM domain. In order for this to domain to be representative of the surrounding ice shelf a we choose specific boundary conditions and impose load forces within the domain. This creates stresses within the domain that are representative of those we can infer from modern velocity products. Linear fracture mechanics can then be used to predict the rift propagation propensity and direction.

GLACIOLOGICAL CONTEXT OF THE HWD-2 BOREHOLE ON THE ROSS ICE SHELF

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Keywords: Antarctic glaciology, Aotearoa New Zealand Ross Ice Shelf Programme, HWD-2, radio echo-sounding, ice shelves

Two boreholes were drilled through over 360m of floating ice to reach the ocean below the Ross Ice Shelf (RIS) in West Antarctic. The approximate location of the boreholes was 80.658 degrees south latitude, 174.463 degrees east longitude, roughly 345 km southeast of Scott Base. A small group of scientists and support staff conducted this work during the months of November and December 2017 at the remote camp, Hot Water Drill Site 2 (HWD-2), on the Ross Ice Shelf. This work was in support of the New Zealand Antarctica Research Institute's (NZARI) Aotearoa New Zealand Ross Ice Shelf Programme, which aims to understand the vulnerability of the Ross Ice Shelf in a warming world.

The glacial ice through which we drilled exhibited a sequence ranging from firn, to bubbly glacier ice, to bubble free glacier ice. The basal ~60 metres of ice contained glacial debris and we observed a few cm-thick layer of new ice crystals at the base of the ice near the borehole.

The two boreholes lie along the margin of a slight along-flow oriented surface depression that is the downstream trace of a suture zone between ice flows from different outlet glaciers of the Transantarctic Mountains. The ice located in the region of the two bore sites appears to have originated near the left margin of Liv Glacier, located approximately 480km to the southeast of HWD-2.

We conducted subsurface imaging using a variety of geophysical techniques over the course of several field seasons, including seismic surveys, autonomous phase sensitive radar echo-sounding (ApRES) and low frequency radio echo-sounding (RES) to provide glaciological context of the ice shelf around HWD-2. RES allows us to image ice layers and detect variations in the physical properties of adjacent layers, such as the interface between the ice of the Ross Ice Shelf and the seawater below.

In the region of the boreholes, we observed a strong RES reflector at approximately 300 m depth, shallower than the 360+ m depth to the bottom of the ice anticipated from its freeboard and measured directly in the two boreholes. In addition, a large upwarping of the strong reflector was imaged in both the along flow and across profiles to the east of the two boreholes. We conclude that the reflector and basal feature represent an internal boundary within the ice, probably the boundary between bubble-rich, clean ice and the deeper bubble-poor, debris-rich ice. The debris content suggests that this is not marine ice frozen on in the ice shelf cavity environment, but rather, it must have frozen on to the base of the Liv Glacier margin or in the ice shelf hinge zone near-coast environment.

STRESS, STRAIN AND FRACTURE ON THE BRUNT ICE SHELF

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The Brunt Ice Shelf is home to the Halley VI research station and glaciological activity in this area strongly impacts base operations. It is therefore one of the most heavily monitored ice shelves in the world with a network of GNSS stations recording horizontal strain, frequent visible and radar satellite data acquisitions, ground-based radar and other instruments used to identify the processes responsible for fracture and variability in strain rates. Chasm 1, which reactivated in 2012 has propagated rapidly recently, necessitating the move of the base to a safer location in 2016/17. A second rift, known as Halloween Crack also appeared in 2016 making the glaciological situation more complex. Here I will explain the pattern and timescales of rift development, the processes and behaviors occurring on the ice shelf and how very detailed observations and modelling are helping our understanding of calving processes.

TIDAL VARIABILITY OF ICE DYNAMICS IN THE GROUNDING ZONE OF THE PRIESTLEY GLACIER, ANTARCTICA, BASED ON OBSERVATION AND MODELING

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Tidal variations in the flow-speed of glaciers regulate the rate of Antarctica's ice discharge into the ocean. The mechanism behind the tidal modulation of ice discharge across the grounding line, however, remains poorly understood. It has been proposed that the magnitude and extent of observed velocity change is caused by tides lifting the glaciers off the bed, changing basal properties by 'pumping' ocean water far upstream of the grounding line and softening the basal till. Observations of changing basal properties to support this theory, however, are entirely lacking. Here we propose an additional, more microscopic process that is associated with large-scale velocity changes: With flexural stresses in the glaciers' grounding zone as well as mechanical weakening of ice in shear margins, ice crystals align in their preferred orientation to facilitate the ice flow. This results in a significant reduction of viscosity along lateral shear margins, with the potential to reduce ice-shelf buttressing on very short time scales.

The lack of consensus on the mechanism behind short-term velocity change means that tidal variability is not yet parameterized in Antarctic-wide ice sheet models, directly affecting the reliability of predictions of future ice loss. In November 2018, we therefore deployed a high-precision radar system (TRI) on the Priestley Glacier, Antarctica, where adjacent rock outcrops provide the rare opportunity to install the TRI at fixed anchor points. This imaging radar system measures ice dynamics at both high temporal resolution and over the entire grounding-zone area with millimetre precision. Simultaneously, an array of glacier stations across the grounding zone record vertical and horizontal movement of the ice (GPS), changes in surface slope from tidal flexure (tiltmeters) and changes in basal properties from potential intrusion of ocean water upstream of the grounding line (ApRES). This in-situ data is complemented by satellite interferometry from TerraSAR-X, Sentinel 1a \& 1b and CosmoSkyMed plus an airborne ice thickness mapping campaign. We use this novel field data to constrain a state-of-the-art numerical model of tidal ice dynamics, to identify the mechanism behind short-term modulation of ice discharge. Although the Priestley Glacier is a small, little-studied glacier, it is representative of many outlet glaciers that drain Antarctica through the Transantarctic Mountains into the Ross Sea. If we are to better predict the rate of sea-level rise in an ongoing climate change, fully understanding of tidal modulation of ice dynamics is vital for estimating future ice loss with confidence.

PATTERNS AND LAKE FORMATION ON A FLAT-BEDDED MODEL ICE SHEET

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By modeling instabilities in the coupling of an ice sheet and subglacial drainage system, we describe feedbacks that force the formation of sharp spatial structures in basal conditions and ice flow. Our 1D model predicts the spontaneous formation of periodic subglacial 'sticky spot'-lake pairs, that correspond in shape to previous empirical and modeled descriptions of similar structures. This instability is driven by a feedback whereby periodic humps in ice thickness redirect subglacial water to slippery spots that lie immediately upstream of the ice humps: the slippery regions increase ice flux into the ice humps, making them grow.

CLIMATE CHANGE AND SEA ICE LINKAGES

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We examine how sea ice extent would change in the future under three different idealized scenarios of Antarctic ice sheet and ice shelves outflow changes. We ran three climate model scenarios of changes in outflow from Antarctic ice sheet and ice shelves in CCSM4 starting in 1980 to examine potential future impacts on sea ice extent and feedback effects on climate (e.g., surface air temperatures). We then ran two idealized experiments starting at 1850 for comparison. We chose to run from a base year of 1980, which we assumed to be when the Antarctic ice sheet was in mass balance, and then increased freshwater fluxes to give the approximate equivalent of 3 m of sea level rise over a 150 year period. The rate of freshwater input was increased linearly from 0 Gt yr^{-1} in 1980 to 17 529 Gt yr^{-1} in 2129. Forcings used were 20th century to the end of 2005, then RCP8.5 from 2006 onwards. Two shorter runs to 2100 were then conducted, branching at the start of 2058 (approximately where sea ice area behaviour "turned around" from increasing in the initial run).The first branched run switched off the additional fresh water and latent heat effects at 2058. The second branched run held the amount of freshwater constant at 2058 values, which was 9294 Gt yr^{-1}. Next, we carried out two shorter runs starting in 1850; both had ramped freshwater and with latent heat effects included, but one had historical greenhouse gas forcings and the other had greenhouse gas forcings held constant at 1850 levels. This was to separate out the effects of greenhouse gas forcings on the ramped freshwater and latent heat effects over long time periods.

EFFECTS OF INCREASING MASS LOSS FROM ANTARCTICA ON OCEAN AND SEA ICE PROPERTIES

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Mass loss from Antarctica is increasing, both through negative ice shelf mass balance and from increased mass flow through ice shelf grounding lines as some grounded ice streams accelerate. The rate of increase is spatially, and possibly temporally, variable. Estimates of the variability are uncertain, as are observations of instantaneous rates, which makes parameterization difficult. This means that the changing mass loss can generally only be fully represented in a global climate model through coupling a dynamic ice sheet model, which is beyond the computational budget of most climate modeling groups. A fixed rate of mass loss is therefore generally assumed for coupled model studies and it is important to understand the effect of this assumption on model projections of climate. We have carried out experiments using a CMIP6 model configuration for a state of the art fully-coupled climate model, HadGEM3-GC3.1, to investigate effects on sea ice and ocean properties. In our experiments we increased the mass loss from Antarctica, distributing the resulting increased mass fluxes around the coast of the continent according to the same glaciological estimates used for the standard model configuration. We looked at dividing this increased mass flux between an iceberg calving flux and an iceshelf melt flux as in the standard model configuration, and in two further experiments, we looked at representing the entire flux as icebergs, and the entire flux as exclusively entering the Southern Ocean as iceshelf melt. We used fixed pre-industrial forcings for our model configuration to avoid any trends attributable to other forcings, which may affect the sensitivity of the model to the increased mass loss. In an additional experiment, we used the so-called 1% CO_2 scenario from the CMIP6 standard experiment set, whereby CO_2 increases by 1% annually but all other forcings remain fixed.
In addition to providing an aid to interpretation of climate projections, it is anticipated that this work may help to target future observation and model development work on melt areas associated with the greatest climate sensitivity, where an appropriate parameterization of mass loss is likely to impact climate projections most.

REPRESENTING SEA ICE FORM DRAG MORE ACCURATELY IN CLIMATE MODELS

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As the ocean and atmosphere move relative to sea ice, they experience a drag due to pressure ridges and floe and melt pond edges of the ice. This drag is not currently well represented in most climate models. In 2014, Tsamados et al proposed a scheme to parameterize this drag, using separate terms for atmospheric and oceanic components. They implemented their scheme in an uncoupled climate simulation for the Arctic and found significant effects on the simulated sea ice area and thickness, relative to simulations where drag was neglected. Different effects may be expected in the Antarctic, where there are no melt ponds and where sea ice processes are driven by different atmospheric and oceanic processes. Different effects may also be found when drag is included in a coupled climate environment, where feedbacks between atmosphere, ocean and sea ice processes are represented. To investigate this, we are looking at the effect on sea ice in the Antarctic of different implementations of the Tsamados scheme in a coupled climate model, relative to a control simulation with no drag included. Our different implementations of the scheme correspond to different tunings for the oceanic and atmospheric components of the drag and it is hoped that this work will provide insights into whether the tuning appropriate for the Arctic is appropriate for the Antarctic. The UK Met Office are currently developing a new sea ice model and this work contributes to studies to determine which processes have a significant effect on climate and should therefore be included in the new model. Drag as parameterized by Tsamados et al, can be separated into form drag and skin drag, which combine to produce the profile drag, represented by a total drag coefficient for both the ocean and atmosphere. Form drag is the drag experienced by an object due to the shape of its cross sectional area as it moves through a fluid, while skin drag happens when a layer of the fluid attaches to the object and travels along with it, experiencing its own drag. We are looking at the effect of different tunings for these different components.

GEARING UP NEW ZEALAND'S OCEAN AND SEA ICE MODELLING

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To understand the changes in Antarctica's ice it is prudent to gain better knowledge of the climate related transformation of the Southern Ocean and Antarctica's continental seas. A new ensemble of coupled and nested models to simulate the interactions between ocean, atmosphere, sea ice, ice shelves and grounded ice sheets on resolutions between 0.1 and 8km and temporal scales ranging from months to centuries will be introduced. This newly developed toolkit aims to support, facilitate and develop New Zealand based research centred around sea ice formation and drift, polynya processes, ocean circulation, ice shelf and sheet stability and water mass formation. A brief exposition will be given of its current capabilities, applications and research questions including some first results. Future developments and ways to access existing components or easily setup new suitable sub-models will be touched and discussed.

SHOULD THE NEW ZEALAND DAIRY INDUSTRY CARE ABOUT CLIMATE CHANGE?

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Amidst the rapid conversion of agricultural land to dairy farming, New Zealand is facing -- perhaps for the first time -- the potential for water stress. High water consumption and fertilizer use needed to make land suitable for dairy are posing challenges to water quantity and quality, and nowhere is this more present than the Canterbury Plains. The source waters for the rivers that feed the plains lie in the climate-sensitive snowfields and glaciers of the Southern Alps. In a warming world how will the hydrologic regimes of the river systems like the Rakaia, Waimakariri, Ashburton and Rangitata Rivers shift? I will present the scope (results not yet available) of a recent study of the Rangitata River in January 2019 aimed to quantify the meltwater contributions to water supplies downstream. This study utilizes a combination of in situ sample data (isotope and hydrochemical tracers that drive mixing models) and remote sensing data processing techniques to anticipate climate's influence on the rivers sourced by snow and ice reservoirs of the Southern Alps, and what it may mean for the dairy industry downstream. This is a comparative study to previous work in melt-fed agricultural areas in High Asia, and I will briefly present those results to contextualize the NZ study. I present this work-in-progress with an open mind, welcoming your insights, ideas, lessons-learned, interest in collaboration, and suggestions for complimentary data sets.

WAITAKI WHITESTONE GEOPARK: UNESCO GLOBAL GEOPARK IN THE MAKING

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Bordered by the Southern Alps to the west, the braided Waitaki River plains to the north, and the spectacular sea cliffs and volcanic headlands of the eastern coast, the Waitaki region encompasses a diverse variety of rock types, geologic time periods, and landscapes shaped by Quaternary glaciation. These features preserve key components of Zealandia's geologic history, while the marine sedimentary rocks contain important middle Eocene to early Miocene age marine fossils, including the giant extinct *Kairuku* penguins, the baleen whale *Tokarahia*, and shark-toothed *Squalodon* dolphins. For the past 17 years Vanished World Incorporated has brought the geologic significance of the Waitaki region to the public through the development of a Visitor Centre in Duntroon and a self-guided tour around geological sites in North Otago. Arising from local interest in research on fossils from the region (primarily carried out by Professor Ewan Fordyce, University of Otago), the Vanished World Centre and Trail are community-supported initiatives that have played a fundamental role in promoting geoconservation in the district.

In November 2018 the Waitaki District Council, alongside Ngāi Tahu, Vanished World Inc, Tourism New Zealand, the University of Otago, the North Otago Museum, Tourism Waitaki, Environment Canterbury, the Waitaki Tourism Association, the Otago Museum, the Department of Conservation and the people of the Waitaki, submitted an application to become New Zealand's first UNESCO Global Geopark. The establishment of an UNESCO Global Geopark in the Waitaki District will provide an opportunity to highlight, celebrate and preserve the intersection of geologic and cultural heritage in this district. The Geopark will also provide a foundation for geoscientists conducting research in the Waitaki region to raise public awareness about their work, contribute to education and outreach programmes, and protect significant geologic features and landforms for future research needs.

THE CARTOONS OF TREVOR CHINN (1938 – 2018)

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Trevor Chinn has been one of the dominant snow and ice scientists in New Zealand for fifty years. His recent death is a great loss to the future, but a chance to re-discover his past work. The cartoons with which he illustrated his research articles are one of his endearing legacies. A selection of these cartoons are presented for us to continue to enjoy and learn from him.