The Snow and Ice Research Group Workshop

UNDERSTANDING MOUNTAIN CLIMATE II

9-13 FEBRUARY 2021

HAERE-ROA UNIVERSITY OF CANTERBURY

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UC UNIVERSITY OF CANTERBURY Te Whare Wānanga o Waitaha CHRISTCHURCH NEW ZEALAND

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Brewster Glacier, Todd Redpath

WELCOME

Nau mai, haere mai to the 18th annual Snow and Ice Research Group (SIRG) annual workshop

Connecting Through Change

Waiho te toipoto, kaua i te toiroa

(Let us keep close together, not far apart)

In the spirit of our chosen whakataukī, the University of Canterbury SIRG group decided to connect and collaborate with Antarctic Science Conference and the 2nd Understanding Mountain Climates workshop, to provide a week-long celebration of snow and ice research. Given the various challenges of the previous year, and that as a group we study the effects of climate change, the UC organising committee decided that connecting and working with Antarctica New Zealand and NIWA would not only deliver a great week of science, but also lessen our carbon-footprints by reducing travel.

This week you will find the Antarctic SIRG community presenting their research during the first part of the week and those SIRG members who conduct research in alpine environments presenting their work in the later part of the week. The combined nature of the workshop has also freed up some space for SIRG members to once again have opportunity for discussion around key topics. For example, thinking about how as a community we can best support key long-term monitoring programmes, and what role our science plays in the hazard and hydrology spaces?

This year we also introduce a plenary that celebrates the contribution to our discipline by Professor George Denton through the voice of one of his mentees Associate Professor Aaron Putnam. In keeping with our theme of connecting though time Aaron will take us on a journey demonstrating the how the connection between supervisors and students is fundamental to the progression of our knowledge.

So on behalf of the UC-NIWA SIRG organising team we welcome you to this workshop and look forward to inspiration that comes from sharing research.

Heather, Gemma, Drew & Wolfgang

AARON PUNTMAN

'Mercer's Paradox'

In 1984, John H. Mercer stressed a problem that "defies satisfactory explanation" by classic Milankovitch ice-age theory, which rests on the effect of summer insolation intensity on ice fields. From radiocarbon-dating of glacial tills in the Chilean Lake District of South America and along the former southern margin of the Laurentide Ice Sheet in central North America, Mercer noted that the last glacial maximum and the last glacial termination were broadly synchronous in the middle latitudes of the Americas in both polar hemispheres, despite opposing summer insolation. If the Milankovitch theory is correct, then why was there synchrony of glacier behavior on the orbital timescale between the hemispheres when the summer orbital signals were anti-phased? Broecker and Denton (1989) later observed that not only was the timing of the last glacial maximum broadly synchronous between hemispheres, but that the severity of interhemispheric cooling deduced from snowline lowering in the American cordillera was of similar magnitude. They concluded that "If glacial climates are driven by changes in seasonality, then another linkage must exist." We refer to this conundrum as 'Mercer's Paradox'. Broecker called it the "fly in the orbital ointment". The search for a satisfactory orbital-climate linkage remains a fundamental problem of ice-age theory.

We explore Mercer's Paradox further by comparing surface-exposure chronologies of moraines deposited by climatically sensitive mountain glaciers in both polar hemispheres. We focus on an Asian/Australasian transect of mountain glacier reconstructions, underpinned by ^{10}Be surface-exposure chronologies of moraines in the Southern Alps of New Zealand and in the mountains of interior Asia. Our primary observation is similar to that obtained earlier in the Americas and thus reinforces Mercer's Paradox. Namely, we found that the last glacial maximum, and its termination, occurred synchronously between the outer edge of the Southern Ocean and the interior of Earth's largest continent – despite the opposing signatures of summer insolation that were employed by Milankovitch to drive glaciation. Furthermore, the switch between glacial and interglacial climate modes was rapid – beginning close to 18,000 years ago and occurring in a millennium or two. We interpret the moraine chronologies to indicate that the switch from glacial to interglacial climates was big, fast, and global, therefore requiring a physical mechanism capable of producing widespread and rapid change in the energy content of the atmosphere. We suggest that such a mechanism, and hence a solution to Mercer's Paradox, may lie in southern and tropical latitudes. From the moraine chronologies and from simulations with a GFDL earth system model, we posit a mechanism by which non-linear changes in the latitude and strength of Southern Hemisphere westerly winds, paced by orbital forcing, elicit global changes by their influence on Pacific subtropical gyres and the heat engine of the planet in the Pacific Warm Pool. We suspect that the continent of Zealandia, a large topographical obstruction to austral ocean-atmosphere circulation, may be a primary source of non-linear behavior of the ocean-atmosphere system. Southern Hemisphere circulation may therefore be fundamental to driving glacial cycles and abrupt climate change on a global scale.

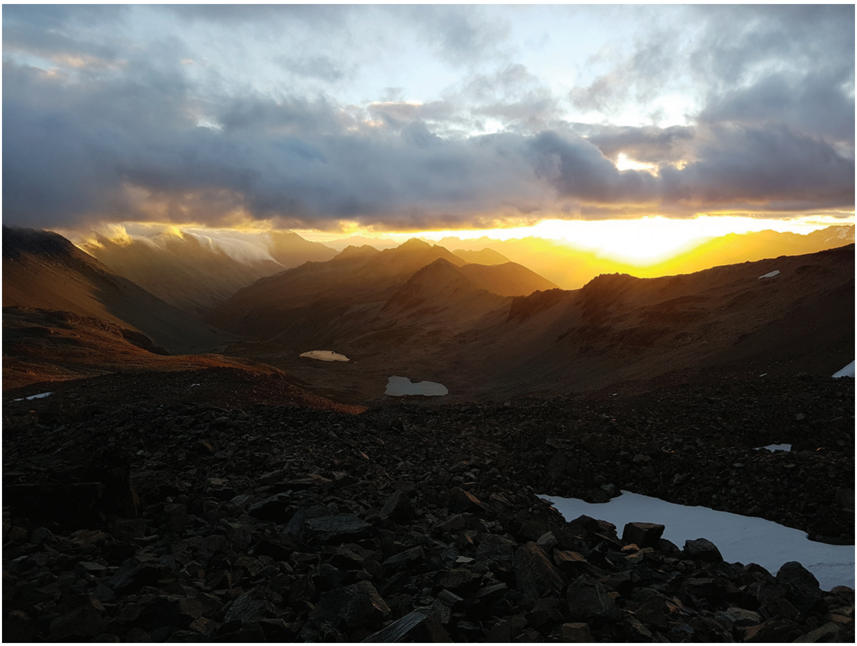
Aaron Puntman

Aaron Putnam is an assistant professor at the University of Maine, where he studies the geologic record of Earth's mountain glaciers and ice sheets to gain insights into the dynamics of past global changes, such as ice ages and abrupt climate change. Aaron is also interested in climate drivers and feedbacks responsible for the industrial-age worldwide retreat of mountain glaciers and shifting global rain belts. Since participating in a scientific cruise to study the dynamics of Arctic sea ice in high school, Putnam has logged over 200 weeks conducting fieldwork in remote glacial environments, such as in Antarctica, the Southern Alps of New Zealand, the southern Andes, and the mountain chains of Asia. His research focuses on charting the demise of Earth's terrestrial ice masses during the termination of the last ice age, with an aim toward identifying the climatic mechanisms that drove massive and rapid changes in the global energy budget. An overall goal of his is to improve knowledge of climate dynamics and ice melt in a warming world.

George Denton

George Denton is Libra Professor and Distinguished Maine Professor in the School of Earth and Climate Sciences and Climate Change Institute at the University of Maine, USA. He earned his Ph.D. at the Yale University in1965, and was the first scientist from the University of Maine elected to the

National Academy of Sciences. George's primary interest is the geological history of large ice sheets and smaller mountain glaciers, and in particular the role of these ice sheets in Quaternary and late-Tertiary ice ages. He also focuses on the abrupt ocean-atmosphere reorganizations in glacial cycles. He has researched the Quaternary and late Tertiary history of the Antarctic Ice Sheet, with a focus on using late Quaternary glacial deposits to elucidate the role of the Antarctic Ice Sheet during the last few ice ages. His work on late Tertiary deposits bear on fundamental climatic changes that preceded Quaternary ice ages. His other projects have also focused on reconstruction of Northern Hemisphere ice sheets during the last ice age and the alpine glacier history of the Chilean Andes and New Zealand Southern Alps. Denton has been widely acclaimed for his research in glacial geology and the Denton Glacier and the Denton Hills in Antarctica were named in his honor. In 1990, he received the prestigious Vega Medal (Gold) from the Swedish Society for Anthropology and Geography and in 1996 he was elected to the Royal Swedish Academy of Sciences. Denton's research has inspired several generations of students, many of whom have picked up researching in Earth Science.



Irishman Stream, Ben Ohau Range, Todd Redpath

FIELD TRIPS

2021 SIRG FIELD TRIP: AN EXPLORATION OF THE GLACIAL HISTORY IN THE WAIMAKARIRI AREA

Saturday 13th February, 8:30am to 6pm

Hosted by the University of Canterbury Te Whare Wānanga o Waitaha, School of Earth and Environment Te Kura Aronukurangi.

The Waimakariri is a braided river system that flows from Kā Tiritiri-o-te-moana (The Southern Alps) to Te Moana-nui-a-Kiwa (the Pacific Ocean). Today, glaciers are only found at the very top of the catchment perched on the highest mountains. But during the Pleistocene, ice filled this valley system, leaving behind an impressive landscape that tells a story of past climate variability.

Built in 1915, the University of Canterbury's Cass Research Station is nestled in amongst this geomorphological haven, and for over a century, staff and students from the university have been exploring this landscape.

Professor Jamie Shulmeister and Dr Heather Purdie will lead a one-day field excursion of their 'back-yard'. Be prepared for a great mix of geomorphology, cultural history, and ever evolving research narrative.

Itinerary

We will have an 8:30 am departure from University of Canterbury, Ilam Road carpark, travelling in mini vans directly to the Cass Field Centre, arriving at around 10:30 am. After a short comfort stop at the field centre, we will head out into the field on foot, finding a good spot for a picnic lunch as we explore the

Field teaching at Cass, Andrew Fletcher landscape. We aim to be out in the field for approximately 4-5 hours (weather dependent), with a planned departure at approximately 4pm, arriving back in Christchurch by 6pm.

What to bring

Please bring you own packed lunch and drink bottle (although drivers may also be persuaded to stop at the world-famous Sheffield Pie Shop!). Wear good sturdy footwear for hiking over untracked ground, and be sure to have 'layers' to accommodate inclement weather, as well as sun protection (hats, glasses, sunscreen). In the event that the weather on the day is not conducive for walking, then the trip will be modified to a more 'driving' tour of the regions geomorphology. But please be prepared for a good days walking – as Heather and Jamie believe this is by far the best way to explore the landscape.

Number are limited, and spaces will be allocate to registered conference participants on a first-in-first-served basis. Any questions please contact Heather at heather.purdie@canterbury.ac.nz.

Glacial geology, Heather Purdie (left), University of Canterbury, Cass Field Centre (right)

PROGRAMME

Thursday 11 February

1330	**Welcome and housekeeping**	Bentleys
1340-1420	**Session – Alpine hydrology, hazards, and ecosystems** *Simon Cox – Accelerated slope response in a destabilized alpine landscape* *Aubrey Miller – Snow avalanche hazards in Aotearoa New Zealand: Using extreme events from the past to plan for the future*	Bentleys
1420-1530	**Session - Glacier - climate connections** *Todd Redpath – Monitoring the presence and persistence of particulate impurities on New Zealand Glaciers using VENμS satellite imagery* *Oliver Wigmore – Mapping debris thickness over Haupapa/Tasman Glacier with thermal drone and satellite imagery.* *Shaun Eaves – Holocene climate change as told by New Zealand glaciers*	Bentleys
1530-1630	Afternoon tea	Ti Kouka
1630-1730	**The George Denton Plenary Presentation (by Aaron Putnam). Introduced by David Barrell (GNS)**	Ngaio Marsh
1730	**SIRG Icebreaker**	Bentleys

Friday 12 February

0850	**Welcome and housekeeping**	Bentleys
0900-1000	**Session - Glacier-climate connections contd.** *Jono Conway – Cloud forcing of surface energy balance in diverse mountain glacier environments* *Heather Purdie – Rolleston Glacier: First decade of mass balance measurement and the implications of climate change on mass balance monitoring* *Nariefa Abrahim – An examination of the surface energetics controlling the recent and dramatic loss of ice on Brewster Glacier*	Bentleys
1000-1030	Morning tea	Upstairs foyer
1030	**Session Glacier climate connections contd.** ***Keynote***: *Lauren Vargo – Measuring New Zealand glacier change from aerial images* *Ruzica Dadic – Wind Driven Snow Distribution on Brewster Glacier, NZ* *Pascal Sirguey – Going, going, gone! Reconstructing the reconstruction of Brewster Glacier mass balance record 1977–2018* *Discussion: Glacier observations and monitoring*	Bentleys
1200-1300	Lunch	Upstairs foyer
1300-1350	**Session - Alpine hydrology, hazards, and ecosystems** ***Keynote***: *Warren Chinn – Tracking the snow line: Responses to climate change by New Zealand alpine invertebrates* *Rasool Porhemmat – Rain–on-Snow in the Southern Alps: hydrometeorolgy and impacts*	Bentleys
1350-1500	**Session - Glacier-climate connections contd.** *Jim Salinger – The impacts of the 2017/18 and 2018/19 heatwaves on Southern Alps glaciers* *Brian Anderson - Projections of future glacier volume changes for the New Zealand region* *Discussion: Impacts and Extremes*	Bentleys

1500-1530	Afternoon tea	Upstairs foyer
1530-1730	**Session - Alpine hydrology, hazards, and ecosystems contd.** *Tim Kerr – Winter Snow storage is a poor predictor of spring streamflow: two case studies from the Southern Alps.* *Joanna Borzecki – The impact of glacier retreat on long–term water availability in the Waitaki Catchment, New Zealand* *Shelley MacDonell – The hydrological role of rock glaciers in an Andean desert* *Shane Bilish – Managing water resources in marginal snow environments* *Christian Zammit – Climate change impacts on snow and ice resource to support decision making: How precise do we need to be?*	Bentleys
1730-1800	Closing remarks	
1800-2000	**BBQ Dinner**	

Saturday 13 February

0830-1800	**2021 SIRG field trip** *An exploration of the glacial history in the Waimakariri area*	Cass

Tapado Glacier penitents, Chile, Shelley MacDonell

Glacier-climate connections

The impacts of the 2017/18 and 2018/19 heatwaves on Southern Alps glaciers

Jim Salinger[1], Blair Fitzharris[2]

[1]*University of Tasmania, Hobart.*
[2]*University of Otago, Dunedin*

Abstract
The back to back heatwaves of 2017/18 and 2018/19 warm conditions caused massive ice loss in South Island glaciers. The two summers were the first and third warmest over the 150-year period, with the average combined average air and sea surface temperatures being 2.1 and 1.2 °C for 2017/18 and 2018/19 respectively above the 1981-2010 normal. They produced the estimated largest annual losses of glacier ice in four decades of records for the Southern Alps back to 1977. Satellite data from end-of-summer snowline measurements at the Tasman Glacier suggest that the Southern Alps lost 22% of glacier ice during last summer alone from 2017 values. The total ice volume loss was 8.9 km3, reducing total Southern Alps ice volume from 41 km3 in 2017 to 32 km3 in 2019. The warming was a result of several atmospheric and oceanic teleconnections. Both were caused by very positive phases of the Southern Annular Mode (SAM) which suppress the troughs and promotes many more anticyclones in the Tasman Sea extending across the South Island to the south east. The light winds in the 2017/18 and 2018/19 events allowed the ocean surface and atmosphere to warm rapidly in the New Zealand region.

Going, going, gone! Reconstructing the reconstruction of Brewster Glacier mass balance record 1977-2018

Pascal Sirguey[1], Tobias Brunk[1,2], Nicolas J. Cullen[3], Aubrey Miller[1]

[1]*School of Surveying, University of Otago, Dunedin, New Zealand.*
[2]*University of Heidelberg, Heidelberg, Germany.*
[3]*School of Geography, University of Otago, Dunedin, New Zealand*

Abstract

Brewster Glacier has been the centre of attention for New Zealand glaciology and a proxy for the behaviour of many glaciers in the Southern Alps/Kā Tiritiri o te Moana. Sixteen years of in-situ glaciological measurements, 20 years of satellite monitoring of surface albedo, and 43 years of photos documenting the end-of-summer snowline has yielded one of the longest mass balance series in the Southern Hemisphere.

Using geodetic mass balance over the 1986-2018 period derived from photogrammetric reanalysis, we calibrated and validated the mass balance series to reveal a new picture of the glacier demise. The long-term ELA over the period was found to be 165 m higher than previously thought, with a growth period in the 1980s and 1990s merely subduing a pronounced negative trend. The calibrated series shows a three-fold increase in the rate of ablation since 2008, while surface elevation changes reveal strong ablation in the glacier's highest regions and the loss of the long-term ELA. The unabated retreat since 2008 culminates with the loss of -5.3 ±1.1 Mt during the unprecedented 2018 heatwave, and establishes the trend for a disappearance of Brewster Glacier by mid-century.

Measuring New Zealand glacier change from aerial images

Lauren Vargo[1], Brian Anderson[1], Ruzica Dadic[1], Huw Horgan[1], Andrew Lorrey[2], Andrew Mackintosh[3]

[1]Antarctic Research Centre, Victoria University of Wellington, Wellington.
[2]NIWA, Auckland. 3Monash University, Melbourne

Abstract
Measuring glacier fluctuations is important for understanding how the cryosphere responds to climate variability and change. New Zealand has a unique record of glacier change: aerial photographs of over 50 glaciers, taken annually since 1978. These images document changes in glacier length, area, and snow cover at the end of summer, which is a proxy for mass balance. In 2015, the survey evolved, taking more (20 - 200) images of each glacier and collecting location data for each image.

Using the historic and modern images, location data, and the photogrammetry method Structure from Motion, we can better measure New Zealand glacier change. We are able to quantitatively measure past glacier fluctuations from historic images. We also use the modern images, taken since 2015, to develop high-resolution and high-accuracy orthophoto mosaics and digital elevation models (DEMs) of the glaciers. We use the DEMs and orthophotos to measure changes in snowline elevation, length, and geodetic mass balance. Application of these methods to Brewster Glacier show that the glacier retreated 422 ± 12 m from 1981 - 2020, had a maximum snowline elevation of 2311 m a.s.l. in 2018, and geodetic mass balance of -6.8 ± 1.3 m w.e. from March 2016 - March 2019.

An examination of the surface energetics controlling the recent and dramatic loss of ice on Brewster Glacier

Nariefa Abrahim[1], Nicolas Cullen[1], Jono Conway[2], Pascal Sirguey[3]

[1]*School of Geography, University of Otago, Dunedin.*
[2]*National Institute of Water and Atmospheric Research, Lauder.*
[3]*School of Surveying, University of Otago, Dunedin*

Abstract

A revised mass balance time series calibrated and validated by a recent geodetic survey has revealed a shift to significant mass loss on Brewster Glacier since 2008. The ablation has been widespread and has led to changes in the mass balance gradient, compromising the glacier's ability to store mass. This provides a unique opportunity to assess in detail what components of the surface energy balance have been responsible for the dramatic shift towards negative mass balance. To do this we use a physically-based surface energy and mass balance model run in a fully spatially distributed mode. The model computes the mass balance as the sum of solid precipitation, melt, sublimation, surface deposition and englacial accumulation due to refreezing of meltwater. Our initial modelling period uses in situ meteorological observations collected from two weather stations on and next to Brewster Glacier to determine mass balance, which is compared to glaciological observations for calibration and validation. The modelling challenges, including the configuration of the parameter set and input variables used will be discussed and compared to previous work in the Southern Alps and elsewhere, before providing insights in to the surface energetics responsible for the strongly negative mass balance on Brewster Glacier.

Wind-Driven Snow Distribution on Brewster Glacier, NZ

Ruzica Dadic[1], Lauren Vargo[1], Nora Helbig[2], Rebecca Mott[2], Brian Anderson[1]

[1]Antarctic Research Centre, Victoria University of Wellington, Wellington.

[2]WSL Institute for Snow and Avalanche Research, SLF, Davos

Abstract

Snow accumulation is a crucial part of the water balance - both on seasonal time scales and, in the case of glaciers, annual to decadal time scales. Previous work shows that some catchments have a very high contribution of snow melt to stream flow, but also that snow accumulation variability is key for stream flow simulations, as deep, late lying snow significantly influences the hydrograph in late summer. Snow melt is reasonably well understood, but there are large deficiencies in modelling snow accumulation. The high spatial variability in snow accumulation results from two processes - firstly preferential deposition and redistribution of snow by wind, and secondly avalanches. These processes interact, and it is ultimately the wind-driven distribution of snow accumulation that may influence avalanching. To improve snow accumulation models, usually at least 2D wind speed and direction data are needed. Until recently it has not been possible to derive wind-speed data in steep mountain terrain without high-resolution atmospheric modelling, but we here we present a new empirical wind downscaling scheme in combination with an existing parameterization of preferential deposition of snow. We show the effects that snow distribution may have on glacier mass balance and runoff for Brewster glacier in New Zealand.

Cloud forcing of surface energy balance in diverse mountain glacier environments

Jono Conway
NIWA, Lauder

Abstract
Glaciers are iconic features of mountain landscapes with significant cultural, environmental, scientific, and economic value. While we know that glaciers are sensitive to changes in their local climate, the extent to which cloud cover will amplify or reduce the melting of a glacier in response to warming is uncertain. Clouds alter the solar and infrared radiation available for glacier melt and can enhance or dampen the influence of surface meteorology, albedo feedbacks and subsurface processes (e.g. refreezing) on melt. However, how these processes interact in different mountain glacier environments and climate regimes has not been well established. To address this knowledge gap, published surface energy and mass balance datasets from 15 mountain glaciers around the world haves been collated and analysed in a common framework. The framework seeks to understand which processes are more important for determining how cloud cover modifies melt. For example, does cloud radiative forcing dominate the effect of clouds on melt, or is the relationship between clouds and other meteorological forcing more important in different environments? By unravelling the interacting effects of clouds and other atmospheric processes on glacier melt in diverse mountain locations, we hope to add fundamental understanding of the processes determining mountain glacier response to climate change.

Monitoring the presence and persistence of particulate impurities on New Zealand Glaciers using VENµS satellite imagery

Todd Redpath, Pascal Sirguey

National School of Surveying, University of Otago, Dunedin

Abstract

The Austral spring and summer of 2019/2020 saw an unprecedented Australian bushfire season, as well as several significant dust storms in the south east of Australia. Such events provide a source for airborne particulates that, when deposited on snow and ice surfaces, modify the surface energy balance by reducing albedo and enhance ablation of snow and ice. This study set out to assess the potential of high spatial and temporal resolution imagery from the Vegetation and Environment monitoring on a New Micro-Satellite (VENµS) mission to detect and monitor a snow impurity signal in New Zealand's central Southern Alps over spring and summer of 2019/2020. A band rationing approach, leveraging the blue (490 nm) and near-infrared (865 and 910 nm) bands allowed the efficient segmentation of discoloured snow, clean snow and exposed ice on the accumulation areas of Tasman, Franz Josef and Fox glaciers. This analysis revealed that widespread areas of discoloured snow occurred as early as November 24, 2019, and that the spatial extent of discoloured snow varied throughout the ablation season. These findings support a working hypothesis that particulate impurities are deposited during precipitation events, and exhumed as snow melts, resulting in the observation of strongly discoloured snow.

Mapping debris thickness over Haupapa/Tasman Glacier with thermal drone and satellite imagery.

Oliver Wigmore, Brian Anderson, Matthew Tankersley, Huw Horgan

Antarctic Research Centre Victoria University of Wellington, Wellington

Abstract

Debris-covered glaciers are common in steep mountainous terrain. Debris cover is often highly heterogeneous and can enhance or reduce glacier melt depending on its thickness. Thus understanding the thickness and distribution of glacier debris is critical to accurately model how these glaciers will respond to rising temperatures. Debris thickness can be measured manually at the point scale or with ground penetrating radar. Debris distribution can be estimated empirically from thermal satellite imagery, or modelled via energy balance inversion. However, both methods require measurements for validation, and there is often a significant spatial mismatch between the estimates and validation measurements. Furthermore, important patterns of spatial heterogeneity are often missed with point and coarse satellite/model estimates. Here we develop a method to estimate debris thickness at sub-metre spatial resolution by combining intraday drone-borne thermal maps with topographic indices and statistical analyses. We apply this methodology to a ~10 ha area on the lower Haupapa/Tasman Glacier. Statistical models are trained and validated on a set of point measurements that match the pixel footprint. Observed patterns of spatial heterogeneity in debris thickness are assessed. Finally, our thickness estimates are aggregated to Landsat pixel size and used to estimate debris thickness over the entire Haupapa/Tasman glacier.

Holocene climate change as told by New Zealand glaciers

Shaun Eaves

Victoria University of Wellington, Wellington

Abstract
The Holocene Epoch (~12,000 years ago to present) is Earth's current interglacial and is characterized by relative climatic stability following the end of the last glacial period. Climate proxy records from this interval thus offer the opportunity to establish baselines of natural climatic and environmental variability, against which, we can better evaluate ongoing anthropogenic modification of the climate system. Mountain glaciers are hyper sensitive to climate variability and effective agents of landscape change. Geological records of past glacier extent thus yield useful insights to past climate change.

In this presentation, I will synthesize new and emerging results from cosmogenic surface exposure dating, glacier modelling, and transient climate modelling, which informs climate variability over the last 12,000 years. Key findings include: (i) the disparate nature of Holocene moraine systems (ii) a dichotomy between biological climate proxy reconstructions and the mountain glacier record; and (iii) low probability of past glacial minima akin to present-day.

Rolleston Glacier: First decade of mass balance measurement and the implications of climate change on mass balance monitoring

Heather Purdie[1], Tim Kerr[2], Wolfgang Rack[1], Andrew Lorrey[3]

[1]School of Earth & Environment, University of Canterbury, Christchurch. [2]Rainfall NZ, Christchurch. 3National Institute of Water and Atmospheric Science, Auckland

Abstract

Rolleston Glacier is a small glacier located near Arthurs Pass. It is one of only two NZ glaciers at which mass balance is directly measured. After the first decade of monitoring (2011-2020), the cumulative mass balance is -6.8 m w.e., or -0.7 m w.e. per year. Rolleston Glacier is also photographed each year as part of NIWA's end-of-summer snowline monitoring program. There is a statistically significant relationship between measured annual mass balance and the position of the EOSS (R^2 0.89, p=0.0001). However, neither method accurately records ice volume loss in strongly negative years, and sometimes the only remaining mass input on the glacier is derived from snow avalanche off Mt Philistine. This secondary snow input is estimated to be approximately 25% of winter snow accumulation; but the actual volume gained by this process is yet to be determined. A recent purchase of a Riegl VUX-240 laser scanner (pers. comm., J. Brasington), provides new opportunity to supplement the existing field program with geodetic mass balance measurement. Such an approach will not only be more robust in extremely negative years, but will improve understanding of spatial variability in accumulation and ablation processes, and increase our ability to estimate future changes to alpine hydrology.

Brewster Glacier, Lauren Vargo

Alpine hydrology, hazards, and ecosystems

Snow avalanche hazards in Aotearoa New Zealand: Using extreme events from the past to plan for the future

Aubrey Miller[1], Pascal Sirguey[1], Nicolas Cullen[2], Yves Bühler[3]

[1]*School of Surveying, University of Otago, Dunedin, New Zealand.*
[2]*School of Geography, University of Otago, Dunedin, New Zealand.*
[3]*WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland*

Abstract

Aotearoa New Zealand (NZ) is a dynamic island nation. Natural hazards such as volcanic eruptions, earthquakes, landslides, flooding, glacial thinning and avalanches constantly reshape landscapes across a multitude of temporal and spatial scales. One natural hazard in need of further investigation in NZ is the snow avalanche, which poses risks to NZ alpine region visitors and key infrastructure, such as roads, tracks, and backcountry huts that help sustain NZ's economy.

With relatively sparse observational records in NZ compared with alpine regions in some northern hemisphere countries, investigation is needed on avalanche dynamics to support extreme-event planning and preparedness. This project leverages the latest advances in geospatial science, including ongoing efforts to measure alpine topography with satellites (Matariki Project at Otago) and the remote sensing of snow avalanches (research at WSL-SLF in Switzerland), to calibrate dynamic models and simulate extreme avalanche events in NZ.

Uncertainty around possible changes to avalanche frequency and magnitude from climate change poses challenges to avalanche preparedness. This project will link past events with future climate scenarios to simulate possible effects on extreme avalanche events in NZ.

This presentation will detail the project aims and initial results of analysis.

Accelerated slope response in a destabilized alpine landscape

Simon Cox[1], Pascal Sirguey[2], Clare Lewis[2]

[1]*GNS Science, Dunedin.*
[2]*University of Otago, Dunedin*

Abstract
An inventory of landslides and quantification of landscape change in the Aoraki/Mount Cook National Park between 2008 and 2017 has been derived from photogrammetric digital surface models and orthoimages. Over 570 instances of landslide, rock avalanche, rockfall, debris flow or gulley erosion were mapped using change models and feature tracking. Large-scale mountainside failures are associated with snowfield retreat and trunk glacier down-wasting. Ice-loss is interpreted to remove rock-slope support, generate elastic and stress response and changes in groundwater pressure, which in turn cause loss of frictional strength, creep, dilation and velocity weakening of hillslopes. Primary, large, slow, creep-dominated disturbances involving kilometre-scale movements ~2 m/yr, appear responsible for many secondary, hazardous, rapid rockfalls and catastrophic rock avalanches. The new photogrammetrical products and 3D change detection enable environmental monitoring at a precision and scale never previously achieved. They highlight that rock collapses are commonly linked to larger-scale slope movements that can be observed. The next challenge is to link observations to underlying physics of processes, particularly the transition from creep to triggered collapse. High-resolution change detection improves the quantification of the magnitude and frequency of geological hazards in the Southern Alps of New Zealand, and landscape destabilization as climate changes.

Winter Snow storage is a poor predictor of spring streamflow: two case studies from the Southern Alps.

Tim Kerr

Rainfall.NZ, Christchurch

Abstract

The amount of seasonal snow that accumulates in a catchment will melt and augment stream flows during spring. This indicates knowledge of the size of the seasonal snow storage provides a predictor of the upcoming stream flow.

Seasonal flow forecasts using winter snow storage have been investigated in two catchments in the Southern Alps. The skill of the forecasts are very low. Efforts to improve the forecast skill by considering specific aspects or periods of the seasonal hydrograph has provided little improvement. The cause of the poor forecast skill appears to be related to the high variability in the occurrence of large rainfall events. The seasonal snow-melt signal in the hydrograph seems to be dwarfed by the flow impact of these rainfall events. The occurrence of large rainfall events at any time of the year is a distinguishing feature of the Southern Alps when compared to many other mountain ranges of the world.

The findings of these seasonal flow forecasting investigations are described and contrasted to similar forecast efforts undertaken in other mountain climates of the world.

The hydrological role of rock glaciers in an Andean desert

Shelley MacDonell[1], Ben Robson[2], Álvaro Ayala[1], Rémi Valois[1], Nicole Schaffer[1], Mike McCarthy[3], Giulia de Pascuale[1], Eduardo Yáñez[1], Camilo Guzmán[1], Gonzalo Navarro[1], James McPhee[4], Francesca Pellicciotti[3]

[1]CEAZA, La Serena, Chile.
[2]University of Bergen, Bergen, Norway.
[3]WSL, Birmensdorf, Switzerland.
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Abstract
In high altitude areas vulnerable to climatic change, rock glaciers act increasingly as important sources of water, especially during summer and dry periods. In arid and semi-arid mountain regions, these cryoforms are often considered to be long term water reservoirs that support efficient water storage and slow delivery. In the semi-arid Andes, rock glaciers are more abundant than glaciers, but their role in the wider hydrological system is little known, which is the driving impetus for this study. As water resources become increasingly scarce, and demand increases, there is a need for improved understanding of existing sources, and changes within the context of a warming climate. This study uses a multi-method approach, combining glaciological, geomorphological, geophysical, geochemical, remote sensing and modelling techniques to better elucidate the role of rock glaciers within the wider hydrological system in a semiarid catchment. We will highlight new methods and results for inventorying rock glaciers, modelling the energy balance, distinguishing hydrological sources and as well as quantifying possible hydrological contribution. We will finish by providing a roadmap for future work.

Tracking the snow line: Responses to climate change by New Zealand alpine invertebrates

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Abstract

We review and test ecological paradigms that suggest alpine invertebrate communities may shift upslope with climate warming. Our model couples the end of summer snow line (EOSS) elevation with invertebrate populations in New Zealand's Southern Alps, using a forty-year data set, from fifty index glaciers. We show the snow line has risen an average 3.7 m a−1. This is equivalent to raising alpine isotherms by almost 150 m and presents alpine biotic populations with four possible scenarios: upslope tracking, stasis, horizontal dispersal, or local adaptation. We characterize the alpine invertebrate biota (AIB) and present two case studies that show that high-elevation taxa have tracked the snow line within a narrow range (<20 m), whereas lower elevation taxa have potentially shifted by tens of meters. Relationships between the EOSS and Southern Oscillation Index (SOI) are investigated because precipitation and temperature influence snow line elevation by 25 percent. We also highlight the utility of invertebrates for monitoring climate change impacts on alpine ecosystems with a proposal for alpine climate monitoring units (CMUs), complementing an existing network of ecological management units (EMUs). We include an annotated list of New Zealand alpine invertebrates as potential indicators of climate change.

Managing water resources in marginal snow environments

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Abstract
Seasonal snowpacks in marginal snow environments play an important role in the availability of water resources. While marginal features are likely to become more widespread among snow-affected regions in a warmer climate, there are significant challenges to accurately measuring and modelling these resources. Many of the tools commonly employed are based on generalised relationships and assumptions that are applicable to colder and more persistent snowpacks but become less valid with the high spatial and temporal variability found in marginal settings.

Here we describe the physical and dynamical properties of the snowpack in the Australian Alps, and show how these limit the accuracy of traditional approaches to water resource management. The spring peak snowmelt season accounts for the largest and most reliable component of annual catchment inflows, though rainfall and snowmelt are common throughout the snow season and winter inflows make a greater contribution to annual variability. In such environments there is an increasing need to explicitly consider the dynamic nature of snowpack water storage and variability within the system.

The impact of glacier retreat on long-term water availability in the Waitaki Catchment, New Zealand

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Abstract
As climate change reshapes our water resources, long-term water security is becoming increasingly important. Glaciers can act as a significant water resource in regions with seasonal snowfall, specifically for hydroelectric power generation and water supply. The Waitaki basin, where some of the largest glaciers in the New Zealand are located, is one of the country's primary sources of hydroelectricity and water storage. Contributions to glacier runoff, namely ice melt, snow melt and rainfall, are particularly sensitive to climate change because small changes in temperature or precipitation can lead to large changes of seasonal water storage. We aim to understand how ice loss will affect runoff in future climate scenarios and how this relates to overall long-term water availability in the Waitaki.

Glacier mass balance for the Waitaki basin will be simulated using local climate data. Glacier geometry and extent will be sourced from digital elevation models and outline surveys completed in 1978 and 2016, respectively. Future mass balance will then be calculated using global climate models and annual glacier geometry projections to the year 2099 for four climate scenarios. The impact on runoff from seasonal changes to ice melt and total changes to the catchment's glacier volume will be determined.

Climate change impacts on snow and ice resource to support decision making: How precise do we need to be?

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Abstract

As climate change impacts the state and source of our water resources, water security and sustainability at across time horizons is becoming increasingly important. In mountainous catchments, snow and ice provide a critical resource that could buffer climate change impacts on downstream water users (electricity generation, tourism, environment, agriculture, cultural).

Climate change projections on snow and ice resources are available in New Zealand through the combination of climate projections and an ensemble of cryospheric models (DSC- Frozen water project) representing the whole spectrum of model structure (simple conceptual model to fully distributed high-resolution energy balance model). However, the current sparse observational network in New Zealand result in large uncertainties in those projections.

Using the example of the issue faced by regional council water managers in regard to the implementation of the newly update National Policy Statement for Freshwater Management, this paper is aiming to answer the question of on the level of model complexity to support policy decision making process. Analysis and model intercomparison at regional and catchment scales on snow resources and associated relevant hydrological fluxes is carried out and supported by a case study on the Waitaki basin for which local calibration is available.

Rain-on-Snow in the Southern Alps: hydrometeorology and impacts

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Abstract
Rain-on-snow (ROS) events are important hydrometeorological phenomenon in alpine catchments. Despite the frequent occurrence of ROS in the Southern Alps, the hydrometeorological characteristics of these events remain poorly understood. Of particular interest is understanding the characteristics of water vapour transport and its role in providing moisture and warm temperatures during the days leading to ROS events. Mid-latitude Southern Alps have been found to be largely influenced by frequent landfalling atmospheric rivers (ARs). The aim of study was to identify the role of ARs in producing winter- and spring -time ROS events by analysing integrated vapour transport (IVT). The climate variables from Mueller Hut automatic weather station located near the Main Divide of the Southern Alps were used to identify rain-on-snow events. In order to characterise the general patterns of moisture transport during major ROS events the 10 topmost ROS events with the highest daily accumulated rain were selected during the periods when snow was on the ground and a decrease in snow depth occurred. Our findings showed that all ten identified events were associated with strong fluxes of tropical water vapour travelling over Tasman Sea within a north-westerly airflow. Using an AR detection method, it was found that out of these 10 ROS events, nine were associated with ARs.