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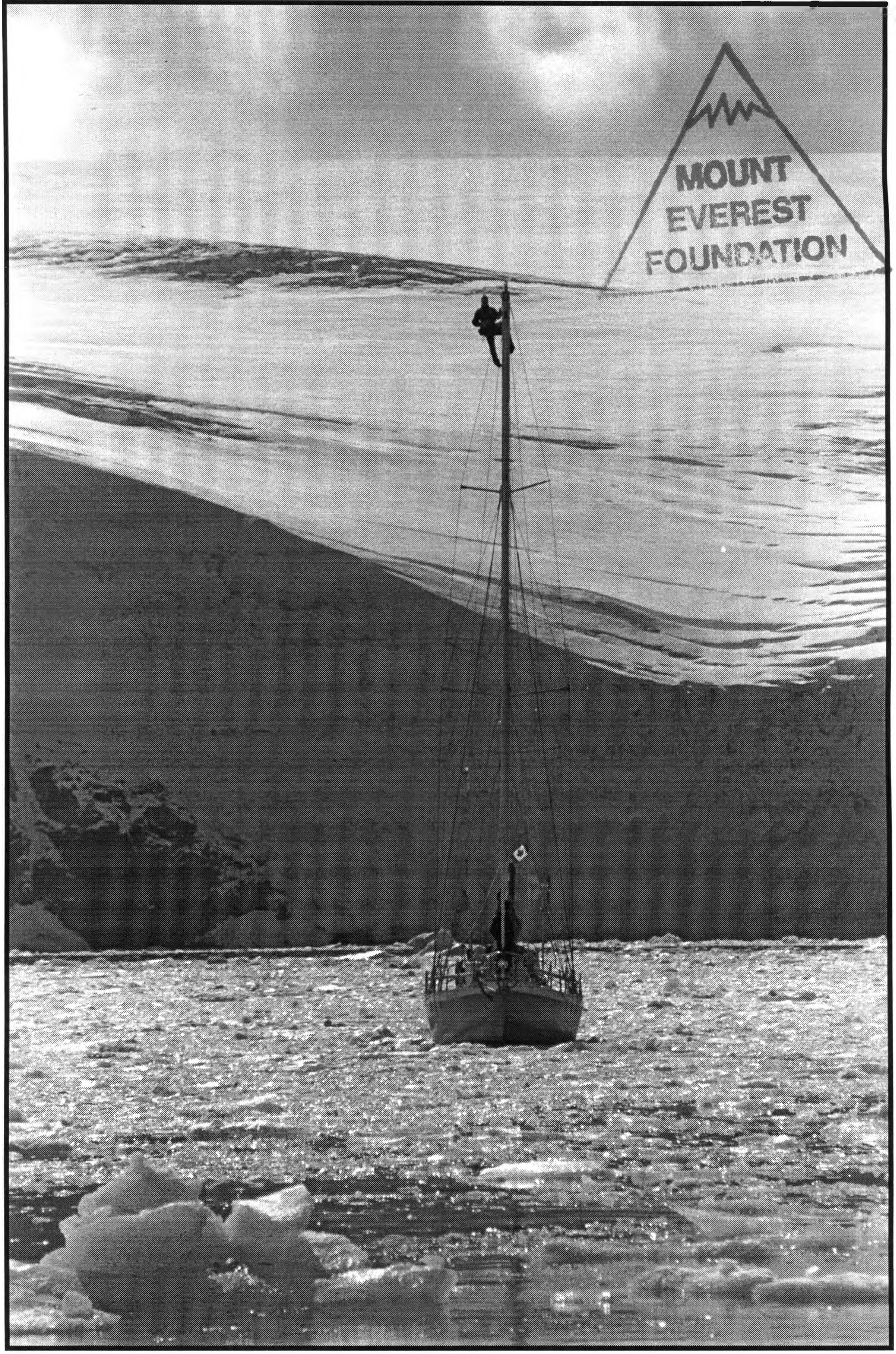

MOUNT
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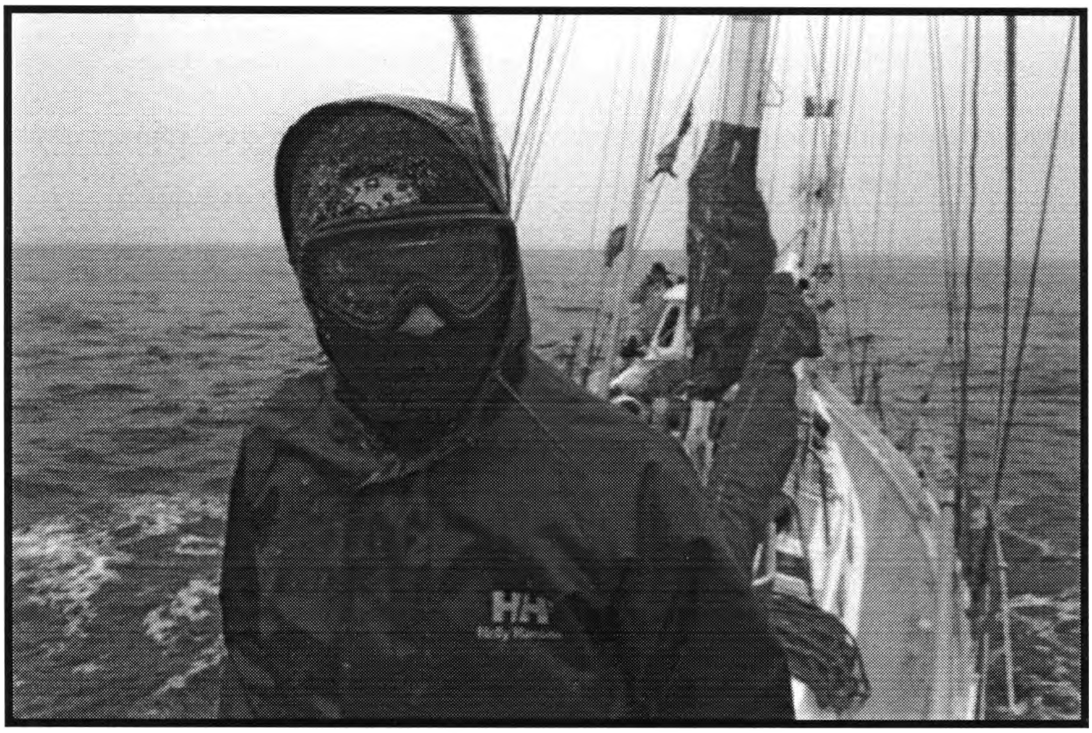


This expedition is dedicated to the memory of Jon Millar (on ice watch, above), who I was very fortunate to have on board *Gambo* for this voyage from New Zealand to Antarctica and who disappeared on the unclimbed NW Face of Devil's Thumb, April, 2003.

Frontispiece: *Gambo shunting brash and bergy-bits in Potter Cove, King George Island, March 2002.*

CONTENTS

TRIP REPORTS -

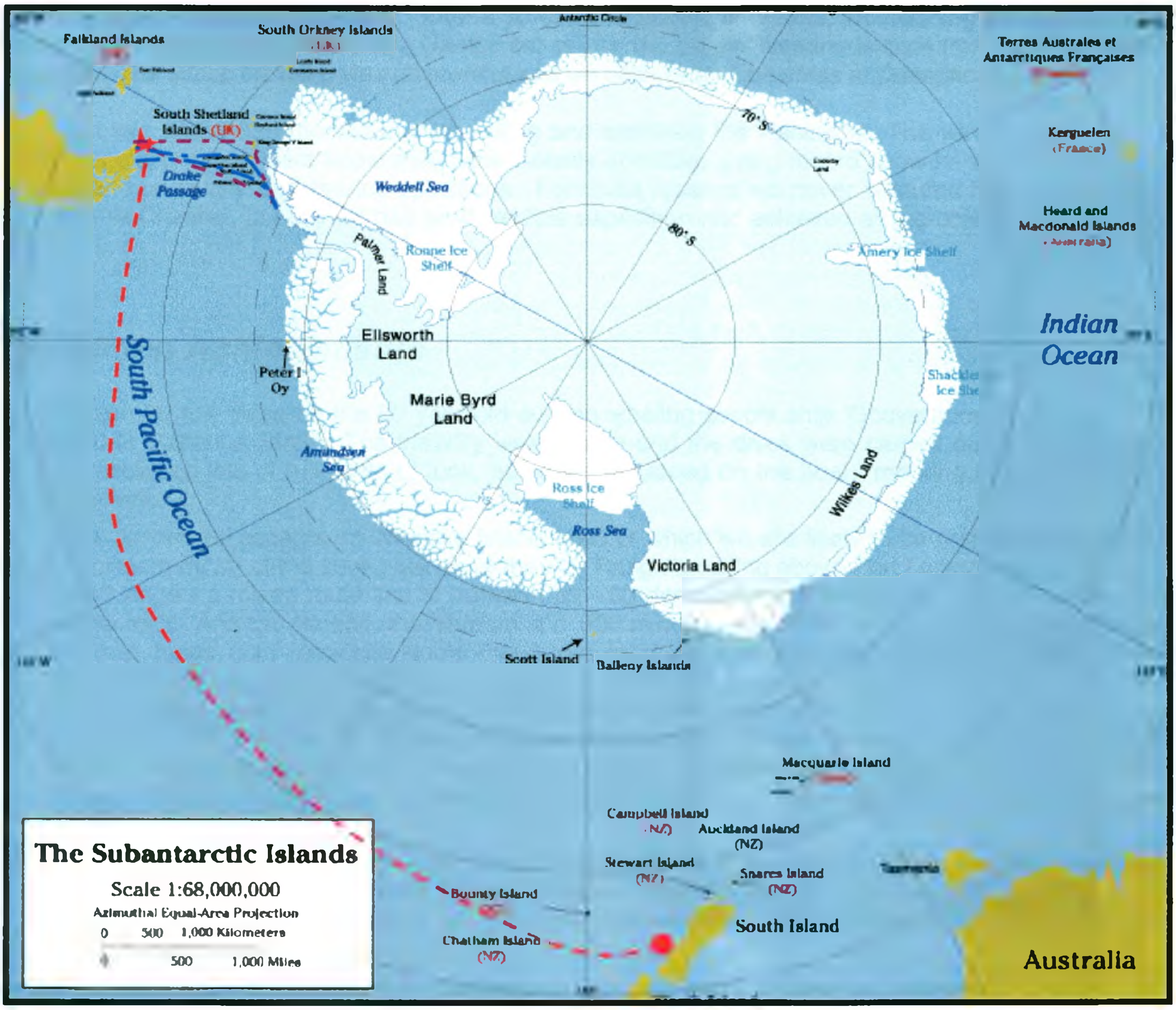
SCIENTIFIC REPORTS -

The Team

Leader & skipper – Dr Alun Hubbard, *Glaciologist* at Edinburgh University (32, Welsh)
co-skipper – Dr Dave Hildes, *Glaciologist* at UBC, Canada (33, Canada)
Peter Taylor, Self-employed *Photographer* (30, USA)
Grant Redvers, *Environmental Consultant* (30, NZ)
Jon Millar, *Unemployed Geologist* (24, Canada)
Elliot Robertson, *Publicity Officer* for RGS (28, UK)
David Fasel, UIAA *Mountain Guide* (29, Swiss)
Fraser Bernie, *Outdoor Recreation Guide* (31, Scottish)
Dr Andy Mitchell, *Water Chemist* at University of Toronto (24, UK)
Lena Rowat, *Tree Planter* in B.C. (29, Canada)
Penny Goddard, *Student* at Canterbury University, N.Z. (24, NZ)

Overview

Over a period of 6 months the above team successfully logged over 7,000 nautical miles of Southern Ocean sailing including a non-stop New Zealand to Cape Horn passage and four separate crossings of the Drake Passage to extensively explore, dive, mountaineer, kayak, ski and carry out glaciological and water quality monitoring on the West Antarctic Peninsula.



Synopsis

After two months intense refit and overhaul, *'Gambo'* and 4 crew (AH, GR, PT, JM) left Lyttelton, New Zealand on the 2nd Nov and made a c. 5,000 NM, 40 day crossing to Puerto Williams, Chile via Cape Horn. The first four weeks of the passage (sailed between 45 - 52 degrees South) were fairly uneventful but during the last 2 weeks we experienced a succession of 'deep low' systems. These systems gave sustained winds up to 80 knots, some 15 - 20 m waves and led to a 140° knockdown, which despite a few bruises and chaos below resulted in no major damage to crew or vessel. We 'hove to' for 48 hours before approaching the continental shelf west of Cape Horn, which was toasted in the traditional manner as we passed it the 10 Dec in fine weather. After a 10 day shakedown of repairs, provisioning and a successful rendezvous with the rest of the team, *Gambo* set sail for the South Shetland Islands from Ushuaia on the 22nd Dec. The Drake crossing was uneventful and we celebrated Christmas at Deception Island.

We spent two and a half months in total sailing and exploring the Peninsula. The weather and sea-ice conditions experienced were apparently exceptionally unstable, giving record snow-falls, high winds, bad visibility and unusually bad sea-ice conditions. For these reasons we never ventured further south than the Lemaire Channel, but still we had an incredible expedition and achieved all the objectives we set out to.

Expedition Achievements

- A dozen 20 m+ dives on the 80 year old sunken whaling supply ship 'Gouvernoren I' at Enterprise Island in Gerlache Strait. The visibility was superb and the dives were carried out without a hitch. We recovered lots of rusty bits of junk, harpoons (replaced on the boat), mooring lines (new) and a Nikon lens.
- Three successful ascents on Wiencke Island - two of which we are likely to be first ascents: the first (or northern-most) of the seven sisters of the Fief Range towering above Port Lockroy – c. 1,200 m by its NW ridge - a mixed route line of between 30 - 60 degrees with a crux steep rock pitch with very chossy rock. And the second, the 'shroom' a c. 900 m corniced summit on the Wall Range - climbed via 'Crag Jones' gully (opposite Noble Peak) to a nasty corniced ridge heading up left (north). Third, Mt Luigi (1400 m) climbed by its East Ridge via an exceptionally good ski route (we may claim the first split-board ascent and decent) with a snow climb of 300 m to the summit of up to 50 degrees. We also attempted many other projects on Wiencke Islands but due to exceptionally poor weather windows we had to abandoned. However, to keep sloth at bay we completed between 5 -10 ascents (almost daily: a total of 50) of Jabbet Peak each - including a first ever snow-boarding by a total novice.
- Three first ascents on the Peninsula: 1) Stolze Peak (c. 1,580 m) via skis, 2) the western-most peak of the Laussedat Heughts, and Mt Hoegh all carried out on skis with short technical sections at the end. Mt Hoegh was climbed in as welcome collaboration with members from the BAAE and completely led by the ACZE team.
- First ascent of Mount Britannia (c. 1,500 m) on Ronge Island - climbed via two routes - the first - the more technical east ridge - directly opposite Danco Island; and the second, carried out mostly on skis via its southeast ridge.
- A ski traverse onto the Peninsula Icecap Plateau via a route from the Orel Ice Fringe to the Downfall. Unfortunately, the team were weathered off the downfall - at the crux before they could get fully established on the Peninsula and a first ascent of Mt Walker achieved.
- We also completed some remarkable feats by inflatable kayak of which I am too sheepish to mention in print.
- The majority of our scientific work was concentrated into three weeks at King George Island:
  - Completed a surface and basal topographic survey of the Warzawa Icefield by Radio-Echo Sounding and GPS,
  - Took DGPS ground truthing fixes at numerous rock outcrops of Admiralty bay to constrain 1950's aerial photography indicating the extend of glacier and icecap retreat,
  - Collected a suit of over 150 sub-glacial and supra-glacial water-samples to investigate the spatial and temporal impact of minor and trace metals and other run-off nutrients into the Southern Ocean and,
  - Took over 50 samples of glacogenic material for biological extremeophile analysis.

Independent Report from Australian Antarctic Division

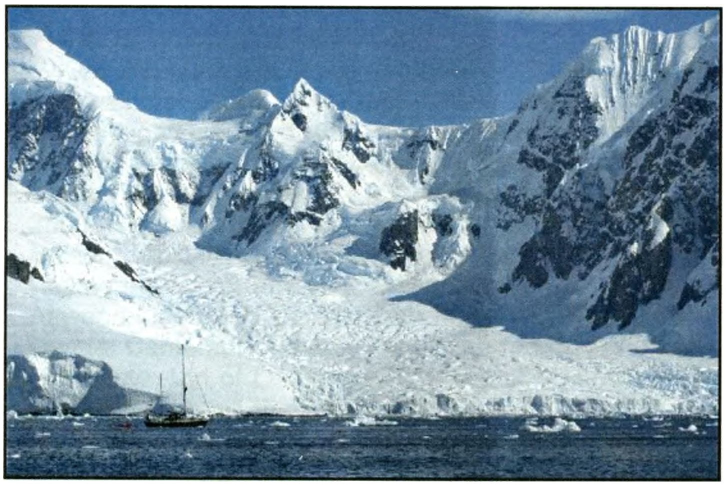
from **ANAN News 70/02**, *Antarctic NGO Activity News*, 10 April 2002

Members of the Antarctic Convergence Zone Project (ACZP) returned to Ushuaia, Argentina, late last month on the 15-m ketch 'Gambo' after a busy ten-week voyage to the Antarctic Peninsula region. The international group, whose aim is to combine adventure activities with serious research, spent the majority of its time climbing and recorded a number of first ascents. Sampling in support of the project's scientific goals was also undertaken (ANAN-48/03, 6 June 2001).

Canadian-registered 'Gambo', left Ushuaia on 22 December with seven people from Canada, New Zealand, Switzerland, the United States and the United Kingdom on board. The yacht visited Deception Island in the South Shetland Islands before sailing south to Enterprise Island in Gerlache Strait. There, a dozen dives to depths of up to 20 m were made around the sunken whaling supply ship 'Gouvernoren I' over the New Year period. Underwater visibility was described as "superb" and the diving program was reported to have been carried out "without a hitch", with many "rusty bits of junk", including harpoons, much newer mooring lines and a camera lens, being seen.

Most of the next ten weeks was spent in the area around the southern end of Gerlache Strait, a region that has attracted an increasing number of climbers over the last decade (ANAN-16/01, 1 March 2000). 'Gambo' then moved to Wiencke Island where a number of climbs, two of which may have been first ascents, were made during the first half of January. These included: a 900-m peak on the Wall Range; the 1,200-m high northern-most 'sister' in the Fief Range; and 1,400-m Mount Luigi in the same range, the descent from which was made on snowboards (ANAN-65/05, 30 January 2002). Other projects planned on Wiencke Island, but which had to be abandoned due to a prolonged spell of bad weather, included a full traverse of the seven sisters, an extremely technical mixed-rock and ice route on the Wall Range, and a "complete traverse" of 2,760-m Mount Francais on nearby Anvers Island.

Dr Alun Hubbard, ACZP's leader, told ANAN last weekend that the longest weather windows that his group got while they were at Wiencke Island were "rarely more than 18-hours long, and often less than 8 hours". Under such conditions, when the weather deteriorates very quickly, it was often a difficult challenge to retreat safely from committed climbs. The climbers frequently had to retreat out of gully and cornice systems in high winds and zero visibility, accompanied by constant powder and block avalanches as cornices broke off. One long-term observer of the region claimed that the weather in the area in the 2001-02 season "was exceptionally unstable and poor and the worst [he had] experienced for 20 years".



Climbing activities then moved to the Paradise Bay region. Mount Hoegh at the northern end of Paradise Bay was climbed with members of the British Army Antarctic Expedition (BAAE)(ANAN-65/05, 30 January 2002), however, further bad weather led to the abandonment of "numerous other projects" in that area. Ice and weather conditions combined to keep the yacht from travelling further south, so 'Gambo' sailed the short distance north to the Errera Channel from where numerous climbs were conducted over a three-week period.

Two "possible" first ascents were completed there, the first of 1,580-m Stolze Peak on the Arctowski Peninsula to the east of the Channel, and the second the western-most peak of the Laussedat Heights above the Orel Ice Fringe. Both were carried out on skis, although what were reported as "short technical sections" were encountered close to each summit. A third climb, which is also believed to have been a first ascent, was made of 1,160-m Mount Brittania, Ronge Island's highest point. A route up the eastern ridge directly opposite Danco Island was used, although later a second more straightforward ascent via the south-eastern ridge was also conducted.

In addition to those ascents, an attempt was made to ski to and climb 2,200-m high Mount Walker, a snow-covered feature near the northern end of the Forbidden Plateau. After ascending to an elevation some 1,500 m above the Orel Ice Fringe at the southern end of the Errera Channel, bad weather forced the climbers to retreat when they were almost across 'The Downfall', an area close to plateau level near the head of the Arctowski Peninsula. A party from the then British national program station on Danco Island had tried to reach the Forbidden Plateau from the Orel Ice Fringe in 1956, but they were forced to retreat by the very steep slope that was later given the descriptive name of 'The Downfall'.

The majority of the ACZP' scientific work appears to have been concentrated into the 2-3 weeks 'Gambo' spent around King George Island in late February and early March as it headed north towards Ushuaia. "Numerous" field trips were made from the yacht in Maxwell Bay to: "complete a surface and basal topographic survey of the 'Warzawa' Icefield; obtain global positioning system fixes at numerous rock outcrops of Admiralty Bay to ground truth and constrain 1950's aerial photography; collect samples of sub-glacial and supra-glacial water samples for the assessment of minor and trace metals and other run-off nutrients; and to obtain over 50 samples of glaciogenic material for extremeophile microbe analysis".

The data collected are currently being processed by Alun Hubbard as part of post doctoral work he is undertaking at the University of Edinburgh in the UK. Part of the work involves attempting to numerically model the recent past and future response of the 'Warzawa' Icefield to climate warming trends.

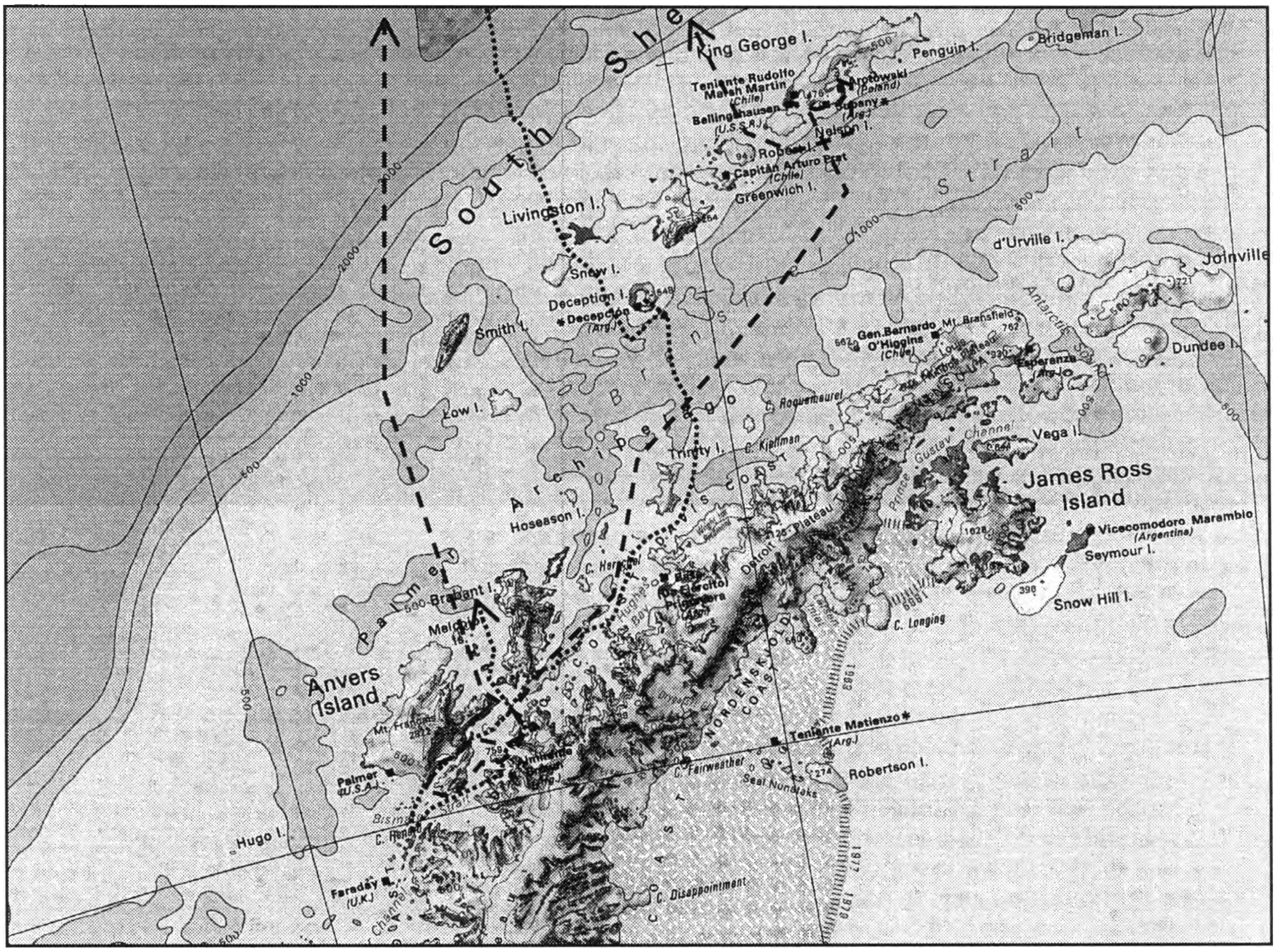
This season's voyage to the Peninsula was the first of what was planned as a three-year venture that involves visits to glaciers, ice-caps and glacierised islands in the Antarctic Peninsula and sub-Antarctic regions. Plans announced last year called for 'Gambo' to spend the 2002-03 austral summer visiting the South Orkney, South Georgia, South Sandwich and Bouvet Island areas (ANAN-48/03, 6 June 2001), but Hubbard told ANAN last weekend that while future plans are "open at the moment", 'Gambo' is now likely to return to the Peninsula again in 2002-03.

Hubbard says that while he personally considers the recently completed season to have been a "superb success", future ACZP activity will most likely have more of a scientific focus, and could continue for at least the next four years. 'Gambo' is expected to spend the coming austral winter in Ushuaia.

Acknowledgements

Myself and team would like to tribute the incredible support, hospitality and generosity extended towards us by almost everyone we met in New Zealand, Argentina, Chile and whilst in Antarctica itself. We are greatly appreciative of the RGS and Neville Shulman, the MEF, BMC, The Duke of Edinburgh, Gino Watkins Society, Capt Scott Society, Trans-Antarctic Association and the Polartec Challenge for financial support totalling some £14,000 without which Gambo would never have left Canadian waters back in 2000. We are also extremely grateful to the support and generosity of Garry Paulton, Matt Wood, Chris Nelson, Liz Cox, Sue Stubbenvoll, Dr Jo Kippax, Tom on Arikinui, David on Signet, Hubbard Cereals, Raymarine, Mark at Lusty & Blundell, Len of Slatecraft, the Naval Point Boat Club, Julian Freeman Attwood, Jane and Christchurch Museum, Barry Groom at WBMR, Gary and others at the Geography Dept at Canterbury Uni, my brother and Pete Nienow for support at home, Celia and the Ada crew, Yuge and Marie Ann of La Soree, Alain of Kotik, Dave, Jo and Ken at Port Lockroy, and all the cruise ships, yachts and bases that showered, wined and dinned us making our time down south such an enjoyable and memorable experience.

Expedition Timetable



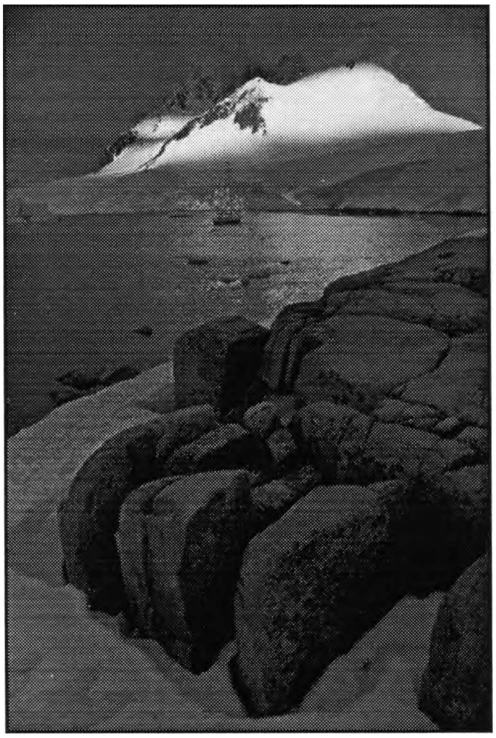
Maintaining a timetable and 'plan' was obviously necessary in terms of people coming and going, planning for food and safety, the mixed demands on our time due to sailing, mountaineering and scientific work, the limited weather 'windows' and the short Antarctic summer. Flexibility was the key due to weather, sea-ice conditions and the need to be always thinking at least a step ahead. Thus, the plan evolved as we went along but roughly took the following course:

- *Gambo* to depart Lyttelton, New Zealand late October, 2001 to corss the southern Pacific arriving at Ushuaia, Argentina, via Cape Horn in early December.
- Re-stock and final checks, additional crew to arrive and depart Ushuaia mid-December.
- Cross Drake to arrive at Deception Island, South Shetlands before sailing as far south onto the Peninsula proper as safety and sea-ice allow.
- Spend 5 weeks sailing, mountaineering, scuba diving and ski touring before leaving a well provisioned shore party of four with a RIB and fuel at an appropriate region for committed non-supported mountaineering and ski-traverse, whilst *Gambo* returns to Ushuaia with reduced crew.
- Arrive Ushuaia early February for crew swap, re-provision, re-fuel and return to Peninsula asap.
- Rejoin and relieve shore party and spend 3 further weeks exploring, mountaineering and ski-touring.
- Sail north to King George Island for three weeks of scientific work on the Warzawa Icefield and depart early-mid March for final sail across the Drake.
- Arrive in Ushuaia, clean up – maintainance for over-wintering *Gambo* at Puerto Williams.

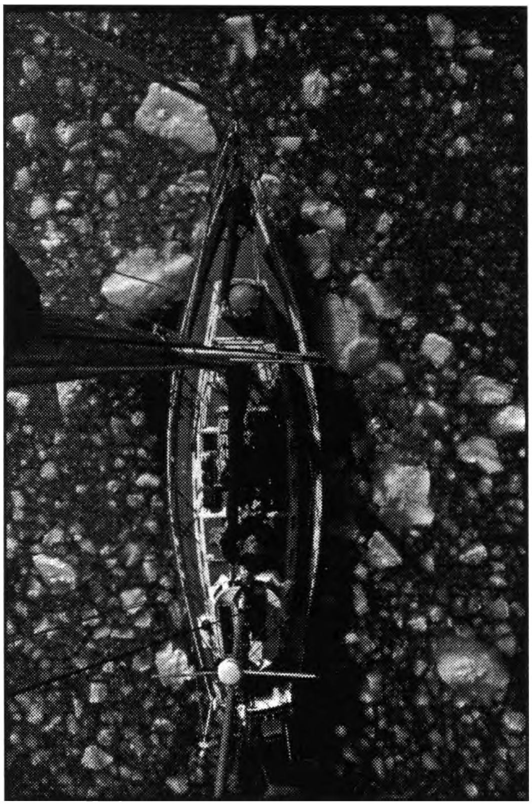
The Antarctic Environment and Wildlife

The wildlife and land- and seascape of the Peninsula, sub-Antarctic Islands and Southern Ocean are truly spectacular. In retrospect there was barely a moment when there was not some fantastic sight to experience, and then, at the time, it often felt so overwhelming it had little comparison. Despite this, the physical characteristics of the environment presented considerable challenges and it is this juxtaposition of the sublime and yet unforgiving nature of the environment wherein lies the real fascination of attempting to explore such an region under sail and ski independently.

Much of our time was spent considering how best to negotiate this environment safely and planning for contingency need the necessity arise. The Drake passage is notoriously hostile and lived up to expectation. Ocean legs were committing, with weather and sea conditions changing rapidly as the funnelling effect of Tierra del Feugo and the Peninsula, coupled with the Circumpolar Current means many systems are likely during an average 4 – 6 day crossing. *Gambo* cruises at roughly 5 – 7 knots (120 – 180 nm/day) but is often slowed up depending on prevailing winds, currents and sea-conditions thereby enhancing the likelihood of increased cruising time. High winds, up to Force 10, some 50 odd knots and large swells up to 4 m, breaking waves and blizzards were experienced often. In-shore sailing, often in fog or whiteout meant that icebergs were also a major problem, especially at night towards the latter part of the expedition and often radar was used, but could not be relied on since it would not pick up 'growlers' which lie deep in the water only just penetrating above the surface. Homogenous sea-ice or pack ice was definitely to be avoided (despite *Gambo's* 1.5 inch steel stem & additional HP) except on a couple of occasions where we could see across to clear waters ahead, and ultimately prevented us from sailing as far south as we would have ideally liked. Typically though, the swell was considerably improved inshore of the Peninsula, which made ice watch and general conditions much more amenable to the boat, crew and safety.



Katabatic winds, generated from cold air descending from the ice plateau down outlet glaciers, regularly blow at 80 mph and can easily reach 180 mph. These are a constant concern when the yacht is inshore and especially on mooring lines or in areas where there is much sea ice or wandering bergs. A couple of the crew on ice watch or checking mooring lines is vital. Navigation in ice-strewn water is perfectly feasible, although inevitably slower. Winds and tidal currents mean that there is a constant circulation and movement of ice bergs and brash, and concentrations can in the worst case, trap or severely damage a yacht. *Gambo* is extremely strong, but her trim-tab and steering gear is definitely an Achilles heel and much time and effort was often spent fending off various bergs and brash from her rear quarters. Big bergs (> 20 m above water) were plentiful, easily navigated and always a spectacle of fascination with their infinite and varied wind and sea sculpted details at every scale. Permanent sea ice (fast ice) formed over winter begins to break up throughout November and starts to reform in March though as noted above, where it breaks out to or indeed if it does at all, depends much on the winds, currents and the vagaries of Antarctic weather in general. We unfortunately had a bad year, the previous two seasons had been record good seasons. A particular difficulty in freshly glaciated landscapes like Antarctica is the lack of holding ground from which to anchor a yacht. In Antarctica where most of the shallows have been recently scoured clean by eroding glaciers, one has to resort to a series of long but very sturdy shorelines tethered with steel strops to appropriately sized boulders of anything else that may help hold a 22 ton vessel being blown about in a 100 mph wind. In total we usually put out between 4 and 6 such lines depending on the layout of the cove in question and the nature of the winds that hit it. We usually put out the anchor as well but that was more to prevent the boat from drifting too much whist the mooring lines were being deployed. Some of the best such coves, eg Dorian Cove have a shallow reef across the entrance which can only be navigated at high tide and which subsequently block big bergs which may drift into the vicinity in a strong NW'ly. Although at first a challenge, the use of shorelines, once mastered was straightforward and in our experience was successful even in some ferocious katabatics. The key to success would be to have at least one line to each corner of the yacht so that they can be loosened of tightened accordingly so that the gusts could be taken on the nose, and hence reduce windage to an absolute minimum.



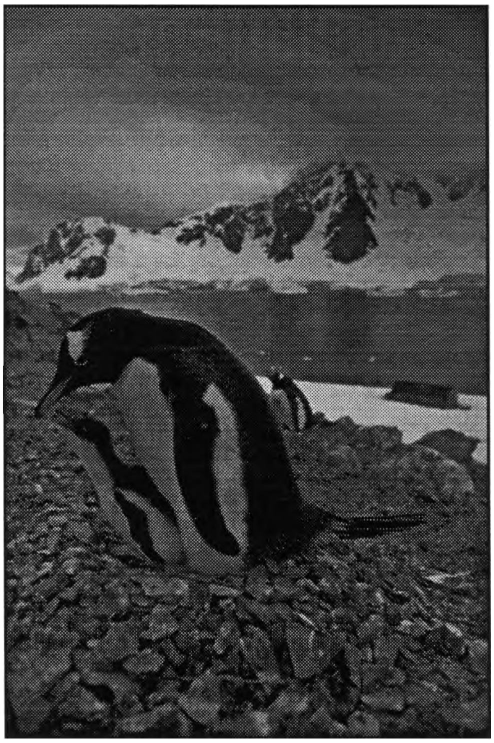
During our time there, the weather conditions were typically unstable and characterised by rapid deterioration. Windows were rarely longer than 18 hours and often less than 8 hours. Sea ice conditions further south were exceptionally poor and prevented navigation south of the Lemaire Channel, into Marguerite Bay where we hoped to establish our shore party. It was 'an exceptionally poor and unstable' year as put by Dave Burkett at Port Lockroy who has been with BAS in the Antarctic since the 1970s and the polar high pressure that typically dominates this area and which deflects the incoming systems further north into the Drake unfortunately failed to form. The impact of poor weather and sea-conditions meant we had to remain further north, thus restricting our activities to areas more prone to incoming low pressure systems.

Almost exclusively, travel ashore was dominated by methods suitable for travel in glaciated regions. The sea – land boundary is almost entirely calving glacier or steep snow fields, and offers few good places to land and off load. Access to good landing sites is thus a significant factor in any mountain approach though careful scrutiny and reconnaissance usually pays dividends. Once ashore, travel is only possible by ski or snow shores due to continuous fresh snow cover and danger from collapsing crevasses. There is very little exposed terra firma except on steep terrain and most of the Peninsula is characterised by steep and broken outlet glaciers draining the inland plateau at some 1800 m and above. Continuous fresh snow, coupled with prolonged warm temperatures due to the long Antarctic day meant that avalanches were a constant feature. Similarly, glaciers were often heavily crevassed with soft snow bridges often heavily sagging at low elevations where the lack of clear cold weather, warm temperatures and continuous fresh snow fall enhanced all these objective dangers. Travel became considerably easier with elevation as slope angles eased and temperatures dropped, though such forays for longer multi-day trips were then logistically hampered due to extra food and fuel required in contingency. Temperatures over all were mild, 10 to -10°C but lowered to -35°C and colder with wind-chill towards the very end of the expedition. Whiteout was very common and made travel with no maps next impossible often for up 12 – 36 hours at a time.

Wildlife was a continuous joy when on or near the ocean. On land, bird and seal colonies were limited to areas of easy access and terrain, away from the coast there was little sign of life. The number of birds and the variety was humbling, with regular sightings of gulls, albatross, skua, duck and petrels plus tern, sheathbill, shag, cormorant, heron and kingfisher. The bird life cannot be passed over without mentioning Penguins and without doubt the abundance of Gentoo, Adelie and Chinstraps were the mainstay of non-stop inspired entertainment for the expedition. Seal were also common, with regular sightings of Elephant, Fur, Weddell, Crabeater and Leopard. Their behaviour ranged from curious to disinterested to outright aggressive, but always proved great to watch as they played, hunted or lazed on passing ice floes.

Whales were also regularly sighted, the most common being large pods of Minke. We were also graced at close quarters by Humpback and Orcas who showed a healthy curiosity in our RIB activities. The Minke were extremely curious and friendly and wonderful to watch as they would come into close quarters with *Gambo* playing in the bow wave and rolling and diving around the hull for hours on end and often accompanying us until late into the night. The larger adults (up to 8 m) would typically remain nearby while the younger animals would rub up against the hull or RIB and inspect us. Similarly porpoise and Jackson dolphin would come close up, riding the bow-wave or doing back flips. The overall impression was that wildlife was bountiful and thriving though we were throughout very aware of our impact and so limited our time near colonies or sensitive areas. Similarly, our FCO permit governed our activities in such areas and throughout the expedition the guidelines were strictly adhered to.

ENVIRONMENTAL IMPACT



Waste Disposal

The ACZE and its members strictly adhered to the environmental guidelines outlined by the FCO and in the ACZE's Section 3 Antarctic Permit application. All waste apart from human and grey water were compacted, double bagged, sealed and returned to Argentina. Batteries and plastics were sealed and stored separately but again returned to Argentina for appropriate disposal. There were no hydrocarbon spillages. As detailed in our application, all camping fuel was carefully decanted from main 5 li storage containers into 1 li sig bottles before use onshore. Outboard fuel was transferred from 20 li storage containers to the two 20 li outboard tanks before use in the cockpit of the yacht where any spillage could be contained and dealt with by detergent and absorption mats which were always on hand. No paints, radio-active materials, substances with harmful levels of heavy metals, toxins, POPs or other prohibited products were used.

Grey Water & Human Waste

Grey water and human waste were disposed as outlined in the application in accordance with FCO guidelines and Antarctic Treaty Regulations.

Grey water and liquid human was disposed of in snow pits or diluted by natural running water (not fresh water) if available, both of which will be chosen away from any wildlife concentrations or sensitive areas. Detergent or cleaning agents were not released on shore. For remote onshore operations, human waste and grey water was disposed of in deep snow pits. If possible human waste was disposed of on the shore below the high-tide mark. Camps were in every case sited on snow and ice to minimise disturbance to ice free sites.

Sensitive Areas and Huts.

No SSSIs were entered and the expedition members made every effort to minimise disturbance to any Heritage sites; e.g. the wreck of 'Gouvernoren I' at Enterprise Island and the derelict whaling station at Deception. Four expedition members spent 5 nights at Danco Hut, Danco Island on the basis that our overall impact on the adjacent snow-free areas taken up by a Gentoo Colony would be significantly reduced. The team left Danco Hut in a better state of repair than they found it, having cleaned up inside and completed repair work on the steps and roof of the building. It is badly in need of attention since it is starting to leak through the roof and a few windows are broken. No supplies or other resources were used from Danco Hut and the team remained totally self-sufficient during their short stay. Similarly, whilst Gambo was moored in Dorian Bay, Wiencke Island, the team used Damoy Point Hut as a shelter and to store gear and food. Again the hut was left in immaculate condition (it is in excellent condition though tins are leaking in the ceiling) and we also removed c. 23 semi-empty rusting and leaking 5 gallon steel fuel containers which were located beside the adjacent Argentine shed. The remaining contents of these rotting steel containers were decanted into plastic fuel containers and then they were sealed, double bagged, lashed on the deck of Gambo and disposed of in Argentina. I decided it was prudent to remove them since they were actually leaking petrol and contaminating the ground soil. There still remain a number of rusting fuel drums at this site but they are empty (of fuel) with little risk of significant ground contamination.

DECLARATION

As far as I am aware, the members of the ACZE fully adhered to all conditions under the Permit for activities under Section 3 of the Antarctic Act 1994 issued by the F.C.O. (# S3-17-01/2001). Furthermore, to the best of my knowledge, no harm occurred to any native mammal or bird or their habitat as a result of the activities of the ACZE.

Dr Alun Hubbard

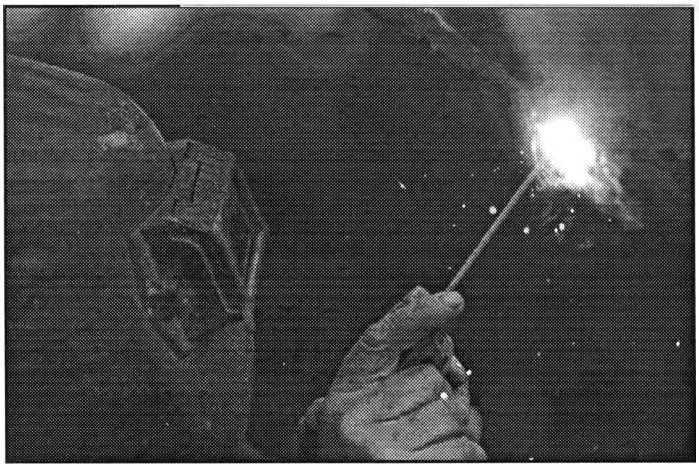
LYTTELTON TO CAPE HORN

THE SOUTHERN OCEAN FOR ROOKIES...

BY Alun Hubbard

Take a 47' steel ketch, a dreamer brought up on the Welsh coast on a diet of Bill Tilman and David Lewis with a penchant for high-elevations and latitudes, add the un- (mis-) directed enthusiasm of a bunch of oddball mountaineers come glaciologists and eventually that Terra Incognita, Antarctica will become a vision. This project was conceived on an uneventful, if unusual Christmas Day snow-bound in a blizzard, with an Italian, a Chilean and another Brit towards the end of a 6 week ski-traverse of the Patagonian Icefields. It was day six of this unrelenting tempest, our tent was no more, we were buried under 11' of snow, and all that remained to sustain us was a very well used tea-bag, a handful of prunes and swear-word scrabble ('International Edition'). As one does in these situations, we were idly speculating on the lengths human idiocy could go for adventure and exploration when it occurred that cruising Antarctic waters in a well stocked, floating and mobile mountain hut was the way forward.

Four years later, armed with an appropriate boat, some 'accelerated learning' yet idyllic Alaskan, Pacific and Kiwi cruising experiences and a motley bunch of acquaintances, I was hauling anchor at Pigeon Bay, Banks Peninsula; next stop Cape Horn, 5,000 NM off. It was 2 Nov, 2001 and to reaffirm maritime superstition is not total cobblers (i.e. with a Friday departure), we were promptly blown in much the wrong direction by a Force 8 SE'ly. It was a tad too close for comfort to Wellington (Grant Redvers, our Kiwi's hometown) when the wind eventually swung to a relaxed 30 Knot SW'ly 30 hours later and we were eventually headed west. After many years of planning and scheming, it was undoubtedly good to be on our way.

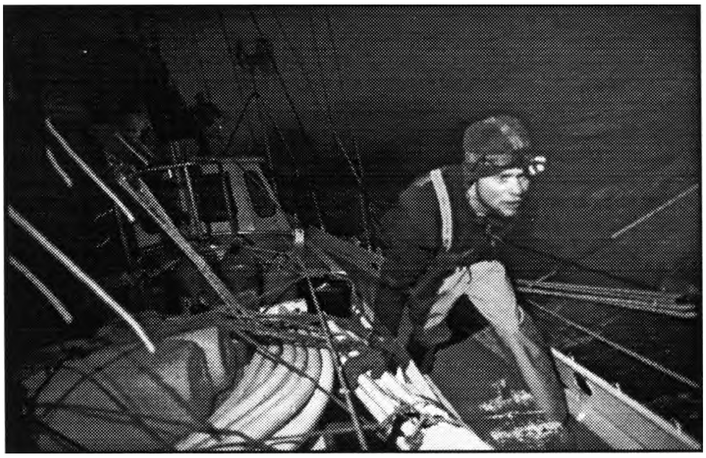


However, it was not in the original plan to set out from New Zealand, but one that I am grateful came about. Myself and partner, Dave Hildes (a speed skater from Winnepeg, Canada; a town about as landlocked as one can find on the planet) stumbled upon *Gambo*, a custom-built Ganley design, in British Columbia under very fortunate circumstances. After two years of frustrated hunting (to a point when we were considering building our own boat), and with little more than dingy sailing and maritime hearsay and lore to guide us, *Gambo* miraculously materialised. Ideal for our needs; she was strong, basic and bombproof. At 45' on deck, 12' beam and 6' draft, *Gambo* was certainly heavy at 22 tons.but then she was built like a tank, had a hull of 5/16" steel plate, a solid cutter rig, tremendous water and fuel capacity, a heap of weighty ground tackle and a new set of sails. Her owner and builder, Dai (another Welshman, hence her name and red dragons on her bow) was definitely old school. In twelve years since he had built *Gambo,* Dai had clocked over 45,000 NM of Pacific cruising with just 146 hours on the diesel and prided himself on a solo voyage from Vancouver to the Marquaises and back using less than a 'cup-full' of diesel. As one may expect, state-of-the-art gismos were scarce (the compass, sextant, wind-vane, 1000s of ancient charts and a well thumbed 1950's Admiralty Book of Ocean-Passages being it) but she was solid, sound and most importantly, affordable and ready to go. Dai had been about to set out on another solo world voyage via the Capes, but sadly, his health had deteriorated, and so it was indeed a fateful day when I spotted those red dragons, paddled over and rapped on the hull.

However, a job researching Antarctic glaciers at Canterbury University put our plans on 'ice' for a while and apart from a 3 month, 2,500 NM trip up to Disenchantment Bay, Alaska to make a first ascent on Mt Cook (that master mariner and explorer was there well before us) I was content to dream and scheme. Furthermore, I realised that *Gambo* would need some extensive modifications in preparation for the ice. Unlike Dai, I am not Luddite and there were a few aspects to *Gambo* that I wasn't happy with, not least her lack of progress when her 40 HP BMW was pushing against any headwind and slop, and there would be much of that in Antarctica. Hence, it was an inspired move to sail her from Alaska across the Pacific in 2000 for some marvellous Kiwi hospitality, debauchery and engineering ingenuity. Throughout 2000/01 *Gambo* and I clocked-up some fantastic cruising around New Zealand (enjoying the post-christmas/pre-new year gale about 100 NM east of East Cape) and ending up, with the enthusiastic support from the Little Ship's Club, on a mooring in Monks Bay, Christchurch. It is an idyllic spot and despite some comical moments midnight skinny-dipping in the 6 kn tidal stream two sheets to the wind, it put *Gambo* into the local spotlight and there was never any shortage of visitors. She was even in the backdrop to the national evening news.

But it was checking out the remains of Lyttelton Mariner after the infamous October storm that I by chance started chatting with Garry, a tall, gaunt and weather-beaten local, as he was pulling out a diesel through the hull of one of the many sorry broken wrecks that lay strewn about. Simply put, this man, subsisting on a diet of cigarettes and coffee, made it happen for *Gambo*. In the frantic 7 weeks before departure, Garry, helped (or possibly hindered) by our team and many friends put in a new 70 HP Nissan diesel and transmission, sand-blasted, ground and ice strengthened the hull, installed a new set of winches, wind-genny, radar, sounder, GPS, wind and other instruments, 'remodelled' the interior, repainted the hull a dozen times over and crucially, installed a fan heater torn out of a scraped Wolsey and a 'gin seat' on the stern-rail. It was phenomenal to be caught in this frenetic activity after all the saving and scheming and I am humbly grateful to all those who got stuck in and helped us out. There were some dark moments but in Garry's words, she was indeed 'a goer' and throughout we were either crashed out on mate's floors or socialising like there was no tomorrow, with one particularly (un-)memorable night at Naval Point Boat Club trying to convince a bemused audience of the sanity of our plans whilst succumbing to endless pints of rum and coke (speakers privilege apparently). It was in this context, with a last minute scramble for provisions (a ton of Hubbard's porridge and bumper-bars), diving, skiing and climbing kit, 'one careful owner' New Brighton Surf-Rescue inflatable and outboard, that we pulled anchor at Pigeon Bay and headed towards Cape Horn. Well, north actually as you know, but those first storm bound days were a fine introduction to conditions expected further south and the somewhat over-laden boat's reactions. In the first days we were hit by gusts over 70 kn but thankfully no big waves and despite being somewhat off-course, the crew taking a while to find their sea-legs, I felt comfortable with the boat, the sea conditions and there was no turning back. Indeed, it felt strange, a rather intimidating baptism of fire even, but also very exciting.

Strategically, I was over cautious at first, sticking to the 45th parallel only slowly edging south past the Chathams and eventually much later into the furious 50s as my confidence in our abilities grew. Taking it so conservatively added another 800 NM odd to the great circle route of 4,200 NM which should have taken us SE past the Bounty Islands but I had David Lewis and Gerry Clarke's experiences in the forefront of my mind and was eager not to beat up the crew or boat who were novices to the Southern Ocean. As a result we had slow crossing; it took 38 days in all from New Zealand to rounding the Horn and onto Puerto Williams (compared to Peter Blake's 29 days on the 118' Seamaster the previous year) but the first 3 weeks were marvellous sailing in cool but perfect 20–50 kn winds alternating between NW and SW as the low systems and respective fronts passed over us every few days or so.



A team is usually a pragmatic given, rarely ideally chosen. It's hard finding seasoned sailors who can ski and climb and are willing to drop all for a half-year voyage into the Southern Ocean. But I was very lucky and had done well. None of the crew had much offshore experience to talk of but Jon Millar (23), a stoic, intelligent and peaceable west-coast Canadian mountaineer was a total adept and a trooper from the outset. Peter Taylor (30), a New Yorker with a gift for the gab and some masterful stock-phrases, had sailed the Florida Keys (no doubt with beer in hand and Jimmy Buffet blaring) on his own 28' sloop *'No Pain'*, was an asset despite an urgency which put watching paint dry into the realms of an extreme sport. His 'tuning-up of mission critical systems in fast-track resolution terms' and 'extensive back checks to preclude a real show-stopper' were certainly always appreciated, if mostly for general amusement. And then there was Grant (28), the laid-back, go with the flow Antarctic veteran, who had never set foot on a sail-boat, but what the hell, he'd chucked his job, his girl and was up for the big ride. Once over his appalling sea-sickness which plagued him for the first couple of weeks, he soon got the hang of it all and was a master on deck, knitting hats for all, and had taken on the unenviable role of chief-chef. Morale was good, as was progress and we even managed regular-ish SSB contact with Barry Groom at Waikuku Beach Radio on 4225 kHz and it was about 3 weeks through when we entered 'the Hole' and experienced one of those exceptional magical days one never forgets.

The Hole is the no-man's land of the Southern Ocean and lies approximately 1,600 NM equidistant from the Chathams and Patagonia and Pitcairn and Antarctica's Cape Dart. It is the most distant a person can get from humanity on the planet and absurdly enough we sailed into it with a high-pressure dominating yielding a gentle 15 kn westerly and under a cloudless sky we flew *Gambo's* red and green spinnaker. With weak watery sunlight tripping the kite fantastic, dolphins skipping in the bow wave and shear-waters and albatrosses dancing across the sea, installed in Garry's stern seat I was a content man, made blissful by my first G&T in a long while. But the Southern Ocean was not going to let us get away so lightly. This ocean's elemental might is immeasurable and in retrospect it is an old Scottish saying that springs to mind... no-one messes with impunity. With no landmass on its whole easterly race around the circumference of the earth to deflect it, the westerly winds and seas that the collision of Antarctic and tropical air masses spawn are phenomenal and in the last 12 days of the voyage I believe we felt a little taster of the Southern Ocean's fury.

We were 53°S, well south of the Antarctic Convergence and were used to a consistent 3-5 day pattern; kicking off with force 4-5 NW slowly growing in strength to force 7–8 and then rapidly veering to a vicious force 9–10 SW'ly as the cold front passed over along with a clear, but bitterly cold day of choppy and confused seas as the wind died. Although, the winds were occasionally ferocious, they were never sustained and mostly we sailed with a double reefed or no main and between 10 and 50% of the jenny. Seas were lively with the occasional wave breaking over the boat giving the helmsman a bit of a pooping but they were never threatening and with a 3 hour night and 4 hour day watch cycle, even though it was sub-zero, it was quite comfortable.

About 1,500 NM east of the horn it went pear-shaped; no rhyme nor reason to the systems which hit us (and which appeared to be passing daily) and the barometer was yo-yoing all over the place though never much above 970 mb. We were blasted by some vicious sustained winds, gusting force 12, all westerly and with it some immense waves. It is always difficult to estimate height but these monsters were true grey-beards, just stacked up, wave upon wave upon wave. However, they had a long wave-length, were nicely spaced and never so steep as to threaten a pitch-pole. Still, there were times when I would to stern with a surreal sense of disbelief at the mass of water topped off with a breaking crest that would be almost upon us; relative to our mast, which was dwarfed in the troughs, these sea-swells were well in excess of 50'.

However, I was impressed with the boat and crew. *Gambo* being narrow and heavy with a long fin keel and skeg-rudder was behaving perfectly. One of these waves would catch us and on the verge of overwhelming us when abruptly the stern would jack-lift up and then we'd be headed down an awesome ~20° slope and start picking up speed. It was pretty nervy if elating stuff to be surfing across the faces of these waves at 15-20 kn but the boat held true and responded beautifully. Throughout, we used a wind-vane steering a rudder trim-tab but occasionally helm would be carefully applied to prevent a broach or nose-dive into the troughs. These circumstances were certainly inspiring and nervy not ever out of control; akin to those that Bernard Moitessier describes putting his 40' steel ketch, *Joshua*, through in pretty much in the same place some 33 years earlier. With four of us on *Gambo* though, compared to his humbling solo achievement, it was hardly demanding on us. Jon put prolonged hours in at the helm in his $5 foulies, farmers gum-boots and industrial PVC gloves. Grant and Peter were taking it in their stride too and if they were anxious about conditions or weary of the all pervading cold, damp and dripping hatches as waves crashed over the boat, the strain rarely showed and our banter and meals were up-beat and always entertaining. We even tuned into the BBC world service to keep us updated on the latest apparent non-event in the war on terrorism, which has to be said, felt somewhat removed. Therein lies the joy of sailing with a crew of mountaineers, ignorance is bliss and all of it beats being tent-bound for days on end. Furthermore, the huge excess of charge the Ampair wind-genny was putting out also became a challenge (to dissipate) but for sure, we had LOUD music. In that week we also made superb progress covering 1,000 NM under storm-sail/bare-poles alone and if I was worried, then it was only with respect to the possibility of further deterioration and an unwelcome encounter with big tabular icebergs, of which I'd sighted one.

A week from the Horn we got knocked down, over to about 120 degrees to starboard. The irony is that the wind was not particularly strong (30-40 kn) nor the waves particularly big when it happened. The sea though, was extremely 'lumpy' due to strong S'ly and NW'ly cross-winds which had 'interfered' to give rise to the freak rogue that got us. To be honest, I think there is little preventive action one can take in such random seas; it may appear complacent but preparing for the worst and sitting it out seemed (and probably was in retrospect) the most appropriate course of action. It was late evening, Grant was on watch, the rest of us sleeping, and then we went right over to starboard and back up, all within about 10 seconds. After the initial shock of coming too on the cabin floor surrounded by total chaos (topped off with a vat of chilli I'd prepared earlier), it became immediately apparent just from the feel of the boat that both the rig and hull were intact. Over the next moments, I called out to each crew in turn to establish that all were present with no injuries and once complete, that first adrenaline fuelled panic subsided, I began to see a lighter side to the chaos which prevailed around me. Jon and Peter had been flung across the cabin but other than a few bruises, were fine. Grant who had been stuffing his face at the chart table, sat in horror as the entire contents of the galley rained upon him; knives, pressure cooker and the entire set of 'unbreakable' crockery which were now dispersed across the cabin sole in a zillion pieces. There was even a bread knife embedded in the woodwork next to his head. We had been fortunate, all told.

A knockdown though is par for the course in the Southern Ocean and we were prepared. They always seem to catch one unawares though, but Lewis, Clarke, Moitessier, Knox-Johnston, and all the small boat Southern Ocean pioneers had suffered multiple knockdowns and I knew Alyard Coles 'Heavy Weather Sailing' cover to cover. Even Australian Don McIntyre's Arctos, a brand new high-latitudes custom made aluminium yacht with an 8-man crew on the same route a fortnight behind us suffered numerous knockdowns and had three crewmembers washed overboard. It would be total ignorance to venture out into the Southern Ocean for such a sustained period in denial of such a calamity. However, it is one of those experiences, much like a first lead climbing fall, that one is wholly fearful about before hand, requiring a leap of faith in ones instincts and gear but which after the event infinitely expands the envelope of vision and experience. Certainly we were lucky; it could have been much worse if Grant had been on deck since the wave that hit was evidently big, tearing off our hard dodger and other 'sacrificial accessories'. However, knowing that my trust in the boat and rig was not miss-placed, and that *Gambo* could be thrown right over without breaking-up or the diesel and batteries flying about was, ultimately, a great confidence booster. After such an event, one sees the whole game in a new light and all those thankless hours on the hard in Lyttelton had indeed paid off.

Despite all this, I sailed more conservatively in the subsequent blows that hounded us the rest of the way to Cape Horn and took a more positive line action where appropriate. The boat was doing fine; it was the crew, running rigging and sails that were beginning to show strain and fatigue. One night, the Genoa got caught up as Jon tried to furl it in and it was a distressing time in freezing, wild conditions on the bow-sprint attempting to unravel it. Eventually I cut the sheets, furling line and let it fly before it ripped to shreds, possibly taking the mast with it which was flexing ominously under the strain of the bulging and whipping dacron in 45 kn's and rising. We also experimented towing polypro warps off the stern to slow us down, a tactic that Dai had sworn on whilst caught in a Force 11 off the Patagonian coast but which to us seemed utterly futile. However, 'heaving-to' which we did twice worked wonders, each time deploying a sea-anchor off the bow on 400' of 1.5' nylon and anchor chain in conjunction with a backed double-reefed mizzen. Holding our bows firmly into the seas nicely, we spent 40 odd hours in this configuration riding out a force 10 drifting at 1.0 kn, 100 NM west of Cape Horn just off the continental shelf to allow the sea to pacify before proceeding into the shallows. Although cautious, it was undoubtedly a sound move since even in the calm winds which we eventually approached, the waves that hit us as we sailed onto the continental shelf were phenomenal; only some 25' but very steep and breaking. It is wise never to get complacent in these waters, each year one or two a yachts disappear, and this last season it was a well seasoned German yacht that sank without trace, only an EPIRB signal picked up for a few hours indicating any sign of calamity. For us though, those freak waves did not last long but still, it was an enlightening experience, not least since when they struck I was up the mast scanning the muggy horizon for the first sight of land, on which a bottle of single-malt had been wagered.

We rounded 'Cabo de Hornos' some eight hours later in glorious sunshine and a light westerly breeze and marvelled at this infamous dark and foreboding cliff-face that is central to maritime lore representing an ominous monument to many a watery grave. I cracked the single-malt and we toasted appropriately, took advantage of the 'balmy' conditions and exposed our pallid, salt-sore bodies to the sun and were soon skinny-dipping, jumping first off the cabin-top and then the mast as the absurdity of our unlikely circumstance became apparent. When making a landfall after almost 6 weeks of damp, cold and uncertain isolation it is not so hard to empathise with the sense of euphoria which descended on us. I got stuck into the bottle in earnest and within 30 minutes was out cold as the pent-up anxiety and strain fell away to the exhaustion of the last 40 hours.

Grant woke me 5 hours later with a strong coffee, it was dark, the donk was thundering away and we were fast approaching Isla Lennox and enter the Beagle Channel. I had a very sore head and was disorientated, but the novel sensation of having to deal with new charts, flashing navigation lights, banks, kelp, tides and skerries soon focussed the mind. Suddenly, the VHF perked up and with some seriously flailing Spanish, I attempted to announce our intentions and arrival in South America from New Zealand. I don't know what they made of it but after much conferring, in stuccato Spanglish a voice chirped in with a 'Bien venido a Tierra del Fuego, welcome to Chile'. 'Supa bueno, mucho gracias' I responded grinning to myself and got down to the task of plotting a course up the Beagle Channel and into Puerto Williams, the world's southern most town.

Dawn was sublime, completely still as dark vague shadows of headlands, cliffs and hills made way to the first the greys and then vivid reds and yellows as the sun rose through the mist and *Gambo* threaded her way past the handful of islands, shipwrecks and fishing shacks that welcome one to this *'land of fire'*. For a part of the world which is daily blasted by 60 kn westerlies and katabatics, once again fortune had smiled and by 8 am Jon and Peter had stirred and were poling out the Genoa to make the most of a light easterly which had sprung up. After a couple of hours of scrubbing below, our first freshwater wash, shave and the adornment of our mould-ridden glad-rags, *Gambo* and crew were as polished as could be and motoring through the last of the narrows, past Isla Gable with Puerto Williams in sight. Some novel manoeuvring into a sheltered cove finally saw us safely tied-up to the half-sunken rusting hulk of the SS Micalvi, the 'club' for the handful of hardy boats that brave this tempestuous part of the world. We were home and dry and after the clamour of clearance activities, I was alone as Peter, Grant and Jon made off for the nearest pub. The air was full of enticing birdsong and I sat on *Gambo's* deck marvelling at the vivid greens, exotic spring flowers and rugged snow-capped mountains which surrounded this idyllic haven. In warm sunshine I savoured a sense of achievement that was rising up out of my numbed and shell-shocked state. A sense that is still very much with me, even if just nine days later it was to be put on test again as we headed out past Cabo de Hornos once more, this time heading due south across the Drake Passage and onto the white continent beyond.

A Modern Day Voyage of Discovery to Antarctica

South to the Screaming 60s

BY Peter Lane Taylor

December 21, 2001, the night of the austral summer solstice: We finally pull away from Ushuaia, Argentina, bound for Deception Island, more than 600 miles to the south on the west side of the Antarctic Peninsula. On deck, the 47-foot steel ketch Gambo looks every bit the bluewater expedition vessel she was built to be—and proved to be on the first leg of our journey, 4,800 miles from New Zealand to the tip of South America. Her sails, now quadruple-stitched and stitched again for good measure, fill sharply as we tack east down Canal Beagle, throwing back and forth in the cold, salty air two freshly skinned sheep strung high in the rigging.

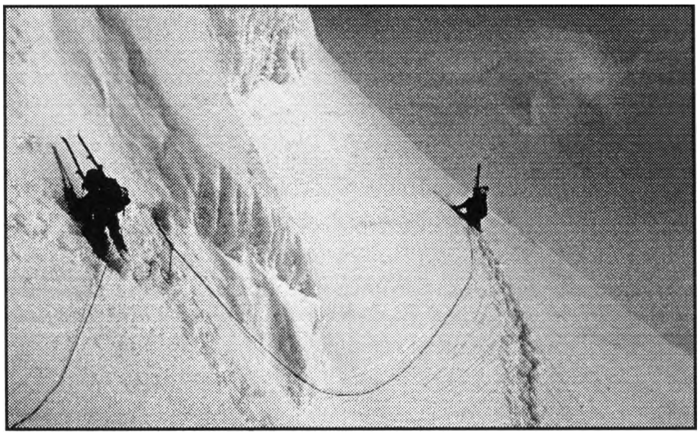
Down below deck, stored in the V-berth, in the head, and in every locker is enough food, fuel, and mountaineering equipment to survive through the winter. Twelve hours later, Gambo charges at seven knots on a broad reach into the open ocean swell off Cape Horn. This is the second of five times we'll skirt the unpredictable edge of South America in less than three months.

The Antarctic Convergence Zone Expedition itself is also a different animal now. Including Gambo's co-owner and co-captain, Dave Hildes, Swiss climber Davide Fasel, and British geographer Elliot Robertson, our expedition now numbers seven. By the end of February, there will be four more, each with a total of seven square feet of privacy below decks. On our first night out in the Drake Passage, I fall asleep in a sail bag outside of the head with a 30-horsepower outboard engine as a pillow. Aft in the pilot berth, Davide, sleeping in his foul-weather gear, wakes every few hours to roll a cigarette and stare silently at the waves.

On December 27, as Gambo ghosts onto the Antarctic shelf in light airs and intermittent fog and snow, we finally cross the Antarctic Convergence Zone. This is the 25-mile-wide ribbon of water between 47 and 63°S where cold, north-flowing currents collide with warmer waters from the Atlantic, Pacific, and Indian oceans. We are now officially in the Great South. Hours later, the South Shetland Islands come into view through a crack in the clouds, rising jaggedly out of the sea like the wreck of a luminous ship. These are the unmistakable peaks of Smith Island, many of them over 4,000 feet high and still unclimbed. Alun smiles widely, climbs out on deck, and sits in the sun alone. According to his most recent position, we'll make Deception Island within half a day. Two days from now, we'll reach Enterprise Island (where is?). Two months after setting out from the other side of the world, we're about to arrive at our destination within 24 hours of our projected ETA. The following afternoon, Gambo arrives at Deception Island, runs through Neptune's Bellows and makes towards the relative shelter of Telefon Cove, where we raft up against the charter boat Hinayana, nestling in the very back of the volcanic crater in a gathering snow squall. We learn that one of Hinayana's passengers has fallen and cracked his ribs, abruptly ending his ice-diving vacation and meaning a 400 mile diversion for them to seek medical assistance.

Meteorologically, the long-term news is not good either. The continental high that normally forms over the Weddell Sea, deflecting storm cells away from the peninsula, has not yet formed, and south of the Lemaire Channel down to Marguerite Bay, our ultimate destination, the winter pack ice is still completely fast. As it turns out, we have hit an exceptional Antarctic year where the weather has gone nuts. At this moment, the Dry Valleys on the far side of the continent are usually deep frozen at -17°C, yet are suddenly awash with floods of melt-water. SO, we are limited in our range for the near future, and spend the next 48 hours splicing mooring cables, sorting shore lines, and exploring the black, lunar landscape of Deception's Telefon Bay. Two days later, on the backside of a departing low, we make a 24-hour run down Bransfield Strait towards the Palmer Archipelago and Hughes Bay. Our destination is the 100 year old, Clyde built, sunken, whaling supply-ship wreck, the Gouvernoren at Enterprise Island, where we spend the next three days and a festive New Year's Eve scuba diving. In steady 20-knot northerlies, Gambo slips southwest in the late evening light under foresail alone, weaving between the icebergs like a fragile bird through a city of skyscrapers. We're in protected waters from this point forward, and without the ocean swell, Gambo responds quickly to the helm, sailing to within a few hundred feet of the icebergs' towering white faces. In the distance, the mainland mountains are now well over 6,000 feet, and the highest peaks turn purple in the midnight polar sun.

A week later we take advantage of the protracted winter fast-ice, mooring up against it at Port Lockroy, Weinke Island, and event indeed is witnessed aboard Gambo. Someone pulls out an ice tool. Next, out comes a pair of crampons. Then a shovel, boots, ropes, and a pair of skis. Within an hour, Gambo's V-berth has been disembowelled onto the ephemeral ice shelf. By twilight, John, Elliot, and David have raised camp 20 feet from the boat and are ready for an 0330 start the following morning to scout for new routes along the Wall and Sisters ranges forming the northeast-southwest spine of the island. For the first time since leaving New Zealand, we are mountaineers again.



The next day, we move Gambo to a small hourglass bay called Dorian Cove to focus fully on climbing. Offering almost full protection from drifting ice and immediate access to both mountain ranges, Dorian Bay is one of those rare spots on the planet where evolution seems to have spent a bit more time getting everything right. To the northwest of our anchorage, Anvers Island's Mount Français, at 9,258 feet the highest peak on the peninsula, soars up from the calving ice cliffs of Neumeyer Channel. To the east, the fluted summits of the Wall and Sisters ranges rip across the horizon like a massive granite saw blade, carrying the echo of the waves thousands of feet into the still, night air. Over the next two weeks, our expedition survives on adrenaline alone. With Gambo securely moored to five shores lines, we log the expedition's first new route up a mixed rock pyramid in the Sisters range on January 13, and three days later, the fourth ascent of 4,708-foot Mount Luigi, the highest peak on Weincke Island. Between climbs, exploring by skiff and kayak in the peninsula's glacial-carved channels, we discover another distinctly biological frontier. Despite 200 years of plunder, the Antarctica Peninsula is home once again to literally tens of thousands of albatross, petrels, penguins, seals, and whales, proof that if given the slightest chance and left alone, nature can indeed rekindle herself.

In late January, the effects of cabin fever finally begin to sink in. Back-to-back ground blizzards have pinned us in Dorian Cove for five days, and south of our position, the winter pack ice is still nine-tenths solid. As the days slip by, we spend the long, grey hours carving whalebone we pick up along the shore, entertaining cruise ships and continually tuning Gambo's shore lines to prevent chafe and keep her securely moored in the 70-knot katabatic williwaws that sweep down off the Wall range, across Thunder Glacier, and knock her over onto her gunnels. By the end of the month, after three more aborted attempts to gain the lower flanks of the mountains, John and David, both full-time climbers back home, are frustrated and demoralized. We decide to move to Paradise Bay for the last four days to rendezvous with the British Army Antarctic Expedition aboard the steel ketch John Laing, and Celia Bull on the aluminum sloop Ada, before Gambo returns to Ushuaia to pick up Fraser, Penny, Andy, and Lena and reprovision for the second half of the season.

The next day, following a short overnight sail, we break our way through a half-mile of brash and bergy bits and squeeze into the narrow bottle-necked entrance of Paradise Bay about 10 miles east of Weincke Island, where we raft up to John Laing and set two lines ashore. To the south, the high, glaciated cliffs of the peninsula rise directly from the water into a low ceiling of clouds, offering little hope for direct access to the mainland plateau. To the north, glaciers calve directly into the ocean like a slow-motion avalanche. For Grant and I, who've been on board since New Zealand, the new company of John Laing's crew is reinvigorating, and we spend the next two days off-mountain in total relaxation. John, Dave, Alun, and five British Army climbers head in the other direction and mount an ascent of Mount Hoegh (where is?) at the northern end of Paradise Bay in a lingering midnight sun. For our own expedition, it's our third major ascent in three weeks. Three days later, Gambo departs for Ushuaia under Dave Hildes charge to exchange crew and replenish provisions.

Through the first 10 days of February, the weather windows on the peninsula continue to be brief and unstable. From the shore of Danco Island, where Grant, Alun, David, and I have set up base camp during Gambo's absence, visibility is often less than a few miles, obscuring the peaks of the Danco Coast in a layer of low, rainy clag. Yet, unencumbered by a sailboat for the first time since leaving New Zealand, we take advantage of the few clear days to free-climb a tabular iceberg, ascend the peninsula itself, and log the expedition's fourth first ascent, up 3,450-foot Mount Britannia.

By the time Gambo returns two weeks later, the evanescent Antarctic summer is already coming to a close. On the cliffs above Danco Hut, where we intermittently take refuge from the persistent storms, the penguins are growing testy and restless. Twelve miles to the south, in Paradise Bay, the 10 members of the Chilean Navy's Antarctic search-and rescue-base have already cleared out for winter.

With the arrival of Fraser, Penny, Andy, and Lena, however, our expedition has undergone yet another well-timed crew transfusion. Along with two skinned and gutted sheep and a carton of cigarettes, Gambo's latest arrivals have brought with them a renewed motivation to put up one more first ascent before summer slams shut for good. For Alun, Dave, and Andy, all of whom have also come here to study the effects of climate change on the Peninsula's glaciers, immediate action is even more imperative. Together, their research projects will take the next week to complete on King George Island, 200 miles to the north, and 20 miles south of our position the pack ice is already closing in.

Over the next two weeks, there are no more breaks in the weather. As the temperature continues to drop and the nights close in, snowdrifts begin to pile up around Dorian Cove, where Alun, Grant, Andy, Penny, and I have once again taken up refuge. For a thousand miles west of Cape Horn, the weatherfax shows nothing but storms. Somewhere on the flanks of the peninsula itself, attempting to gain the mainland plateau, Dave, Fraser, and Lena have been pinned in their tents for a week without support. Winter is coming.

"It's too risky to push farther south," Alun confesses late one night over our last bottle of single-malt. "The weather's going to get volatile, and I don't want to be caught too far down here when that happens. We need to pick up the others and get on with the plan to King George Island immediately."

At high tide on the morning February 23, a mile south of Port Lockroy, the Antarctic Convergence Zone Expedition formally logs its final point south and turns north to begin the long journey home. Other than the three seasonal caretakers of the old British Meteorological Station at Port Lockroy, no one's around to say good-bye. Among the dozen charter and expedition crews that were down on the peninsula for the season, we're the last to head back home. Two days later, after picking Dave, Fraser, and Lena up off the Danco Coast, we arrive at King George Island in high winds and light sleet and rain. On the beach at the edge of Admiralty Bay, the Chilean and Russian Antarctic bases rise starkly from the black, volcanic sand like stacks of stranded orange shipping containers. Behind them, the low, windswept Harbor Glacier disappears into a ceiling of clouds. With the exception of a lone smoker huddled against the cold outside the base commissary, the whole place looks deserted and forlorn. The next day, we shift once again from sailors to scientists and assist Andy, Dave, and Alun in collecting the data they need to complete their research programs. Even to the untrained eye, there's something frightening going on here. In the past decade, environmental scientists have discovered that subantarctic ice masses, like those on King George Island, are shrinking rapidly in response to global climate change and might one day be ice-free. What preoccupied our expedition was whether these subpolar islands might be canaries in the global coal mine: If the glaciers on King George Island are any indication of a long-term trend, what might one day happen to the larger, more significant ice sheets farther south?

"If you think in terms of worst-case scenarios," Alun tells me as we ski across the Saddle Glacier above the joint Argentine-German Base, "We may well be standing on bare rock right here within our lifetimes. Although the ice is now over 120 meters thick, it's thinning at a rate of up to one meter a month in summer, and if this trend continues farther south into the Weddel Sea and the Ronne-Filchner ice-shelf, we'll be looking at a total global disaster." For sub-polar regions in the Northern Hemisphere—like Greenland, Alaska, Iceland, Scandinavia, and the high Russian and Canadian Arctic—the situation is no less severe.

By early March, the noise of the cargo ships around Admiralty Bay has reached a deafening roar. It's the unmistakable sound of people leaving. At 2200 hours on March 7, we turn Gambo on to her final windward course toward the eastern approaches to Tierra del Fuego, and the Antarctic Convergence Zone Expedition comes quietly to an end. Behind us in the falling light, the serrated shadow of the peninsula extends for miles along the southwestern horizon. Within an hour, it is gone.

It's been almost a year now since I last saw Gambo or any one of the 10 members of our expedition. Yet, every day when I wake up, I still think about Antarctica. Like few other wildernesses, the Great South gets inside of you. It lingers in strange ways for years afterwards and allows you to forget somehow the things you endured to meet it on its own terms. What lingers most of all is a sense of satisfaction. For seasoned ocean sailors like Bill Tilman, David Lewis, and Bernard Moitessier, Antarctica was a title fight you earned only after you'd taken your hits in every other chump-change arena on the circuit. You circumnavigated the Great South at the top of your game because there was nothing left to conquer. We sailed to Antarctica to see what the challenges could teach us. And as it turns out, they're the kind of lessons you remember for life.

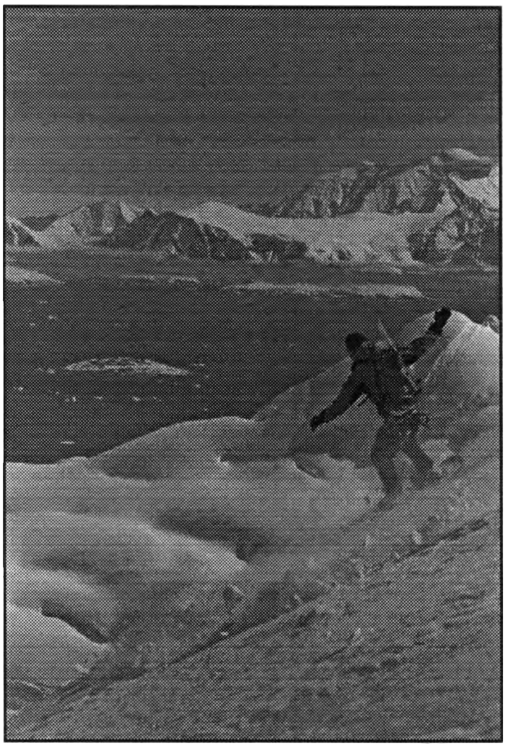
Success with one of the Seven Sisters of Fief,

Wiencke Island, Gerlache Strait

BY Elliot Robertson

Without doubt they were stunning. Seven beautiful sisters. Even if they hadn't been the one of the most jaw-droppingly beautiful ridge of peaks on the peninsula, there was little chance that this particular expedition of seven blokes would have been able to resist the lure of the seven sisters. After all, we had already altered course more than once during the expedition to 'just happen' to be at the same anchorage when the yacht Ada sailed in with her crew of (heaven be praised) seven women. As it was, The Seven Sisters, dominating the skyline over Port Lockroy on the Gerlache Strait, had been on our wish list since we first started pulled out the charts and photos before leaving home.

Dave Burkett, one of the three staff stationed by BAS at Port Lockroy over the summer, pointed out the Sister he thought would go first. He had seen a few attempts over the last few years on the same peak – all taking what looked like the easiest line up the rocky spur, but none getting very far. The spur certainly looked the best bet and even if it stopped us, it should at least give access to the higher snow and ice flanks, which themselves would hopefully lead to the summit. We would climb as two rope of two, lightweight, planning to be back on board without the need to sleep on the mountain. David Fasel paired with Dave Hildes, and myself with John Millar.



With 24 hour daylight and a clear forecast we had as long as we needed for the climb, the only variable being temperature as the sun occasionally dipped towards the horizon as it circled above us. The ski-in took between two and three hours, each of us skiing alone in the cold morning light, each of us wrapped up in the beauty of the glacier reflecting the dawn colours. Short forays on the glacier had our glaciologists on the trip confident that crevasses would not make solo skiing a problem. My confidence was limited to knowing that there would be someone else to blame. A strip of glacier allowed us to ski along past a couple of the Sisters 60 metres above the shoreline until we turned inland and uphill. We re-grouped on the flanks of Mt Luigi where the incline of the snow steepened and it made sense to abandon skis for crampons. Sharing round a flask of tea, we roped up, checked gear and took in the incredible views up and down the peninsula. Gambo, anchored and fastened to shore in a secluded bay far below us, looked even smaller than she'd felt a few days back on the Drake Passage. It felt good to be on land and about to climb.

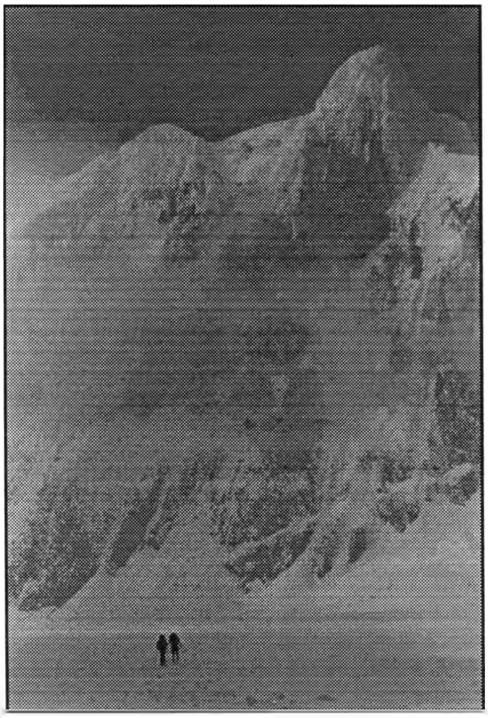
Forty minutes stomping up the snow brought us onto a broad rocky spur that had been foreshortened when seen from Port Lockroy. We scrambled over granite boulders, wary as each one teetered and moved to the slightest touch. They had the feeling of having been there since the beginning of time, but were so loose it defied understanding as to how all but the faintest wind hadn't triggered the whole lot falling off into the sea.

The angle gradually eased off and made for easier progress, especially for whoever was bringing up the rear under a hail of small rocks and the occasional boulder. The spur became more consolidated, eventually stopping altogether and requiring a ten metre down-climb to a short section of snow ridge after which our rocky spur was replaced by a face of steep rock. The ridge linking the two sections of rock was no more than a couple of metres long and angled steep enough on each side to make an attempt to sit astride it very uncomfortable. Pausing together on the left side of the snow ridge, I scanned up the face and thought we might be turning back. It was certainly something I was not prepared to lead in crampons and rucksack. David Fasel had other ideas and set to straight away, removing his gloves and trying a few different lines as Dave belayed him. Dave followed on a tight rope, and John and I let them open up some distance before we got into position. I edged down one side of the snow ridge as John started to climb. He couldn't follow David's route direct and took a traversing line to the right slowly edging out of sight as I paid out more and more rope. Traversing away from the ridge looking for an easier line John opened up an ever greater space beneath him as the ground fell away. Things got quiet and lonely. John had little to no gear to fix and I began to wish I had retreated further down the snow and dug in a better stance before he had began. A calm and welcome "safe" eventually echoed down to me from a distance and I took a moment to get some blood back in my fingers and followed.

After a while the angle eased off again, but this time the spur ended with a large gendarme. Whilst it was easy enough to scramble up, there was no way of free-climbing down the other side and continuing this line. A snow ridge continued the line of the spur after the gendarme, but we had no hope of scaling the 300 metres of almost flawless vertical rock that faced us this time. We abseiled 30 metres down on the snow ridge and kept going down the snow face until the ice was solid enough to take a couple of screws. From here we traversed out left and upwards hoping to side-step the face and re-join the ridge above it. We belayed off from the ice screws, but then began moving together, each pair separated by ten metres kicking in front points and axes on steep, exposed but solid ground. David Fasel, still out in front, picked a line that brought us up through mixed ground that we hoped would lead back onto what should now be the summit ridge. Twenty metres below the ridge line Dave knocked loose a biscuit-tin sized rock. It free-fell straight for John and I, narrowly missing him and thumping heavily into my helmet. Having only had a second to anticipate the impact I tensed my shoulders and gripped my axes. Shaken into silence, and marvelling at how lucky I was to be hit squarely and not one of my limbs, I heard John let out seething plea for the leading rope to be more careful. Looking down at the fall we'd have taken my heart, already beating fast with exertion, went into overtime as the adrenaline surge kicked in.

On the ridge the wind had picked up and was now gusting strongly. Picking our way carefully along the steep ice ridge and cornices we estimated the summit was probably just an hour away. But we had been on the go for 15 hours and the gusting wind and precipitous drops slowed our pace. After more than two hours the exposure reduced and we clambered onto the main ridge running north-south from which the summit of each of the Sister's rise. On this easier ground the gusting wind also became easier and we walked together onto an expansive summit. The views along the sisters, to the sea on the other side from our anchorage and the outlying islands of the Antarctica Peninsula silenced us. The beauty and isolation of climbing on the Antarctic Peninsula is humbling.

Having kicked back in the sun for twenty minutes the cold began to penetrate and, half way there, we turned back. Retracing our steps to the foot of the main face was straightforward, although somewhat slow as we had now been on the go for while. Rather than finding a way of reversing the gendarme and running the gauntlet of the loose boulders, we opted for a longer route on snow and ice. A series of bergshcrunds and crevasses, each of which would take some serious negotiating on the way up, became test grounds for standing jumps. Given your partner is firmly dug into a stance, it is really quite incredible how far you can fling yourself across a yawning crevasse and down the slope leading up to it. Un-roping again at our skis, and with no water and little food left, we made our own way back to Gambo. We may have been shunned by Ada and her crew, but it was fitting indeed to have seen more success with one of the Seven Sisters of Fief.



Two days later JM, GR, PT and AH made an ascent of Mt Luigi, the highest and previously climbed peak (five times?) of Fief range by the standard ski route up Thunder Glacier and doubling back up onto the long east shoulder ending in moderate 45° slopes through a series of seracs up to the summit. The climb took 7 hours in total with over an hour spent at the summit and we encountered pretty much perfect snow throughout. Grant enjoyed ideal conditions for his snow-board descent which he completed in a record 40 minutes including photo opportunities. Two days later the BAAE ascended Mt Luigi on our recommendation and literally in our footsteps. Whilst we were based at Dorian Cove we also made a number of attempts at the highest mountain on the Peninsula, Mt Francais on Anvers Island, and also a number of more technical routes on the Wall Range including a 400 m 'steep' water ice route and a route up the 'shroom from what we called Crag's (as in Jones) colouir. From these we were either thawed, avalanched, or blasted off but we tried many times and always had morning constitutional ski up and down 'the mighty Jabbet' before moving on to Paradise Bay in search of the BAAE's endless whiskey supply.

Ascent of Mt Hoegh with the British Army Antarctic Expedition

Paradise Bay, Danco Coast

BY Tim Hall, photographer and climber with the British Army Antarctic Expedition (BAAE).

22 January 2002

The BAAE team on board the yacht John Laing had now been on stand-by for a break in the weather for a couple of days. However, by now we had company in our cove, the yacht "Gambo" with its team of seven had moored up along-side us. We had already met the "Gambo" crew before as they were climbing around Port Lockroy when we had been in residence there a week or so ago. The two Expeditions had got to know each other and had already shared some 'hospitality' while the weather had been less than perfect. Both teams had been equally frustrated by the weather over the last few days so as the cloud lifted and the sun came out we quickly hit on the idea of mounting a joint climb on nearby Mount Hoegh.

Three of the "Gambo" crew comprising of Hubbard, Fasel and Miller were joined by 6 from the BAAE team comprising of Hall, Biddick, Ayres, Patison, Horne and Harris.

We were landed using 2 inflatables at Waterboat Point at the northern end of Paradise Harbour shortly after 9pm GMT and started to ski round to the south to scale the mountain via the icefall and col, which lie to the southeast of the peak. We travelled with 3 ropes, 3 people on each rope. Hall (BAAE) started breaking the ski trail but at our first stop Fasel (Gambo) switched into "professional guide-mode" and was soon off in the lead forging the way ahead. In clear sunlit conditions we had a reasonably straightforward and beautiful ski up the icefall. We crossed through an area of jumbled ice blocks, testament to some earlier avalanche activity, & onto the steep ice and serac walls that guard the summit. One of the slopes looked an easier angle than the rest at perhaps 65 – 70 degrees and appeared to offer access to the summit ridge. We replaced our skis with crampons and with Miller (Gambo) leading began at first to traverse then climb a couple of hundred feet of steep ice under some rather beautiful but menacing seracs. For the less experienced members of the BAAE, the climb was later described as "exposed and demanding" but Millar (Gambo) placed some ice screws as he climbed to ensured security for all those following behind.

By 2400 the "Gambo" crew had led the way to the summit & were soon after joined by the BAAE team. The midnight sunset reflected up off the sea and the bergs and down from the bases of the clouds. Visibility was up to about 30 miles and the nighttime had arrived with a bitter chill in the air.

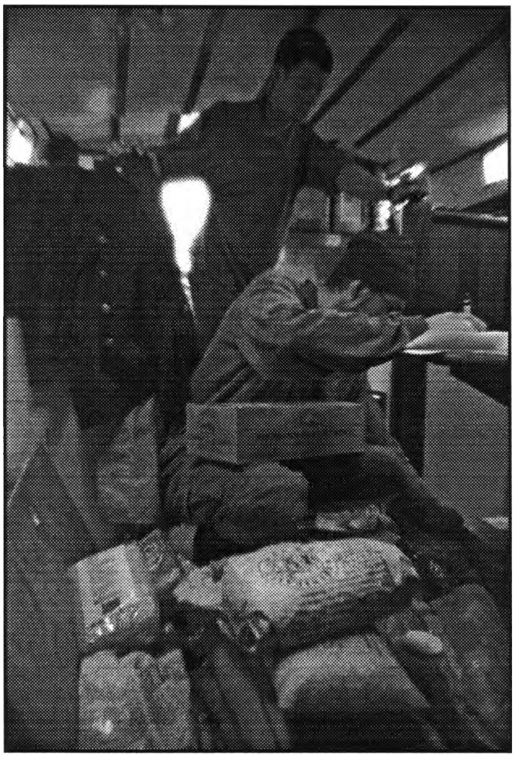
Before beginning our decent we spent about 30 minutes or so at the summit taking photos and marvelling at the panorama that lay below us. As we descended, retracing our route, Fasel (Gambo) set up an abseil to over-come the difficult ice slope, he volunteered to stay at the top to last, release the rope and then down climb the wall. It is a testament to his superb climbing skill that he down climbed the 200 ft wall faster than most of us abseiled down it!

Safely at the bottom of the wall we once more donned skis and set-off down the mountain and to our pick-up by the inflatables at Waterboat Point. For the less experienced skiers the decent was 'challenging' but in under two hours we were all back at the coast. It had been a great climb. However, for all of us the climb was made by the staggering beauty we'd beheld as the midnight sun had coloured Paradise Harbour as it journeyed towards the horizon.

The Drake Passage (or There and Back Again)

BY Fraser Bernie

Leaving Ushuaia was, for me, like leaving behind everything familiar and known. Not having sailed much was not to be a hindrance to trying, even if I had decided to learn in one of the harshest environments on the planet. I was happy in Dave's abilities if all else failed, even though the tales of surfing down giant waves and being knocked down hundreds of miles from land were somewhat off-putting. Having spent much time advocating learning by experience, I put everything else aside and took it one day at a time. With fresh winds and passports stamped we sailed east out of the Beagle. With limited time on board (just a few days re-stocking and packing), none of us had our sea legs except Dave and no desire to sail into a gale, however, time pushed on and we were forced to set sail. It's always a hard call, as you watch the low pressures piling up on the weatherfax as they hit S America, or push through to leave a clear day or two.



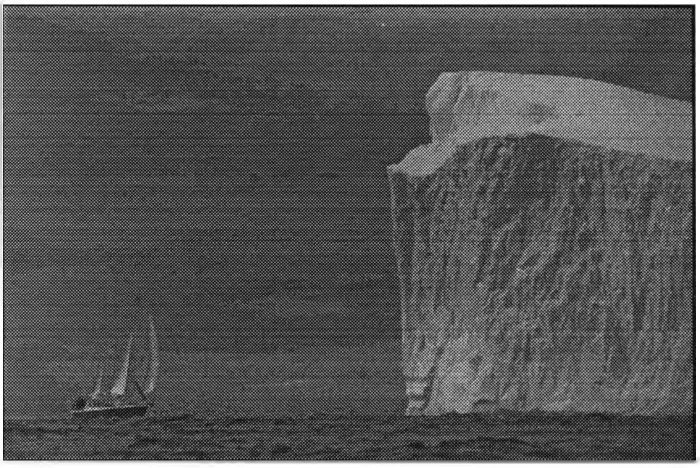
Sailing *Gambo* was generally a pretty straight forward business. We tried to take watches of 4 hours each, keeping an eye on the radar for other vessels, the coarse to our GPS waypoint, and the sails and windspeed. Once around the corner of Cape Horn, it's a straight line south, putting in a waypoint and heading for it. It didn't turn out quite so easy for us, with the fresh winds turning to force 8/9 through our first night. Sea-sickness quickly sets in for most of us, as the swell took a hold and that continuous rocking reeling and plunging motion plays havoc with the inner ear and the body's balance. It affects everyone differently, and I had the misfortune of getting it bad. These are not times to be trying to get to grips with reefing the main, I was laid out flat. Fortunately others were not so bad, and in times of stress, differing strengths have to be used.

Our first night was characterised by raging winds and waves crashing on deck, the window seals blew out and sea-water squirting through the gaps. Anything loose inside flew around, including people. It was already an austere environment, and very quickly it took on the air of a bombed out basement, dark, cold and wet. For me, the next days were frustrating and difficult. I wanted to involve myself but was very sick, struggling to keep water down, never mind the solid stuff. Simple tasks were the ultimate ordeal, and watches became shorter and time for learning about sailing limited. It's easy to sail short handed, as really there is little to do, and it made much more sense not to force things for the sake of it. Crossing oceans is a matter of endurance. Life is, in these circumstances, reduced to the bare minimum. We all slept a lot, perhaps reading or baking, cooking or making brews. Dave kept an eye on the charts and kept up the log and in touch with the weather outlook, and apart from watch, we all managed some time out on deck pondering the vast expanses of ocean and the ice and mountains that lay ahead. It was usually a desperate struggle for me to focus on getting into fowlies ready for the deck, but once there it was hypnotic. The seas were like hillsides of water, massive rolling swell towering above *Gambo*. It seemed we were very small, but the yacht sailed on, slowly but steadily.

With the toss and turn of a sleeping man
it rolls, taking with it a tale
Of daydreams, warm waters and fresh winds
whistle, the ropes and coils bristle.
An energy, fervour, fury and rolling, plodding
Pace. The grey seas tear and push, lift up
and let down, and it sighs and turns over
a new leaf. Not to go this way again
not to crash and break, sweat and moan.
The soft drift of in and out, breaths
the salt and squalid tale. But, ever on,
as a horizon, a thought, a dream, as hope.
Such is the icy wish, the fight against
storms and seas and dreams.

(Journal extract, 14th Feb., '02)

On the sixth day we sighted ice in the water and, soon after, land, and I had arrived in Antarctica. The little storm petrels that had kept us company over the expanse of ocean and the giant wandering albatross now left us, and in their place we had icebergs and snow covered islands looming out of the fog. Life aboard picked up as the swell died down. We reverted back to a sense of organisation rather than mere existence. Without the crashing seas, meals were more regular, the stereo came on, coffee was drunk on a near horizontal deck, and moving around was infinitely easier. We had much tidying to do and more time was spent on deck taking in the stunning views. It all looked just as in my dreams; islands of ice, snow squalls passing through, icebergs and seals in the water. I didn't necessarily feel that I knew anything more about sailing, but I knew much more about how it felt and I deal with it. It was unfortunate that there hadn't been more time, as usually a week is enough to get your sea-legs. I'd not found mine, and was glad the swell was gone among the Peninsula islands.



Over the next weeks, we use *Gambo* as a base some of the time, sailing between mountain areas and field sites and then leaving her for time on land. I'm glad that I had some great days with a brisk wind, whisking us along, taking it all in. Being on watch, alone on deck on a still dawn, or watching the quiet fall of snow pile up on the rigging was magical. I found too, the sea conditions and wildlife always amazing, and *Gambo* was the best viewing platform I could have wanted. Watching the sea freeze, and pancake ice form on the surface, or penguin and whales play among the icebergs were the real rewards of life on-board. In the back of my mind though, I did worry about the return voyage and had pondered getting back by alternative methods, of which there were a few. However, it didn't feel right and I was keen to 'complete the circle', despite the very real potential for more sea-sickness and the hell that goes with it. That's some indication of how bad it was for me.

During those weeks, life aboard was austere. There was no showering, very limited fresh water supplies, only salt water for cleaning, plus nine people in a very confined space with heaps of kit. Typically, we lived out of the same clothes all the time, only changing fowlies for mountain clothes. It was a test of tolerance, but these are things that can be got used to. Physically, we had to deal with cold times out on deck, re-setting the anchor or mooring lines, lashing down equipment or dealing with rigging and sails. Logistics are quite an issue as safely moving people from yacht to land meant lots of packing of kit, sorting food etc. then piling everything into a RIB. People would plan for mountain days or a short ski tour, and some would have to stay to manage the boat, in case of icebergs or winds. Three of the group eventually did 'jump ship' so that we could lengthen our stay at King George Island for extra research time. This meant more room for the six that remained, and a considerably easier time organising logistics. In the end, I opted to stay aboard. Overall, the group worked well together, despite the intensive nature of living, and we managed the situation by dividing into sub-groups. With people leaving, the streamlining meant that we all had more space and time, and this worked wonders. We had plenty of chance to let of steam when we met up with other yachts or landed at a base, and the *Gambo* disco may well have fallen into Antarctic folklore. We were proud to accept the title of the 'International Happening', as given to us on the 'Patagonia Net', a regional HF schedule for Patagonian based marine activities.

Returning north to Ushuaia presented its own difficulties, although we were all a bit more attuned to deal with them. My decision to return on *Gambo* was a good one, although I did end up heaving for three days. Having sailed north and east to King George Island, we needed to regain valuable westing to make our approach to Cape Horn and the Beagle Channel. This is a tough task, especially in the first couple of days plagued by light NW'lies and we were slowly drifting east with the 2 knot current despite sailing north at 5 knots. We were beginning to have visions of arriving in the Falklands in two weeks time when things changed. The next three days and nights we had gale force winds from the south-west, which meant sickness for me but much progress to the NW for the yacht. It was rough going again, beating hard against 50 knot winds, blizzards and steep waves, but these were par for the course now, especially for those crew who had been on board for six months now. We were at least assured that she had once been completely knocked down once and had survived. Thus on the sixth day we found ourselves motoring west up the Beagle back to 'the best bar in the world' at Puerto Williams yacht club. Strangely, over the next few days of cleaning up and off-loading everything and body, *Gambo* took on a very homely and welcoming atmosphere. Thus, it was a sad day indeed when Dave and I finally turned our backs on her in Puerto Williams for winter, despite knowing that I'd be back some day.

Attempted Trespass on the Forbidden Plateau

BY Fraser Bernie

On arrival at Danco Island, where the four man shore party had spent the last two weeks, it became apparent that splitting into two separate groups was the best option, as we felt the need to divide forces around our objectives and to give Dave and the new blood some quality time off the boat. The weather was frustratingly unstable and limiting the options. Some success had been had by the shore party, with a first ascent of Mt Britannia and other technical routes in the area, but they had been beaten off a route up to the Plateau via the Downfall, and had retreated after being storm bound for consecutive three days. This route was to become the focus of my time on the Peninsula and it seemed a worthy challenge. I had wanted to journey and ski-tour up on the plateau, as well as try some more technical day routes. The route had once previously been attempted by a BAS party led by Wally Herbert back in 1956 when they had been surveying the region. They had been forced to retreat by a steep snow slope, and had given it the telling name of 'The Downfall'. With the icecap above called the Forbidden Plateau and Alun's tales of being tent bound, it seemed the worst that could happen is that I'd return home with my own Antarctic epic to tell.

After an ascent of Mt Tennant to clean out the cobwebs, we packed up and got dropped off at a shore camp on the Orel Ice Fringe. *Gambo* and the remaining crew (AH, DF, GR, AM & PG) sailed south to explore a new area. We were alone, the drone of the boat engine eventually faded leaving just Dave, Lena and I and a mountain of food and gear. The seals kept an eye on us and from time to time a Humpback spouted in the bay below. Tower blocks of ice calved from nearby glaciers, sending waves across the bay, and an avalanche rumbled down the mountain side above.

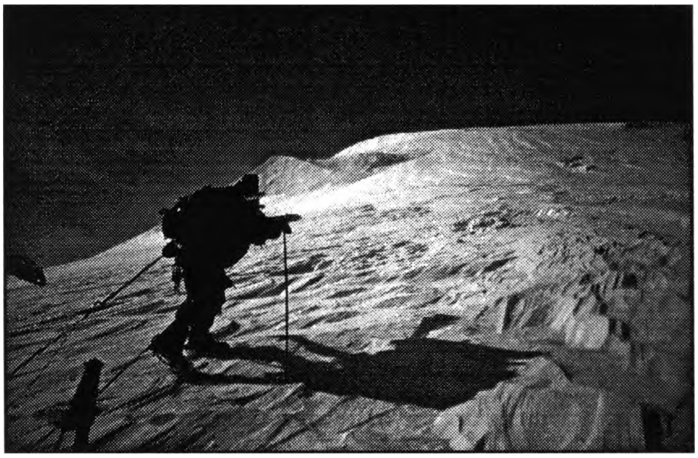
We estimated 8 days food should see us onto the plateau and on to Mt Walker, an un-ascended 2100 m high peak which was our ultimate objective. However, on contingency stakes we had supplied for 25 days all in, but decided to leave most of that along with a tent and extra kit at the shore camp. Each of us had sledges and packs which weighed about 40 kg all in and it was hard going. The route took us along the Orel Ice Fringe and wound up through a series of icefalls and creavasse zones, before we gained the relative safety and easy ground of the upper Wheatstone Glacier. We travelled slowly, roped up and taking turns to break trail. The first day passed slowly, with fair weather turning to white-out just in time for me to collapse exhausted. We had managed only about 6 km but it was tough terrain in difficult snow conditions. The tent was pitched and we slipped into what was to become a familiar routine of melting snow and preparing the dehydrated food. We had only one tent with us to save weight, so living was cosy and the following day was spent tentbound, with zero visibility.

Day three proved fairer, and we managed up to 'Col' camp before white-out set in once again. Here we felt poised for an attempt on the Downfall, although the poor amps and the fact that none of us knew what we were looking for left us wondering what we'd be finding above. We managed to have a short recce that evening, but there was little to see, and Dave and Lena became disorientated and had a tough time finding the tent again. The next morning was settled once again, and we decided to go up as far as was prudent, leaving the tent and main supplies at Col camp.

The cloud had lifted and the wind died down, so for once there was no spin drift. It took us a few hours of skinning up easy snow slopes to get onto the beginning of what was meant to be the fun part. We had great views over to Stolze Peak and across flat, calm waters to Ronge Island with its impressive Mt Britannia which the shore party had ascended just two week previously. The little islands stick up like cones from an ocean of ice bergs. As we climbed, we got glimpses across to the plateau, looming over the fury of glaciers that plunge down to the coast. These glaciers look really vicious, seriously crevassed and broken and seracs everywhere.

Journal extract, 15th Feb. '02

Progress was promising for several hours, and the weather seemed stable enough for us to have a go at the difficulties as they appeared. Ahead lay the Fobidden Plateau, only a couple of KMs distant, wand we were starting to get optimistic when we ran into the routes' namesake. We could see the gap forming ahead of us, perched as we were on a narrowing ridge, the cornice hanging free above the 1700 m faces of ice and snow falling away to either side. Now we knew why it was called the Downfall, the twisting knife-edge of icing-sugar snow dropped away in front of our feet. It was a 40 m drop leading into this 1 km section of ridge. If we'd had the gear with us, and a couple of days back up food we'd have gone for it. But the weather wasn't stable and we were still pondering our options when the cloud descended and wind picked up making the decision for us. We had to head back down, disorientation and white-out up there was not a prospect worth considering.



The following two days were highly frustrating, as we were largely tent bound, making only a brief outing to waste energies climbing some nearby ice blocks and colouirs. Given our food supply The Downfall and Mt Walker was now realistically out of reach and we consoled ourselves with a probable first ascent of nearby Stolze Peak that we'd eyed up on the couple of clear days. It proved straight forward, ascending mostly by ski with a short technical section near the summit. Again, views were fantastic, across the icy mountains, ocean, islands and onto the Forbidden Plateau. It didn't matter if we were the first up there or not, what mattered was how it felt there and then. As with so many moments over the whole trip, in those minutes I had my money's worth. The sense of journey and achievement was complete, even if I still had to get back again.

Our descent back to the coast proved to be a most nervy day, as we were forced to descend in white-out. With limited food, it seemed safer to move than to face a worsening situation, and so cautiously we set off. None of us relished the job of breaking trail, out on the sharp end of the rope, guided only by the compass bearer behind. Crevasses were invisible, and the terrain impossible to read. We navigated on GPS waypoints taken on the way up, as the maps were not accurate but we had not taken enough through complicated terrain and soon ended up in unfamiliar territory. Navigation in white-out is next impossible. But occasionally visibility would improve enough to put back on the right track and after many hours of dicing about gaping caverns of ice, we were down and safe. The next two days we relaxed at shore camp, making the most of our generous food cache and extra tent and even managed to knock off another decent unnamed peak to fill the time. Then early on the third day, a dot appeared on the horizon that looked different from the usual bergs, and *Gambo,* was motoring in our direction. It was great to see the old crate back again, but I still yearned to be back up there, above, listening to the snow against the tent wall, or the heavy breath and crunch of snow as we skied along.

Nutrient Export from Subglacial Antarctic Outflows into the Southern Ocean – a preliminary investigation

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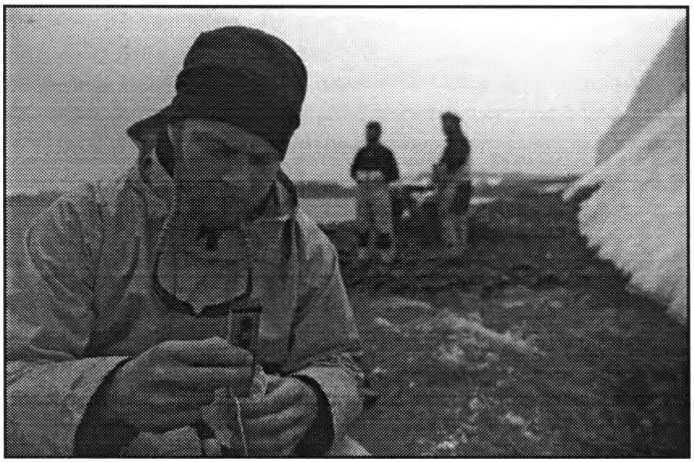
Introduction

Nutrient supply to the polar Southern Ocean is currently an area of great research interest (e.g. Boyd *et al.*, 2000; Abraham *et al.*, 2000; Chisholm, 2000). It has been hypothesised that the supply of nutrients to oceanic phytoplankton may have a significant effect on concentrations of atmospheric CO_2, by altering rates of planktonic carbon sequestration (Abraham *et al.*, 2000). Phytoplankton biomass has been correlated with the amount of bio-limiting nutrients up-welled from the deep sea to the sunlit surface waters in the Southern Ocean, and recent iron fertilization experiments (Boyd *et al.*, 2000) show associated increases in primary productivity and CO_2 draw-down rates. Indeed, iron fertilization in the southern ocean has been controversially proposed as a method for reducing atmospheric CO_2, to combat global warming (see Chisholm, 2000), and has been proposed to affect atmospheric CO_2 on glacial-interglacial timescales (Watson, *et al.*, 2000). While the importance of up-welling oceanic nutrients has been quantified, nutrient and potentially toxic metal fluxes, from the Antarctic landmass have yet to be considered, despite their potential influence on phytoplanktonic productivity, CO_2 draw-down and general biomass activity in Antarctic land and marine environments. Indeed, to date, nutrient fluxes from polar glaciers have only been investigated in one high Arctic catchment (N.W. Svalbard; Hodson and Mumford, University of Sheffield), but as yet remain unpublished. This study aims to address this gap in our knowledge by providing preliminary nutrient export data from the Antarctic Peninsula.

Dissolved nutrients and metals in natural waters may be derived from rock weathering (*e.g.* Holland, 1978), recycled marine salts (*e.g.* Chester, 1990), and anthropogenic sources (*e.g.* Langmuir, 1997). More specifically, dissolved nutrients and metals exported from subglacial environments in glacial outflow water are controlled by the chemistry of inputs to the system (rain, snowmelt, icemelt) and the interactions that occur as these inputs chemically interact with rock debris (basal till and suspended sediments) during transit through the hydrological system (Raiswell, 1984; Brown, 1991; Tranter *et al.*, 1993; Brown *et al.*, 1994; Brown *et al.*, 1996; Mitchell *et al.*, 2001a). The nature of the hydrological system and the characteristics of subglacial sediments therefore control the chemical composition of bulk meltwaters (Brown *et al.*, 1996). The magnitude and timing of dissolved nutrient and suspended sediment export from Alpine glacierised catchments is therefore controlled by the dynamic nature of the subglacial hydrological system (Röthlisberger and Lang, 1987; Nienow *et al.*, 1996; Richards *et al.*, 1996). In Alpine and Arctic glacial environments it has been demonstrated that, typically, during the summer months when surface ablation is at its greatest, the majority of meltwater, suspended sediment and dissolved chemical flux is exported. Recently, however, interest has developed in the particulate-associated transport of nutrients and metals in subglacial environments. That is labile chemical species transported on suspended solids in glacial outflow, which includes sorbed species, precipitated Mn and Fe (oxy)hydroxides and the associated co-precipitation of other metals (Mitchell *et al.*, 2001b). This study aims, for the first time, to characterise and quantify modes of nutrient and metal export from subglacial environments in the Antarctic Peninsula.

Study Area and Methodology

Sampling was undertaken at King George Island, the largest of the South Shetland Islands, located at ~ 58°00W, 62°00S. This island is 1295 km^2 with approximately 90% glacier coverage. Glacier coverage is characterised by multiple large ice caps which calve directly into the ocean at either a land-grounded or marine-submerged ice cliff terminus. Conversely, some areas are characterised by ice tongues fed by the ice caps that terminate on land. Sampling was undertaken between February XX and March XX 2002 (Alun – insert). Appropriate sample sites were located by a sea-bourn and land survey of the island. Two sample locations were chosen, where waters were emerging from subglacial environments onto land. Such sites were necessary due to the logistical complexities of collecting samples from marine submerged glacial outflows. Sample site A was located at the beach of Collins Harbour, approximately 1km NE of the Artigas Uruguay base. Here, a subglacial outflow issued from the base of an exposed ice cliff onto the beach and entered the sea. A crevasse was apparent on top of the ice cliff. Sample site B was located at Potters Cove, approximately 1 km N of the Teniente Jubany Argentinean base. Here an ice tongue fed by the XXXXX ice cap (Alun - insert) terminated on land, ~ 1km inland from the coast. The proglacial area was characterised by a beach of predominately sand to gravel sized, glacial and marine derived sediments, over which a braided proglacial meltwater stream flowed. Proglacial sediments exhibited significant fluvial incision and re-working, presumably by glacio-fluvial action or from subglacial meltwater or rainwater flowing directly off of the ice tongue.



Multiple water samples were collected at each location, which comprised of bi-hourly sampling, and sampling over a complete diurnal cycle. At site B, due to the large proglacial meltwater stream, samples were collected periodically from the glacier snout to the point at which the water entered the ocean, in order to characterise any proglacial weathering processes. Proglacial glacio-fluvial sediment samples were also collected at these points. In addition, supraglacial meltwaters, and snow and ice samples were collected periodically throughout the study period. Meltwater samples were collected by hand in a 1 l Nalgene low-density polyethylene (LDPE) bottle. Snow and ice samples were collected with a clean plastic scoop, and were stored and melted in new plastic bags. For meltwater and snow-ice melt samples, 250 ml of sample was immediately vacuum filtered through 0.45 μm Whatman cellulose nitrate (WCN) membranes using a Nalgene polysulphone filter unit and hand pump. The filtrate was split between two pre-cleaned 60 ml Nalgene LDPE bottles. One was acidified with 0.1ml of PRIMAR HNO_3 for cation, minor and trace element analysis while the other was left un-acidified for anion analysis. One unfiltered sample was also stored in a 60 ml Nalgene LDPE bottle for total phosphorous analysis. Samples were kept in cool conditions in the field, and refrigerated on return to the laboratory. pH was determined in the field using an Orion 250A portable pH/ISE meter, ROSS combination electrode and automatic temperature compensation probe. Calibration was performed using Orion low ionic strength buffers, and Orion low ionic strength adjuster was added to each sample aliquot used for pH determination prior to measurement. Used 0.45 μm WCN membranes and associated suspended particulates were removed from the filter unit with plastic tweezers and retained in individual plastic bags.

To assess the labile fraction of minor and trace elements associated with the suspended particulate load, leaching experiments were carried out on suspended particulates retained on WCN membranes, and on proglacial glacio-fluvio sediments collected at sample site B. Sediments were leached with 100 ml of 0.1 % HCl to assess the labile fraction, in accordance with standard geochemical procedures (*e.g.* Negrel *et al.*, 2000; Mitchell *et al.*, 2001b). This will release minor and trace elements that may easily be removed from the solid phase to solution (sorbed matter, colloids and metal-ligand complexed precipitates) without attacking primary minerals (Mitchell *et al.*, 2001). The membranes were oven dried at 60°C for 12 hours to remove all moisture, and sediments were then transferred from the filter papers into acid cleaned test tubes. The test tubes were agitated every 300 s over a 2400 s period. Each leachate was immediately filtered through a pre-rinsed, acid-washed Nalgene filter unit using 0.45 μm WCN membranes. The filtered leachates were stored in pre-rinsed 60 ml Nalgene LDPE bottles, and refrigerated. The labile concentration of chemical species derived from these experiments was normalised to the sediment concentration of the individual samples to derive a concentration of labile-particulate associated chemical species per mass of suspended particulate.

Bulk meltwater velocity was estimated at sample times using a flow-meter, and water depth was measured at periodic distances over a cross section to determine a cross-sectional area. Discharge was calculated from these data according to equation 1;

Equation 1.

$$Q = V * A$$

where Q is discharge in m^3s^{-1}, V is velocity in ms^{-1}, and A is the cross sectional area in m^2.

Major ion composition of meltwaters and leachates was determined by ion chromatography (Dionex DX-100). Accuracy was ± 3% and precision ± 5%. Minor and trace element analyses were undertaken by inductively coupled plasma mass spectrometry (ICP-MS) on a VG Elemental Plasmaquad. Analysis was undertaken in semi-quantitative mode, using Ru as an internal standard. An acidified standard solution containing the analytes of interest was also used to perform quantitative single point calibration. Multi-element calibration over a wide range of concentrations may be achieved using ICP-MS with single point calibration because the response of signal versus concentration is typically linear over 6-8 orders of magnitude (Jarvis *et al.*, 1992). For meltwater analysis, analytes in the standard solution were

10 $\mu g\ l^{-1}$, while Fe and Ca were at 100 $\mu g\ l^{-1}$ owing to their generally higher concentration in natural waters (Langmuir, 1997). For leachate analysis, analytes in the standard solution were 100 $\mu g\ l^{-1}$, while Fe and Ca were at 1000 $\mu g\ l^{-1}$. During each suite of analysis, the standard solution was run periodically every ~ 10 samples. At the same time, procedural blanks, containing 18 MΩ deionised water and Ru, were also analysed. The semi-quantitative corrected data was then corrected relative to the standard, and water blanks were subtracted. Accuracy and precision was determined by repeat analysis of standards with concentrations of analytes at concentrations comparable to meltwater samples. Accuracy was ± 15% and precision ± 10% for most analytes. Instantaneous dissolved chemical fluxes (dissolved mass per unit time; $mg\ s^{-1}$) from the subglacial environments were determined by multiplying the sample concentration ($\mu g\ l^{-1}$) by discharge ($m^3\ s^{-1}$).

Preliminary Results and Discussion

Supraglacial meltwaters and snow and ice melt was very dilute (EC < 10 µS) and exhibited low pH (~ 6). Conversely, subglacial meltwater samples from sample sites A and B exhibited pH's in the range of 7.5 to 9, and EC's > 100 µS. Low pH / EC waters indicate such waters have had little opportunity to acquire a significant solute concentration which would raise pH and EC as protons are consumed, bicarbonate produced and cations and other anions released as minerals are chemically weathered. This is characteristic of supraglacial and snow meltwaters (Tranter *et al.*, 1993). Therefore, the higher pH / EC of subglacial waters suggests the snow / icemelt waters have been transported from the surface or from subsurface melting areas, and have become chemically enriched in the subglacial environment by chemical weathering processes. For example, during carbonation reactions, acidity produced by the dissolution and disassociation of CO_2 (Equation 2) is consumed by the chemical weathering of silicates (Equation 3) and carbonates (Equation 4), increasing pH by net proton consumption, and increasing EC by the release of dissolved cations and anions (Brown *et al.*, 1994).

Equation 2. Dissolution and dissociation of atmospheric CO_2.

$$\underset{\text{Dissolution}}{H_2O\ (aq) + CO_2} \Leftrightarrow \underset{\text{(carbonic acid)}}{H_2CO_3\ (aq)} \Leftrightarrow \underset{\text{Dissociation}}{HCO_3^-\ (aq) + H^+\ (aq)}$$

Equation 3. Carbonation of feldspar surfaces (albite / microcline - orthoclase)

$$2(Na,K)AlSi_3O_8\ (s) + 2\ CO_2\ (aq) + 9H_2O\ (aq) \Leftrightarrow 2\ Na^+,K^+\ (aq) + 2\ HCO_3^-\ (aq) + \underset{\text{Partially weathered feldspar surface}}{Al_2Si_2O_5\ (s)} + 4H_4SiO_4\ (aq)$$

Equation 4. Carbonation of carbonates

$$\underset{\text{(Mg-)calcite}}{Ca_{1-x}(Mg_x)CO_3\ (s)} + CO_2\ (aq) + H_2O\ (aq) \Leftrightarrow (1-x)Ca^{2+}\ (aq) + xMg^{2+} + 2HCO_3^-\ (aq)$$

It is unclear exactly where dilute, low pH / EC snow and ice melt waters are generated. Supraglacial meltwater enlargement of crevasses, and the development of a connected supraglacial, englacial and subglacial drainage system is typical in Alpine, and to some extent Arctic glaciers (Nienow *et al.*, 1996; Tranter *et al.*, 1994). Sample site A appeared to exhibit these characteristics, as supraglacial meltwater entered the crevasse located on top of the ice cliff above the subglacial outflow. This may also have been supplemented by ice melt generated in warm based subglacial environments that are above the pressure melting point. However, at sample site B during the sampling period, little supraglacial meltwater was apparent. This suggests at sample site B, dilute meltwaters may have been generated predominately by subglacial ice melt in warm based subglacial environments that are above the pressure melting point. However, staff at the Teniente Jubany Argentinean base indicated that throughout the majority of the summer, glacier surface ablation generated large amounts of supraglacial meltwater. Nevertheless, dilute ice or snowmelt waters appeared to become chemically enriched in the subglacial environment by chemical weathering processes.

Chemical analysis of snow / icemelt and subglacial meltwaters allows the enrichment of specific dissolved species in the subglacial environment to be considered. Only analyses of samples for sample site B have been completed at this moment, and the data presented is from this sample site. Table 1 presents enrichment factors for major, minor and trace elements between ice / snow meltwaters and subglacial outflow meltwaters. From these data it is apparent that subglacial outflow meltwaters are significantly enriched with many major, minor and trace elements relative to input waters. Generally, the major ions Mg^{2+}, Ca^{2+}, SO_4^{2-} and HCO_3^- show the greatest enrichment in subglacial meltwaters relative to snow / icemelt input water. Sodium, K^+ and minor and trace elements exhibit much lower enrichment factors. Some of the minor and trace elements have enrichment factors ~ 1 or < 1, indicating average concentrations in input waters are broadly similar or less than bulk meltwaters. These data indicate subglacial weathering processes generate nutrients in Antarctic environments, as demonstrated in Arctic (Tranter *et al.*, 1996) and Alpine environments (Brown *et al.*, 1996; Mitchell *et al.*, 2001a).

Consideration of dissolved concentrations ($\mu g\ l^{-1}$) in subglacial outflow meltwaters as a function of discharge indicates dissolved concentrations of major ions and minor and trace elements exhibit a linear inverse relationship with discharge (Figure 1). However, the flux ($mg\ s^{-1}$) of dissolved species demonstrates a positive linear relationship with discharge (Figure 2). Discharge is therefore a key control on the concentration and flux of dissolved chemical species. While discharge during the sample period was very low (i.e. < 0.5 m^3s^{-1}) staff at the Teniente Jubany Argentinean base suggest that throughout the peak of the summer, discharges appear < 10 times greater than during our sampling period. This suggests that while dissolved chemical concentrations may be lower during the majority of the summer than recorded during our sampling period, the dissolved chemical fluxes may be < 10 times greater. Long term discharge records collected at the Teniente Jubany Argentinean base are being acquired for further analysis.

In order to quantify the importance of nutrient export from the catchment associated with suspended sediment surfaces, dilute acid (0.1 % HCl) leaches were performed on the field collected suspended sediments, and on proglacial glacio-fluvio sediments collected at sample site B. The dilute acid leaches yielded estimates of the mass of labile nutrient (μg) per unit mass of sediment (g) (Table 1). Such labile species will comprise of sorbed species, (oxy)hydroxides, and co-precipitated species in these solids, attached to suspended sediment surfaces, or as discrete (oxy)ydroxide precipitates (Mitchell *et al.*, 2001b). Calcium, Fe, and Al dominate the labile, sediment-associated fraction. Labile Mg^{2+}, K^+, Na^+, Mn, SO_4^{2-} and many minor and trace elements are liberated at lower concentrations. Multiplying the labile nutrient concentrations from the field collected suspended sediments by the discharge at the time of sample collection yielded a flux of labile particulate-associated nutrients, expressed as a function of discharge in Figure 3. As with dissolved fluxes, labile particulate-associated nutrient fluxes are positively associated with discharge. While fluxes were relatively low compared to previously published fluxes (Sharp *et al.*, 1995; Mitchell *et al.*, 2001b), this is again a function of the low discharge, and the low suspended sediment concentration and flux, during the sampling period. Since discharges appear to greater during the majority of the summer months than during our sampling period, suspended sediment and associated particulate-associated chemical fluxes would be expected to increase significantly.

Table 1. Median enrichment factors. Calculated by dividing the concentration of individual dissolved species in individual subglacial water samples by that measured in snow / icemelt samples. The median particulate associated concentrations ($\mu g\ g^{-1}$) derived from weak (0.1 % HCl) acid leaches of suspended sediments. The percentage particulate associated flux is also presented. * Particulate-associated flux expressed as percentage of total flux (dissolved and particulate-associated) at each sample time.

Element / species	Median enrichment factor	Median particulate-associated concentration	Median Percentage particulate-associated flux *
Li	1	10	-
Be	1	1	-
Al	7	1500	25
Ti	6.5	60	13
Mn	1	100	15
Fe	10	3000	18
Co	4.2	3.0	-
Ni	10	5.0	15
Cu	4	5.0	-
Zn	5	50	-
Rb	4	3.0	8
Sr	25	25	4
Cd	1.5	0.30	-
Cs	1.3	0.35	-
Ba	3	35	17
Pb	1	3.2	-
U	8	2	7
SO_4^{2-}	70	100	2

Na^+	15	400	4
K^+	15	740	4
Mg^{2+}	30	850	6.5
Ca^{2+}	25	4700	7

When the dissolved flux is considered as a percentage of the particulate-associated flux, it is apparent that the dissolved flux dominates the total (dissolved plus particulate-associated) chemical flux (Table 1). This is in contrast to that demonstrated in Alpine glacial environments (Mitchell *et al.*, 2001b) where the particulate-associated chemical flux dominates, on average, over the ablation season. This is probably a reflection of the relatively low suspended sediment flux apparent at sample site B. Indeed, Mitchell *et al.* (2001b) demonstrate that in Alpine glacial environments, the particulate-associated chemical flux is very small in the very early and very late ablation season, when discharges and associated suspended sediment concentrations were lowest. Since it appears discharge and probably the suspended sediment flux was much greater during the summer months previous to our sampling period, this suggests that the particulate-associated chemical flux may also dominate nutrient fluxes from Antarctic subglacial environments to the ocean during the majority of the Antarctic summer.

Figure 1. Dissolved concentration of example species as a function of discharge; Ca^{2+} and Al.

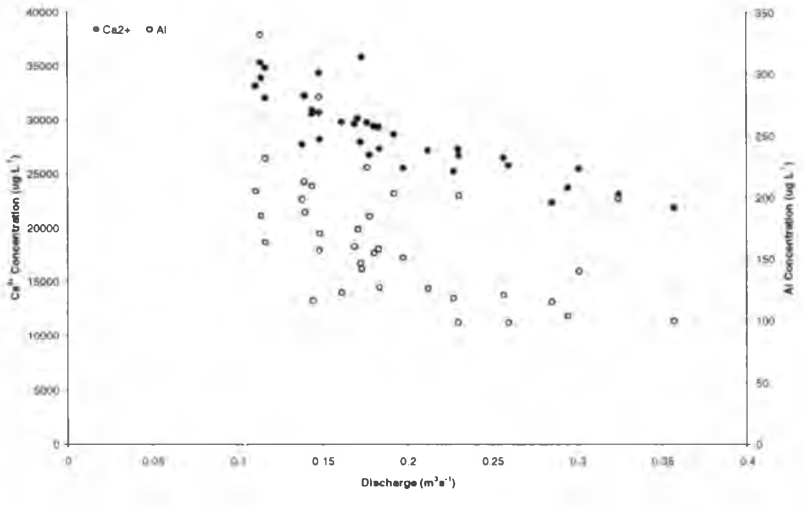


Figure 2. Dissolved instantaneous flux of example species as a function of discharge; Ca^{2+} and Al.

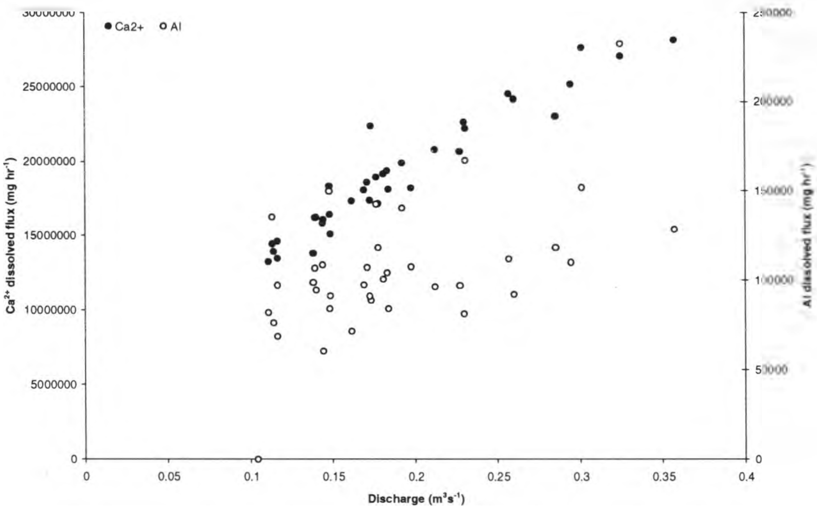
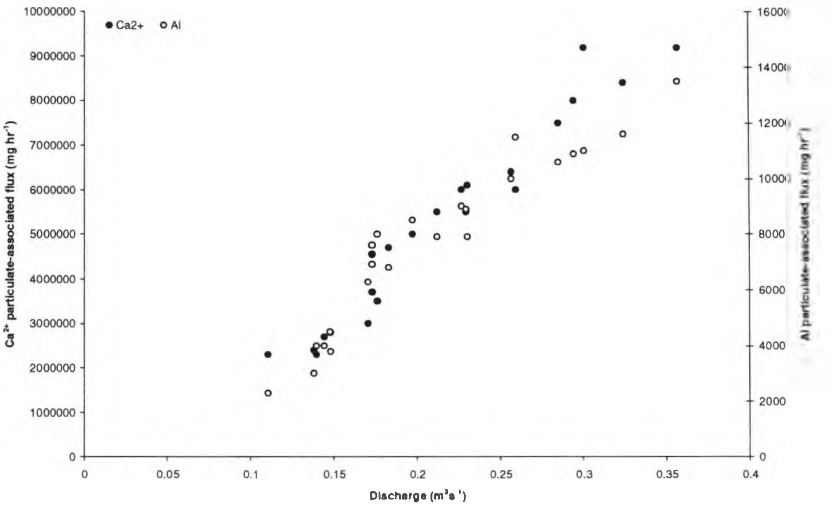


Figure 3. Particulate-associated flux of example species as a function of discharge; Ca^{2+} and Al.



Conclusions and wider implications

This study indicates that ice and snow melt generates little solute, but that subglacial weathering processes significantly enrich these meltwaters with dissolved major ions and minor and trace elements. Similarly, labile major ions and minor and trace elements are associated with the suspended particulate phase. These species appear to be transported as sorbed species, (oxy)hydroxides, and co-precipitated species in these solids, attached to suspended sediment surfaces, or as discrete (oxy)ydroxide precipitates, as demonstrated in Alpine glacial environments (Mitchell *et al.*, 2001b). While the concentration of dissolved and particulate-associated chemical species is inversely related to discharge, the flux of these species increases with meltwater discharge. At all the discharges during the sampling period, the dissolved flux dominated over the particulate-associated flux. However, this probably reflects the low discharge and associated low suspended sediment flux during our sampling period. Indeed, observations by the Teniente Jubany Argentinean base suggest discharge may be < 10 times greater during the majority of the summer months than observed during our sampling period. This suggests nutrient fluxes may be < 10 times greater during the majority of the summer months than observed in our study, assuming the apparent linear response between discharge and dissolved and particulate-associated element flux. This does not take into account local variations in geology and mineralogy, which will affect the magnitude of individual elemental fluxes due to variation in the minerals weathered, but will not affect the discharge-flux relationships outlined.

These data have implications for the large-scale and long-term export of nutrients from the terrestrial Antarctic environments to the ocean. Evidently, discharge is the primary variable which controls the flux of nutrients from the subglacial environments studied. Unlike other parts of the Antarctic, the Antarctic Peninsula has experienced climate warming within the 20th centaury (e.g. King, 1994; Van den Broeke, 2000), and has demonstrated instability by increased iceberg calving and the recent collapse of the Larsen B shelf on the eastern side of the Antarctic Peninsula. While the effect of climate warming upon the Antarctic ice sheet may mostly be reflected by iceberg calving, this must also be accompanied by increased meltwater generation, particularly where ice is not in contact with the ocean, and ice ablation must continue on land, rather than in the ocean. Such increases in meltwater generation and discharge could potentially lead to large increases in nutrient fluxes to the Southern Ocean from the Antarctic landmass, if the meltwater generated is routed through subglacial environments, where significant chemical enrichment may occur, as demonstrated by this study. It is purely conjecture, but if nutrient fluxes were great enough to promote an increase in phytoplankton biomass in the Southern Ocean, planktonic carbon sequestration could increase in response to climate warming induced increases in land-ocean nutrient fluxes (e.g. Boyd *et al.*, 2000; Abraham *et al.*, 2000; Chisholm, 2000). Indeed, phytoplankton biomass has been correlated with the amount of bio-limiting nutrients up-welled from the deep sea to the sunlit surface waters in the Southern Ocean, and recent iron fertilization experiments (Boyd *et al.*, 2000) show associated increases in primary productivity and CO_2 draw-down rates. This could have implications for carbon cycling on glacial-interglacial timescales.

Ongoing Analysis and Future Work

There is much more sample and data analysis to undertake. Most significantly, if we are able to acquire the long term discharge records for sample site B from the Teniente Jubany Argentinean base, we may be able to correlate our flux-discharge relationships to generate a seasonal estimate of the total nutrient export, and temporal changes is the mode (dissolved or particulate-associated) of nutrient export. Also, field collected rock samples will be utilised in rock-water interaction experiments to investigate the mechanisms and rates of solute and particulate-associated nutrient generation in subglacial Antarctic environments. It would also be extremely valuable to further this study, and undertake a more intensive sampling regime during the height of the Antarctic ablation season when discharges and suspended sediment fluxes will be greater than during our sampling period. Similarly, in order to investigate the applicability of the data presented here to other sites in the Antarctic Peninsula, more intensive and long-term sampling at other sampling sites needs to be undertaken. At a larger temporal and spatial scale, contemporary and future meltwater discharges for the Antarctic Peninsula need to be estimated in response to the current climate in the Antarctic Peninsula, and under future estimates of warming. This is of fundamental importance for estimates of long-term and large-scale nutrient fluxes to the southern ocean from the Antarctic landmass.

References

Abraham, E.R., Law, C.S., Boyd, P.W., Lavender, S.J., Maldonado, M.T. & Bowie, A.R. (2000) Importance of stirring in the development of an iron-fertilized phytoplankton bloom. Nature, 407, 727-730.

Boyd, P.W. *et al.* (2000) A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. Nature, 407, 695-702.

Brown, G. H. (1991). Solute provenance and transport pathways in Alpine glacial environments. Ph.D., Southampton.

Brown, G. H., M. J. Sharp, M. Tranter, A. M. Gurnell and P. W. Nienow (1994). "Impact of Post-Mixing Chemical-Reactions on the Major Ion Chemistry of Bulk Meltwaters Draining the Haut Glacier Darolla, Valais, Switzerland." Hydrological Processes **8**(5): 465-480.

Brown, G. H., M. Sharp and M. Tranter (1996). "Subglacial chemical erosion: seasonal variations in solute provenance, Haut Glacier d'Arolla, Valais, Swizerland." Journal of Glaciology **22**: 25-31.

Chester, R. (1990). Marine Geochemistry. Chapman and Hall: London; 698., Chapman and Hall.

Chisholm, S.W. (2000) Stirring times in the Southern Ocean. Nature 407, 685-687.

Holland, H. D. (1978). The Chemistry of the Atmosphere and Oceans. New York, John Wiley & Sons.

King, J.C. (1994) "Recent climate variability in the vicinity of the Antarctic Peninsula", International Journal of Climatology (14): 357-369.

Langmuir, D. (1997). Aqueous Environmental Geochemistry. New Jersey, Prentice-Hall.

Mitchell, A., G. H. Brown and R. Fuge (2001a). "Minor and trace element export from a glacierised Alpine headwater catchment (Haut Glacier d'Arolla, Switzerland)." Hydrological Processes **15**(18): 3499-3524.

Mitchell, A., G. H. Brown and R. Fuge (2001b). Temporal variations in the minor and trace element chemistry of meltwaters draining Haut Glacier d'Arolla, Switzerland: Implications for downstream water quality. Proceedings of the 58th Eastern Snow Conference. Ottawa, Ontario, Canada. 149-158

Negrel, P., Grosbois, C, Kloppmann, W. (2000). "The labile fraction of suspended matter in the Loire River (France): multi-element chemistry and isotopic (Rb-Sr and C-O) systematics." Chemical Geology **166**: 271-285.

Nienow, P. W., M. J. Sharp, I. C. Willis and K. S. Richards (1996). "Dye tracer investigations of the spatial structure of the subglacial drainage system of the Haut Glacier d'Arolla, Valais, Switzerland." Journal of Glaciology.

Raiswell, R. (1984). "Chemical models of solute acquisition in glacial meltwaters." Journal of Glaciology **30**(104): 49-57.

Modelling the response of Warzawa Icefield, Antarctica to recent and future climate change.

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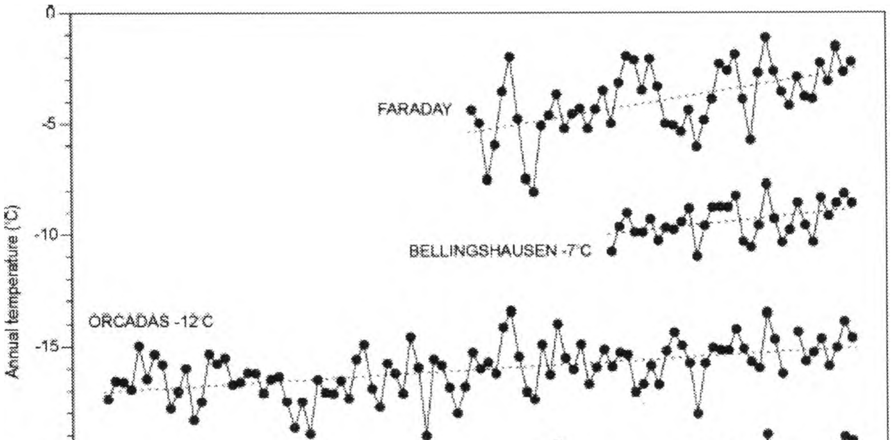
Introduction

Recent climatic warming and its impacts across the Antarctic Peninsula is now a well documented phenomenon (e.g. Jones, 1990, King, 1994, Stark, 1994, Vaughan et al., in press). Warming trends from the last 50 years of meteorological records on the Peninsula (~3.5°C per century, Fig. 1.1) are an order of magnitude higher than the global average given by the IPCC (Intergovernmental Panel on Climate Change, see Houghton et al., 2001 and Vaughan et al., in press). Future global climatic warming is predicted at between 1.4 and 5.8°C by 2100 (Houghton et al., 2001., Fig. 1.2.), this will cause the 0°C January isotherm to migrate southwards, causing enhanced melting of glaciers and ice shelves and increasing the potential contribution to global sea level rise. This study aims to investigate and quantify the effects of the IPCC predictions on Antarctic Peninsula ice masses, through the use of a coupled high resolution ice flow/mass balance model. The model will be applied to part of the King George Island ice cap, situated in the South Shetland Islands (Fig. 3.1.), which has shown dramatic retreat since the mid 1950s (Fig. 3.3.).

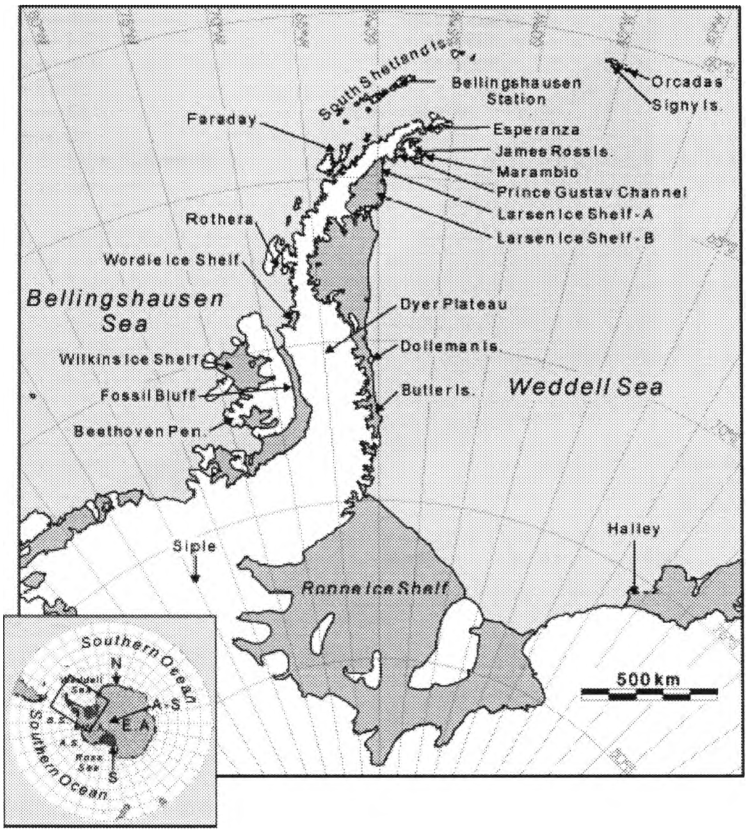
Antarctic Peninsula Climate

Due to its location in the circumpolar westerlies of the Southern Hemisphere, the Antarctic Peninsula has a relatively warm and humid climate compared to the main continent, dominated by a succession of low pressure systems (Braun et al., 2001a). Summer temperatures are regularly above 0°C at sea level, therefore significant ablation occurs on the lower parts of the glaciers and ice caps during the melt season. In such maritime conditions, glaciers and ice caps are very sensitive to temperature changes (Knap et al., 1996). A number of studies into the sensitivity of the ice masses of the Antarctic Peninsula (e.g. Bintjana, 1995, Knap et al., 1996, Braun, 2001) indicate that they are potentially highly sensitive to climate change.

Vaughan et al. (in press) suggest climate proxies show the present warming is unprecedented over the last two millennia, and so is unlikely to be a natural mode of variability. They suggest it may be a regional amplification of global warming, but the mechanism behind this amplification is unclear. Possible mechanisms include changing oceanographic or atmospheric circulation or air-sea-ice feedback (see also King, 1994). Whatever the cause, the impacts of the warming is already apparent, with the retreat of glaciers (e.g. Splettstoesser, 1992) and collapse of ice shelves (e.g. Vaughan and Doake, 1996, Skvarca et al., 1998, De Angelis and Skvarca, 2003) and reduced sea ice duration (Parkinson, 2002) (see also Fig. 3.1). The warming has also impacted ecosystems, with changes in both flora and fauna distributions. For example Adelie penguins, which require access to winter pack ice, are declining in numbers whereas Chinstrap penguins which occur mainly in open water are increasing (Smith et al., 1999).



a)



b)

Figure 1.1. a) Mean annual air temperature from the Antarctic Peninsula (dotted lines are trends given in Table 1.1); b) location map for stations on the Antarctic Peninsula, inset showing location map and main continent stations (from Vaughan et al., in press).

Table 1.1. Trends in mean annual air temperature for meteorological stations on the Antarctic Peninsula (from Vaughan et al., in press).

Station	Trend (°C per century)	Years
Faraday/Vernadsky	5.7 ± 2.0	1951-2001
Bellingshausen	3.7 ± 2.1	1969-2001
Esperanza	3.4 ± 1.3	1946-2001
Orcadas	2.0 ± 1.0	1904-2001

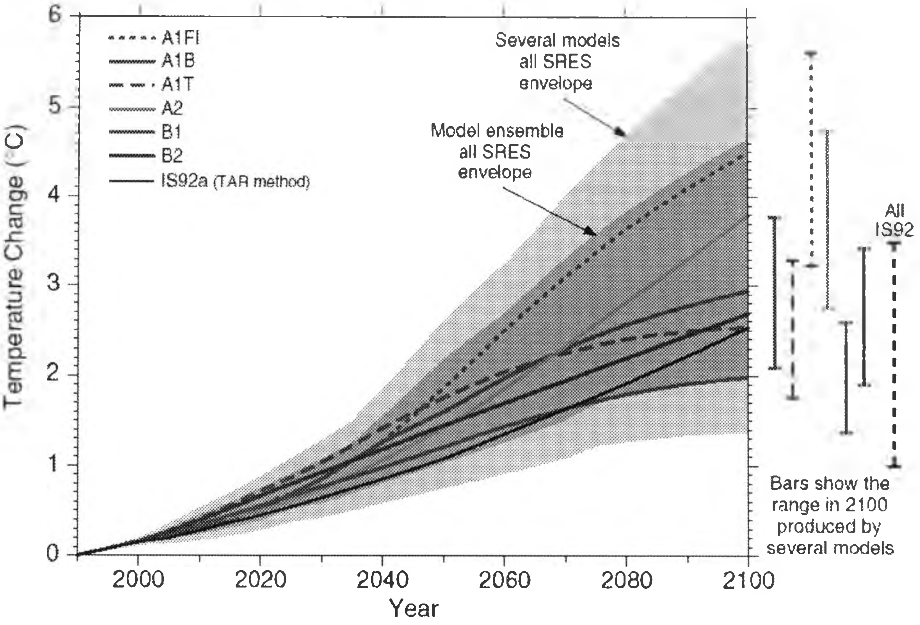


Figure 1.2. IPCC temperature predictions from present to 2100 (for SRES scenario details, see Houghton et al., 2001)

Aims

This study aims to:

- apply a coupled high resolution ice flow/mass balance model to part of the King George Island ice sheet, the Warszawa ice sheet (Fig. 3.2.)
- evaluate the ability of the model to replicate past and present ice extents and dynamics using aerial photography and satellite records.

in order to:

- determine the sensitivity of the Warszawa ice field to the best and worst case IPCC predictions, and to determine the potential response of similar-type ice masses for the rest of the Antarctic Peninsula.

Study Area

The South Shetland Islands are located at the northern tip of the Antarctic Peninsula (Fig. 3.1.). King George Island (Fig. 3.2.) is the largest of the islands, with an area of about 1250km^2, of which 93% is ice covered (Braun et al., 2001a). The Antarctic Peninsula acts as a major obstacle in the southern hemisphere circumpolar westerlies, causing a distinct climatic barrier between west and east coast regions. Therefore the maritime climate of the west coast is around 7°C warmer than similar latitudes and elevations on the east coast (Reynolds, 1981). The South Shetland Islands lie on the west side of the Antarctic Peninsula, and therefore have a relatively warm and humid climate, characterised by a rapid succession of eastward moving low pressure systems. Mean monthly temperatures regularly reach values above 0°C (Bintjana, 1995).

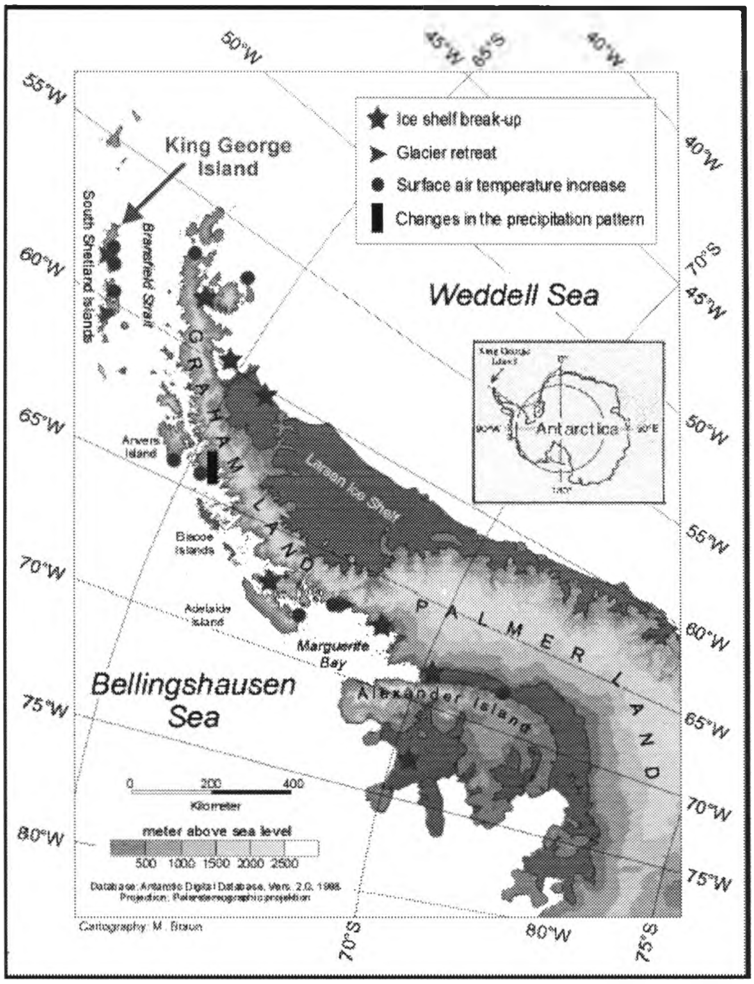


Figure 3.1. Location of King George Island on the Antarctic Peninsula, and indicators for climate change (adapted from Braun, 2001 and Knap et al., 1996).

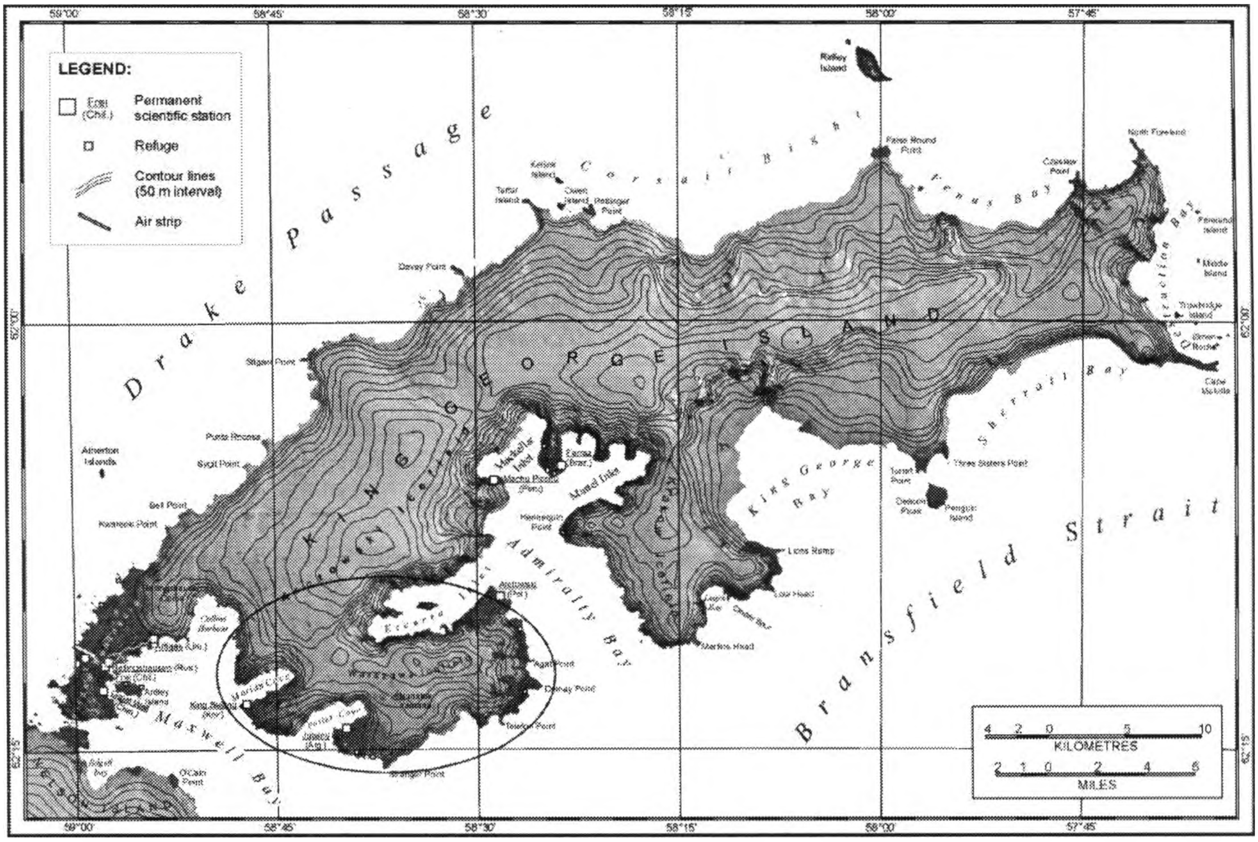


Figure 3.2. King George Island (Specific study area - the Warszawa icefield circled) (From Braun, 2001).

King George Island has been one of the most visited and most densely populated areas in Antarctica since the earliest days of human activities in Antarctica (Braun et al., 2001b). Nine permanent bases exist on the island currently, therefore there are meteorological records and aerial photography archives stretching back over the last century. These indicate significant retreat of the ice sheet since the 1950s.. Park et al. (1998) analysed aerial photography from 1956 to 1994 for two ice streams terminating in Maxwell Bay. Both retreated dramatically between 1956 and 1986, 250m and 400m for Marion and Potter Cove respectively (see also Fig. 3.3.). A similar retreat has been observed for Lange glacier, which has retreated 1340m over the period 1956-1995 (Braun et al., 2001b).

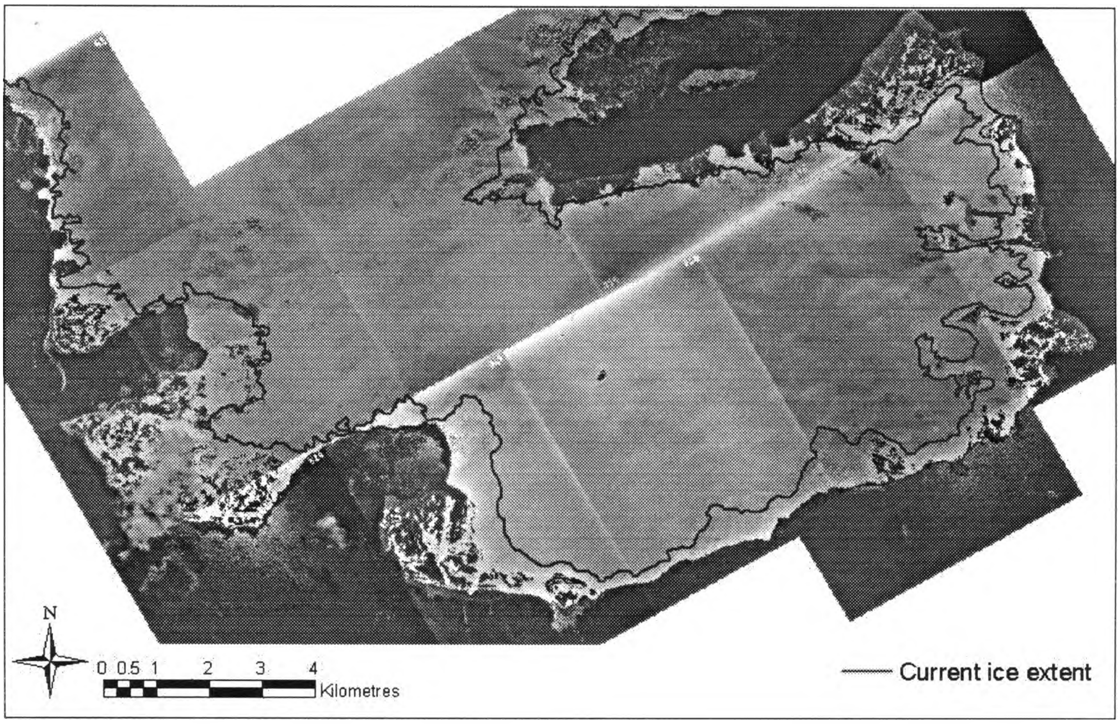


Figure 3.3. Aerial photographs showing ice extent in 1956 (from the Falkland Islands Dependencies Aerial Survey Expedition (FIDASE) expedition, 1955-57) and subsequent retreat.

Bintjana (1995) was the first to attempt to quantify the sensitivity of the ice cap to climate change, finding that an increase of air temperature by 1°C would result in a 15% rise in ablation rates from surface energy balance calculations. From measurements during 1997/98, Braun (2001) found that ablation rates on King George Island were almost double the rates reported in the 1970s. Using a spatially distributed energy balance model, he suggests that a 2°C increase in temperature would lead to 60% rise in ablation. A sensitivity analysis using an ice flow model was performed by Knap et al. (1996). They describe a high sensitivity to climatic changes, suggesting that a 3°C rise in temperature before 2050 would result in a loss of 10-20% of ice volume and almost 50% by the end of this century. 5°C warming is enough to cause the disappearance of the ice sheet completely.

Approach

The modelling approach can be split into a number of parts:

- Part 1 (section 5): Equilibrium Calibration
  The flow model (described in section 5) was initially tested and calibrated by running the model on a simple mass balance-elevation relationship until a steady-state ice sheet was achieved. This was then compared to the present extent and surface.
- Part 2 (section 6): Dynamic Calibration
  As suggested by Oerlemans (1997), one of the problems encountered in modelling glaciers and ice sheets relates to their transient behaviour. Response times of the order of 10s of years to climate perturbation mean that information on present volume and extent are not an indication of their state of balance with respect to the current climate. Oerlemans (1997) outlines a different approach from that used in part 1, called dynamic calibration. Given that extent records are available which exceed the characteristic response time for the ice sheet, a steady state ice sheet can be produced for the first point in the extent record, and modelled through time. The model can then be calibrated by comparing snapshots from the model simulation against the observed extent. In this way, the model

holds the mass balance history in its memory and represents a more reliable estimate than assuming a steady state at the present time (c.f. part 1).

Part 3 (section 7): Future Climate Scenario Predictions

The calibrated model will then be run with six scenarios which represent IPCC predictions (see Oerlemans et al., 1998); an increase of 0.01, 0.02 and 0.04 °C yr^{-1} with no increase in precipitation, and the same temperature scenarios with a 10% increase in accumulation per degree warming.

Flow Model

Model Description

The ice flow model used in this study is identical to that used by Hubbard (1999) to simulate the Younger Dryas Ice sheet across Scotland. It is a quasi-three-dimensional, time-dependent ice flow/mass balance model which includes longitudinal stress gradients, floating ice shelves and calving mechanics. A brief description of the model is given below, for a full description of the flow physics the reader is referred to Hubbard (1999).

The two-dimensional evolution of the ice-sheet thickness (H) through time (t) is determined by the equation of mass continuity:

$$\frac{\delta H}{\delta t} = b - \nabla \cdot \left(H\overline{u} \right) \qquad (5.1).$$

where the change in ice thickness ($\delta H/\delta t$) for a given grid cell is a function of the mass balance (b) and the ice flowing into the cell from the adjacent cells ($\nabla \cdot (H\bar{u})$; where $\bar{u}$ is ice velocity).

Changes in the local ice-thickness therefore occur as a result of changes in the mass balance (accumulation minus ablation) and the vertically integrated ice flux from adjacent grid nodes. Ice motion (eq. 5.2) is composed of internal deformation (Glen, 1958) and basal sliding (Weertman type, Paterson, 1994) using the following relation:

$$\overline{u}_i = A_d H(\tau)^{n-1} \tau_{iz} + A_s \tau_{iz}^{m} \qquad (5.2).$$

where A_d is the flow parameter, τ is the effective stress, n is the flow law exponent (value of 3), A_s is the sliding parameter, m is the sliding exponent (value of 3) and i is the horizontal spatial operator (either x or y) and z is the vertical operator (positive upwards).

Basal shear traction (τ_{iz}) is calculated from the local driving stress and corrected for the vertically averaged longitudinal deviatoric stress computed through a numerical procedure invoking ice surface stretching (Hubbard, 1999).

A resolution of 100m was chosen for the model as this provides a resolution fine enough to replicate the retreat without compromising speed of processing.

Boundary Conditions

Mass Balance

The mass balance was initially constrained using an elevation-based relation determined by Knap et al. (1996) for King George Island which provides a simple representation in order to test the flow model. The curve was determined from an energy balance model run using data from the Arctowski meteorological station (1978-87). Within the flow model it is parameterised using a cubic polynomial relationship, expressed around the Equilibrium Line Altitude[1] (ELA), allowing the model to be forced by ELA changes at different stages of the experiment (Fig. 5.1.).

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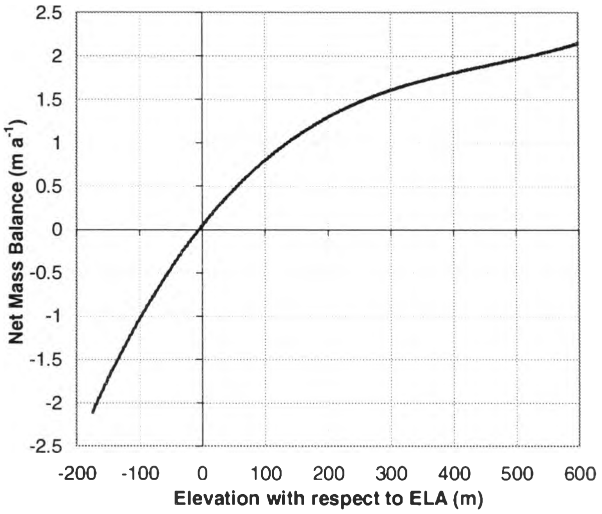
[1] The Equilibrium Line Altitude (ELA) is the altitude at which the net mass balance (accumulation minus ablation) changes from negative (net loss of ice) to positive (net gain of ice).

Figure 5.1. Mass balance curve for KGI: mass balance against elevation expressed around the ELA (from Knap et al., 1996)



Mass is also lost through calving at the ice-ocean interface, this is determined using an empirically defined calving term (eq. 5.3). Calving (c) is related to ice thickness, water depth and the calving front geometry:

$$c = \Phi \cdot A_c H d^e \qquad (5.3).$$

where Φ is the calving front geometry dependent on the number of actively calving sides, A_c is a calving parameter, H is the ice thickness, d is the water depth and e is a calving exponent.

Surface and Bedrock Topography

The flow model also requires a basal boundary condition in the form of sub-glacial topography. This data was provided for use in the project (Fig. 5.2.) and was derived from Radio Echo Sounding (RES) transects from the ice field. The derived depths were interpolated for the entire grid aided by the perfect plasticity assumption for ice (see Van der Veen, 1999) which relates ice thickness to surface slope and a thickness dependent constant (derived from data rich areas). The surface topography was also provided and was derived from Interferometric Synthetic Aperture Radar (see Braun et al., 2001b).

Bathymetry

Offshore bathymetry is also a model requirement and was obtained from depth soundings digitized from Admiralty charts and from a chart provided by the Polish Department of Antarctic Biology. The point data was then interpolated using ordinary kriging (Fig. 5.2.) (for more details see Le Brocq, 2003). The basal topography and bathymetry were then melded together to provide the input surface for the model.

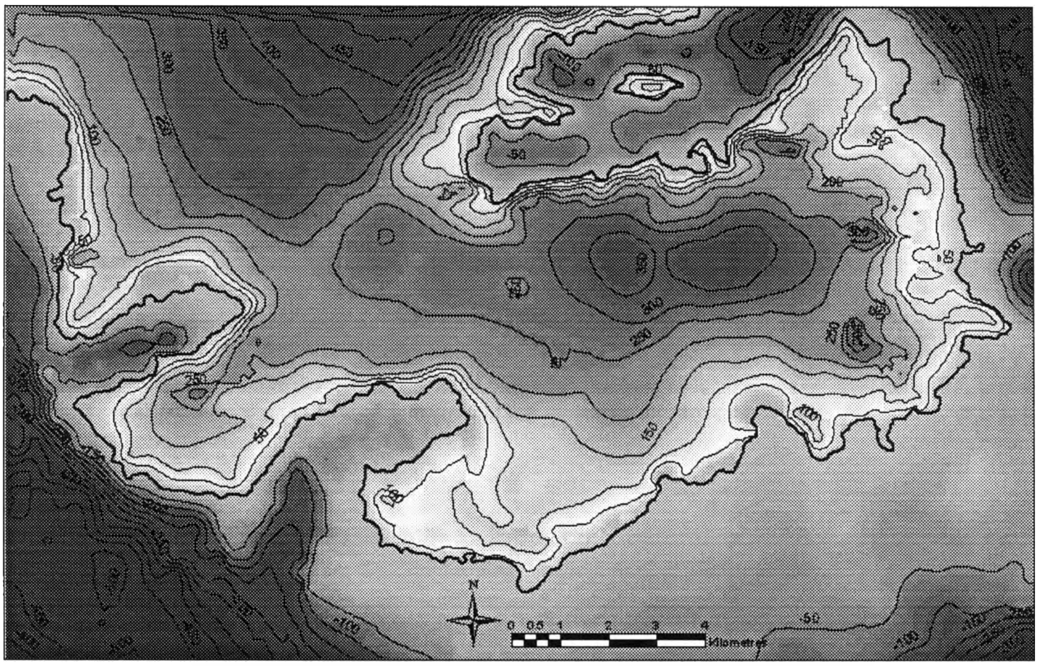


Figure 5.2. Input surface (basal topography and bathymetry)

Model Calibration and Sensitivity Analysis

There are a number of parameters within the model which vary depending on the particular glacier conditions (e.g. temperature and basal regime) and require calibration. The flow law parameter (A_d) represents the viscosity of ice for internal deformation and varies according to ice temperature (Paterson, 1994). The sliding parameter (A_s) determines how basal velocity is related to basal shear traction and also the depth related calving term (A_c) requires calibration. The flow and sliding parameters would ideally be constrained using measurements of velocity from the ice cap, however these are not currently available for the Warszawa Ice cap. Measurements of velocity are available from Lange Glacier in Admiralty Bay (see Fig. 3.2.) and range between 20 and 365 m a^{-1} (Noble, 1965 and Braun, 2001). Different parameter sets were instead evaluated by how well they replicate the present ice surface and extent, modelled from ice free conditions to equilibrium (ELA of 200m). This gives some indication of appropriate values and the model sensitivity to these parameters (Table 5.1. and 5.2.).

Table 5.1. Prediction success statistics for various parameter sets (present volume = 7.30km^3)

A_s (x 10^{-15})	A_d (x 10^{-15})	Number of cells predicted: correct	Number of cells predicted: incorrect	Average surface difference (m)	Total volume (km^3)
-	0.49	11696	1752	18.15	12.98
-	1.6	11300	1724	10.53	10.22
-	2.4	11180	1714	8.59	9.42
-	6.8	10889	1725	5.33	7.63
2	2.4	11173	1716	8.49	9.36
	6.8	10887	1724	5.32	7.61
10	2.4	11123	1713	8.08	9.13
	6.8	10866	1724	5.26	7.49
150	1.6	10849	1694	5.85	7.38
	2.4	10822	1698	5.66	7.22
	5	10774	1688	5.37	6.82
	6.8	10760	1681	5.33	6.62
500	0.49	10717	1661	6.20	5.92
	1.6	10731	1654	6.25	5.87
	2.4	10729	1654	6.28	5.84
	5	10723	1631	6.41	5.72

Table 5.2. Prediction success statistics for calving parameter (A_d = 2.4 x10^{-15}, A_s = 300 x10^{-15})

A_c	Number of cells predicted:		Average surface difference (m)	Total volume (km^3)
	correct	incorrect		
10	10969	1861	5.93	6.76
20	10925	1731	5.88	6.60
30	10758	1663	5.70	6.40

Sensitivity Summary

A_d - Flow parameter:

The modelled volume is sensitive to changes in the flow parameter when basal sliding is not considered or has a small value. The total volume almost doubles for an order of magnitude change in A_d (Table 5.1.). However as the contribution from basal sliding increases, the flow parameter becomes less important and the volume is very similar for an order of magnitude change in A_d. The modelled extent however is not sensitive to the flow parameter.

A_s - Sliding Parameter:

The modelled volume and extent is sensitive to the sliding parameter. As A_s is increased, the extent prediction improves, but this is at the expense of the volume and thickness.

A_c - Calving Parameter:

The model is sensitive to the calving parameter, it affects both the volume and the extent. In order to replicate the present day margins at the ice-ocean interface, a high calving parameter was needed (up to 30). However when the ELA is lowered, this restricts ice growth for the 1956 margins in the fjords. The empirical depth related term may not therefore be appropriate in this case. Vieli et al. (2001) suggest that an empirical depth related calving term is appropriate for slowly advancing/retreating glaciers, but is not appropriate for situations of rapid change. Noble (1965) also suggests that the position of the ice cliffs depends primarily on the temperature of the sea, rather than the ice 'budget', sea temperature is not included in the calving parameterisation of the model. Uncertainty in the bathymetry data at shallow depths is also a consideration.

Mass Balance:

The mass balance curve parameters have little impact on the extent of the ice sheet, however the modelled ice volume is sensitive to changes in the mass-balance elevation relationship; a doubling of mass balance leads to 30% increase in volume.

From these experiments the optimum values of the various parameters were determined: (see Fig. 5.3.)

ELA = 200m

$A_d = 6.8 \times 10^{-15}$ (s^{-1} kPa^{-3})

$A_s = 150 \times 10^{-15}$ (m $a^{-1}Pa^{-3}$)

$A_c = 30$

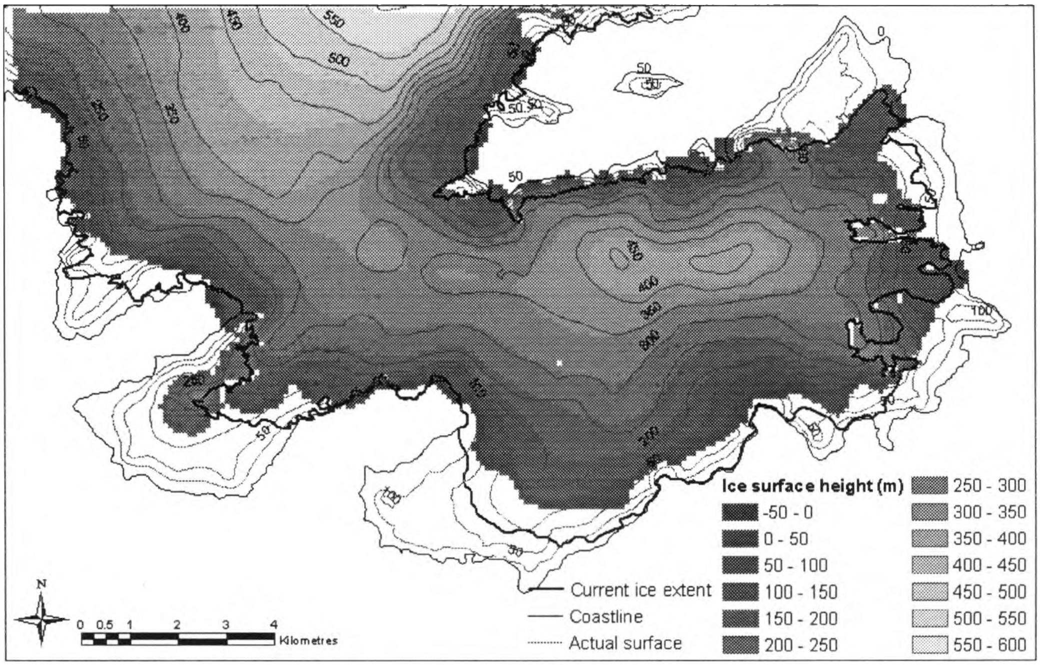


Figure 5.3. Modelled extent and surface (ELA = 200m, $A_d = 6.8 \times 10^{-15}$,
$A_s = 150 \times 10^{-15}$ $A_c = 30$)

Response and Sensitivity to ELA change

The sensitivity of the ice sheet to change in ELA gives a strong indication of its likely response to climate change. Knap et al. (1996) indicate that 1°C rise in temperature is equivalent to raising the ELA by 100m, therefore the ELA was adjusted by 50 and 100m around the present ELA. Raising the ELA by 100m (200 to 300m) leads to a reduction in area and volume by a third (Table 5.3. and Fig. 5.4.).

The response time to an ELA perturbation is also a good indicator of the sensitivity of the ice sheet, a rapid response indicating a highly sensitive ice mass, which will be suitable for investigating climate change. A change in ELA (50 and 100m around present) was applied to the equilibrium surface at an ELA of 200m. Fig 5.5. shows that equilibrium is reached about 40-60 years after ELA perturbation. This suggests the Warszawa ice sheet is highly sensitive to climate warming, and will respond quickly to any perturbation. Its fluctuations are therefore a good record and indication of climate change.

Table 5.3. Area and volume statistics for different ELAs

ELA	Area (km^2)	Volume (km^3)
100	159.79	8.609
150	141.87	7.589
200	124.41	6.622
250	105.65	5.552
300	76.12	3.838

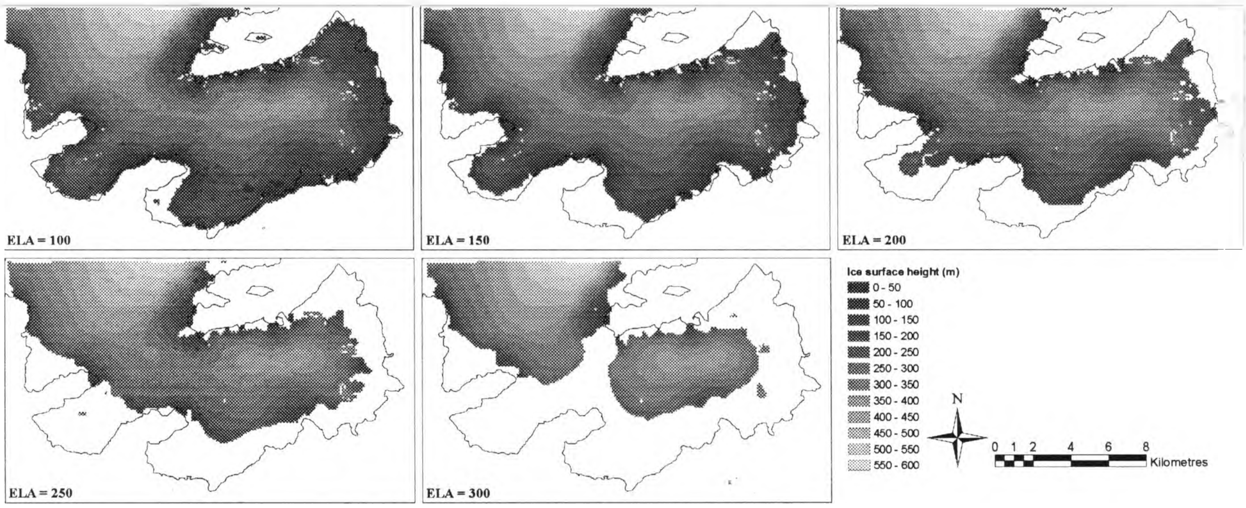


Figure 5.4. Modelled ice surface with different ELAs (100m-300m)

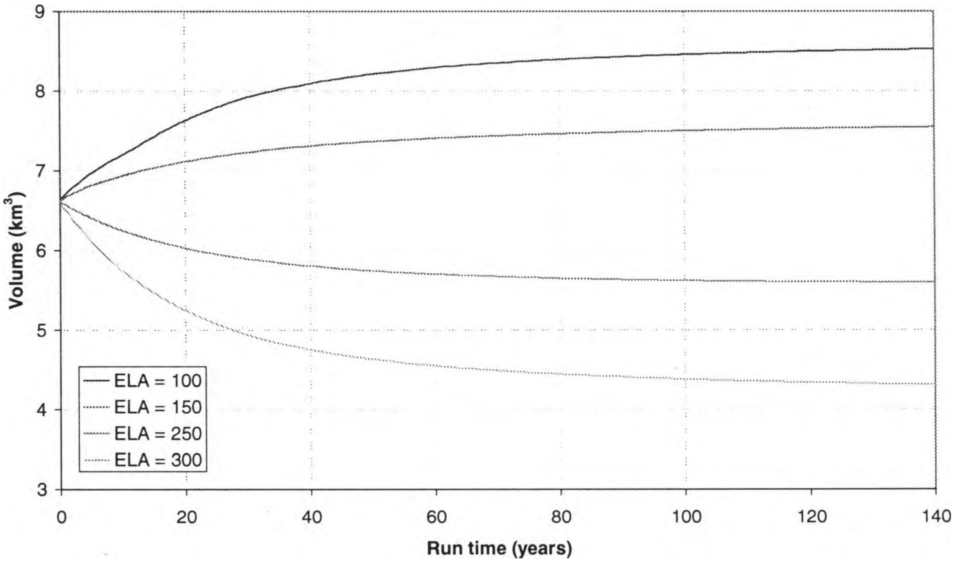


Figure 5.5. Modelled response time to change in ELA (run from modelled surface (ELA = 200m))

Model Evaluation

Overall the prediction of the surface is satisfactory, however visual inspection of the modelled extent suggests that there is generally an under-prediction of ice on the southern margins and an over-prediction of ice on the northern margins. At such a high resolution, it becomes important to consider the factors affecting the spatial distribution of mass balance. Accumulation will vary spatially reflecting the direction of weather systems and redistribution by wind. The prevailing wind is generally north westerly or westerly (Braun, 2001), which would lead to snow being removed from north-west facing slopes and deposited on the lee side of slopes.

Ablation rates will also be influenced by the differing direct radiation received on north and south facing slopes due to topographic shading, aspect and slope angles (Hock, 1999). Braun (2001) states that net radiation is the main contributor to ablation at King George Island, with sensible heat flux being of secondary importance, confirming the importance of aspect considerations. The present ice surface also indicates that ice is present at lower altitudes on the south facing slopes. Ablation will also be influenced by spatial differences in temperature. Temperatures on east side of the ice sheet (around Arctowski station) tend to be warmer than at Bellingshausen station (to the west) due to a föhn type wind (Braun, 2001 and Bintjana, 1995).

Uncertainty in the bed topography may also contribute, if ice thickness is over estimated, then the basal topography will be lower, enhancing ablation and hindering ice formation.

Dynamic Calibration and Simulation of the Historic Record

In order to calibrate the ice sheet dynamically and simulate the volume evolution through time, a temperature-index model (or Degree Day Model (DDM)) was incorporated into the flow model to represent mass balance, this is described in the next section.

Degree Day Model Description

In a DDM, melt is taken as proportional to the total air temperature above zero, the positive degree day (PDD) sum. The degree day factor (DDF or k) determines the relationship between temperature and melt in the following manner:

$$A_N = k_{snow/ice} \cdot PDD \qquad (6.1).$$

where A_N is the total ablation over the N-day period, k is the degree day factor (m d^{-1} K^{-1}) and PDD (positive degree day sum) is the sum total of temperature above zero (°C) for the N-day period.

Hock (1999) outlines a new approach to the DDM, incorporating a radiation index in terms of potential direct solar radiation at the surface. Computation of potential clear-sky direct radiation (I) is calculated using slope, aspect angles and topographic shading derived from the DEM. This is then incorporated into the melt formulation:

$$A_N = (MF + a_{snow/ice} I) \cdot PDD \qquad (6.2)$$

where MF is a meltfactor (m d^{-1} K^{-1}), a is a radiation coefficient (m m^2 W^{-1} d^{-1} K^{-1}) and I is potential clear-sky radiation (W m^{-2}). MF and a are empirical coefficients that need to be calibrated. I was calculated using the model outlined in Hock (1999) as an average for each month for the bed surface and the present day surface. The value of I was then scaled between these two end members based on the ice thickness at any given time in the model run. The melt was then calculated at monthly intervals based on these values and the PDD sum for the month, then summed to give an annual melt total.

Degree Day Model Calibration and Sensitivity Analysis

PDD calculation

In order to calculate the PDD sum, daily temperature values are needed. It is not sufficient to use monthly means, as if the monthly mean is below freezing, some days may still occur that are above 0°C. Daily data is only readily available from Arctowski Station for 5 years, therefore daily temperatures need to be superimposed on the monthly climate data. Van der Veen (1999) describes various methods for this, involving the assumption of normally distributed daily temperatures around the mean. If the standard deviation of temperature for the month is known then random daily fluctuations can be generated. However this method resulted in a large amount of variability in the PDD when repeat runs were conducted for the same monthly mean. Instead a probability distribution function is used in this model, generating the probability of each temperature above zero occurring over a month. This is then multiplied by the temperature value under consideration and added to the PDD sum. Standard deviations for each month were calculated for the available daily data and were found to be linearly related to the monthly temperature.

Monthly temperatures from Arctowski station were lowered by 1.1°C when the monthly mean temperature was higher than 0.1°C, to account for the fact that the measurements would be taken over an ice/snow free surface. A lapse rate of -6.2°C km^{-1} was used to obtain change in temperature with height (Knap et al., 1996). For further details on the model see Le Brocq (2003).

Accumulation

Accumulation was calculated based on Knap et al.'s (1996) elevation-accumulation relationship (eq. 6.3) in order to obtain the annual net mass balance.

$$\text{Accumulation} = 0.0022h + 0.6 \tag{6.3}$$

Parameter calibration

There is little data available with which to initially calibrate the melt model. However values of k are available from other studies, and the parameter is considered to be transportable. Van der Veen (1999) gives values for k of 0.003 for snow and 0.007 for ice. The model was run to equilibrium at the present extent, using the mean of the last 25 years temperature data in order to test values for the parameters. Some melt measurements are available from Braun (2001), these were used to check the predicted melt values are reasonable.

Using the basic degree day model, a value for k of 0.01 gives a reasonable prediction of the present ice extent (Fig 6.2.). Braun (2001) gives melt for a weather station located at 85m above sea level (a.s.l) for the period 02/12/97 to 12/01/98 as 383.2mm. With a value of 0.01, melt for this period is around 408mm. Extrapolating to 120 days (melt season) using an energy balance model, Braun (2001) gives a value of 1100mm, using the DDM this gives around 1500mm of melt. This is over-predicting the melt, but Braun (2001) only considers snowmelt; including ice melt once the snow cover has gone will increase the ablation due to reduced albedo. Wen et al (1998) also give values for melt for 1991/1992 which are of a similar magnitude (Table 6.1.). Again these are over-predicted by the basic degree day model, however Wen et al.'s stations are located on a south facing slope, using the modified degree day model gives lower values which are closer for the elevation (as well as higher values).

Table 6.1. Melt tested against measurements from Wen et al. (1998) - k = 0.01

Elevation	Actual Melt (mm)	Modelled Melt (mm)
45	1430	1750
90	1100	1481
140	550	1221
185	520	1000
252	410	745

Figure 6.1.a) and b) show the mass balance distribution for the degree day model differs slightly from that produced by Knap et al (1996). Mass balance values fall more quickly with elevation than with the degree day model.

Parameter values for the modified DDM are somewhat more uncertain. The model has been applied to a small number of alpine glaciers (e.g. Schneeberger et al., 2001, Hock et al., 2002) but not to an ice field on this scale. Hock et al. (2002) use a value of a of 0.2 x 10^{-3} (mm m^{2} W^{-1} h^{-1} K^{-1}), however they state that required melt conditions are met by a variety of different parameter combinations. Larger values of a can be used, MF can then be adjusted accordingly. Using a value of a of 4.8 x 10^{-6} (m m^{2} W^{-1} d^{-1} K^{-1}, using daily means) and a MF of 0.00912 (calibrated against mass balance values for DDF where surface slope is minimal) gives an increase in annual mass balance of up to 11cm on south facing slopes and a decrease of up to 5cm on north facing slopes compared to using the DDF. Increasing a by an order of magnitude to 48 x 10^{-6} increases the difference by an order of magnitude (Fig 6.1.d)). Wen et al.'s (1998) melt measurements now lie within the range of predicted values at lower elevations (Table 6.2.).

The model was run to equilibrium with different values of a. Comparing the modelled surfaces (using parameters in section 5.3) to the present, a value of 48 x 10^{-6} was chosen for a (Table 6.3. and Fig. 6.2.b)).

Table 6.2. Melt tested against measurements from Wen et al. (1998), a = 48 x 10^{-6}, MF = 0.0011

Elevation (m)	Actual Melt (mm)	Modelled Melt (mm)
45	1430	1084-2166
90	1100	958-1878
140	550	700-1527
185	520	695-1296
252	410	599-963

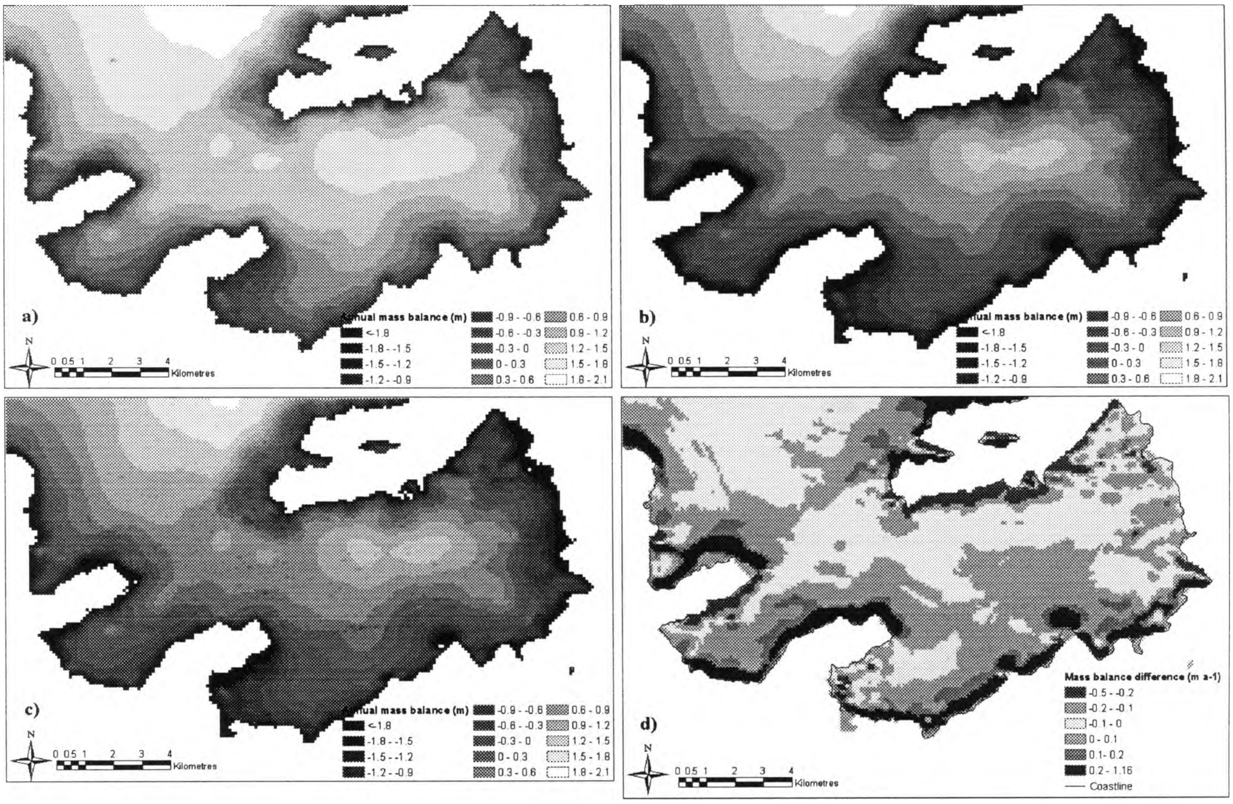
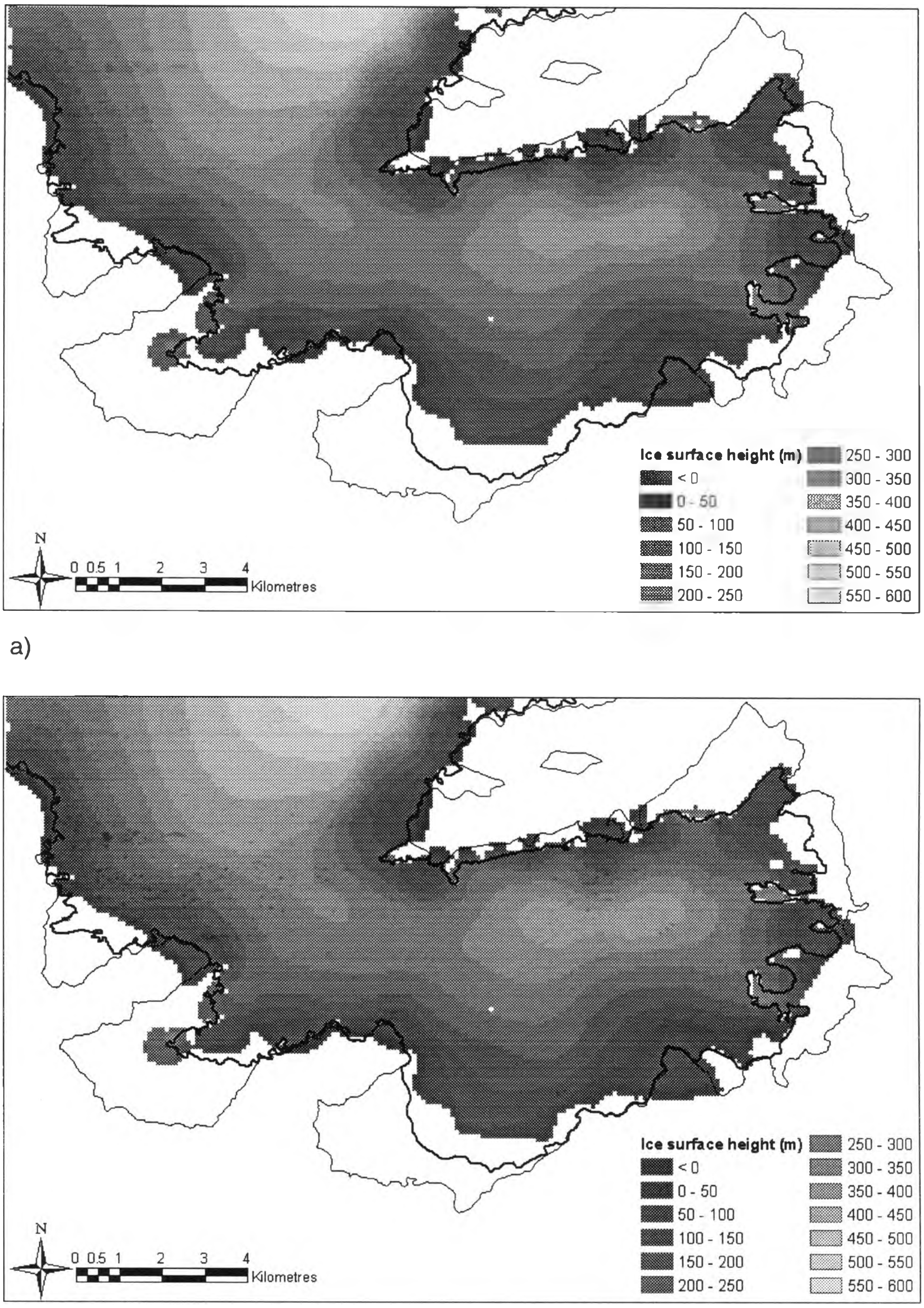


Figure 6.1. Comparison of mass balance distributions; a) using Knap et al. (1996) curve (ELA = 200); b) basic degree day model (DDF = 0.1) for mean of 1977-2000 data; c) modified model (a = 48 x 10-6, MF = 0.0011) and d) mass balance difference between b) and c).

Table 6.3. Prediction success statistics for different values of a.

a	MF / k	Number of cells predicted:		Average surface difference (m)	Total volume (km^3)
		correct	incorrect		
-	k = 0.01	10828	1856	5.84	6.63
12 x 10^{-6}	MF = 0.0011	10879	1807	5.85	6.64
24 x 10^{-6}	MF = 0.0056	10938	1764	5.86	6.64
48 x 10^{-6}	MF = 0.0078	11154	1671	5.90	6.71



a)

b)

Figure 6.2. Modelled ice surface a) basic degree day model (k = 0.1); b) modified degree day model (a = 48 x 10^{-6} and MF = 0.0011).

Dynamic calibration

The Arctowski meteorological station temperature record was lengthened using corrected records from the Orcadas base record, to provide monthly mean temperature for the years 1904-2002 (see Le Brocq, 2003).

Following the method of dynamic calibration outlined in section 4, different parameter sets were tested using two steps:

1. The initial surface (at 1904) was modelled to equilibrium from ice free conditions using monthly temperature data from 1904-1910
2. The model was run from this starting surface to present.

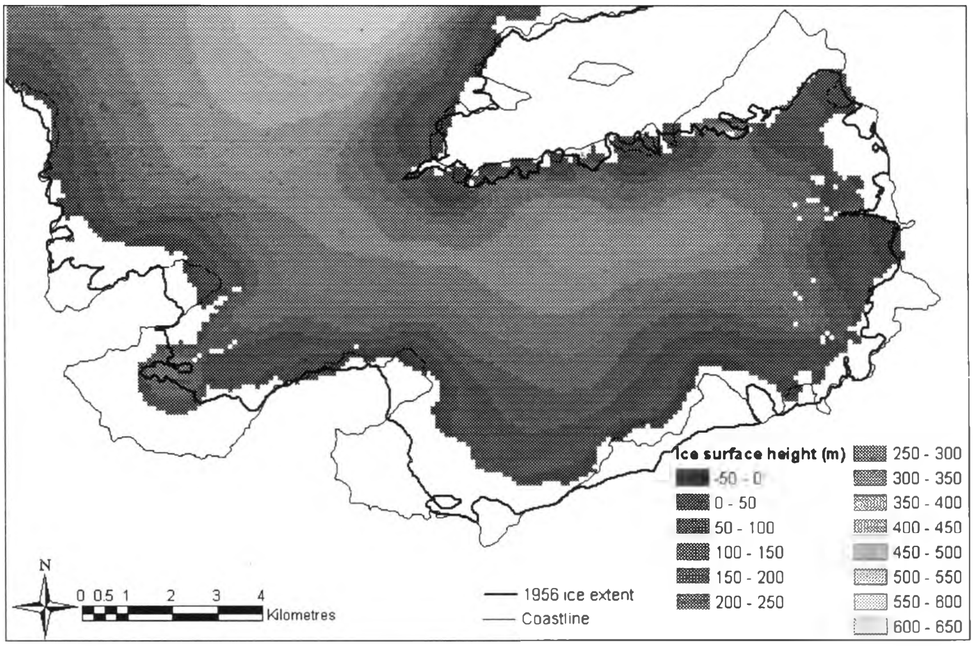
Given an ELA response time of 40 - 60 years (section 5.3) it is assumed that 52 years (1904-1956) is sufficient to remove possible uncertainty in the initial surface condition. Modelled extents for 1956 and present were then compared to actual extents from these years (Table 6.4. and Fig. 6.3.) and used to optimise the values in Table 6.5. The volume of the modelled surface is lower than actual, which requires considered in the future predictions.

Table 6.4. Prediction success statistics for changing parameter values.

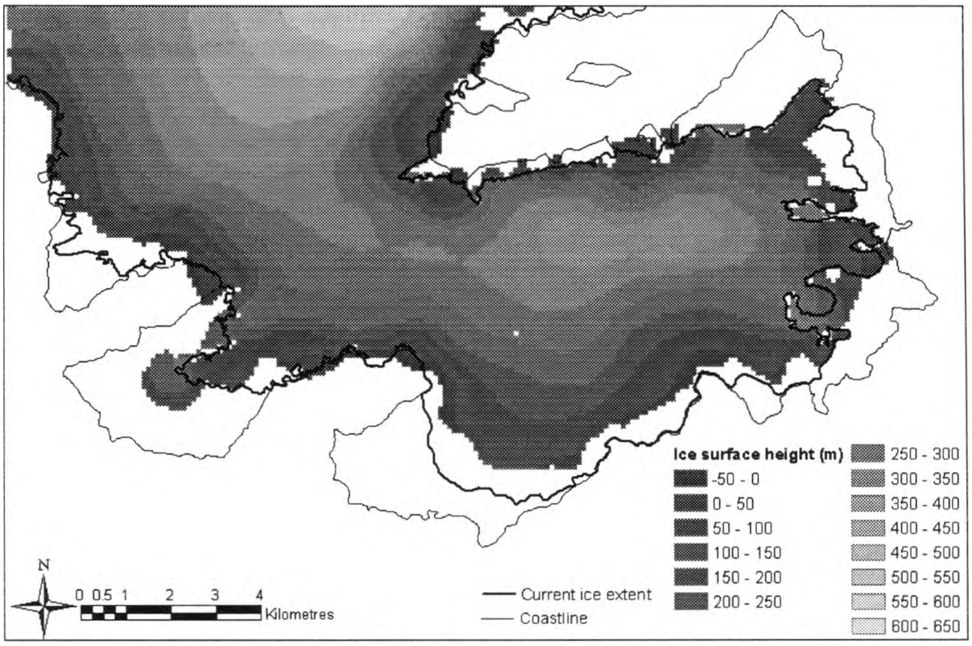
Ad ($\times 10^{-15}$)	As ($\times 10^{-15}$)	Ac	MF	a ($\times 10^{-6}$)	Number of cells predicted: correct	Number of cells predicted: incorrect	Average surface difference (m)	Total volume (km^3)
6.8	150	10	0.002	48	11681	1896	6.31	6.835
6.8	150	10	0.003	48	11157	1770	6.39	6.452
6.8	150	10	0.004	48	10584	1771	6.44	6.130
6.8	150	10	0.005	48	9913	1925	6.54	5.820
2.4	150	10	0.003	48	11293	1794	6.33	7.099
2.4	150	10	0.004	48	10770	1744	6.30	6.755
1.6	150	10	0.004	48	10829	1740	6.37	6.924
2.4	150	20	0.004	48	10669	1628	6.23	6.592
2.4	150	25	0.004	48	10470	1577	6.05	6.375
2.4	150	30	0.004	48	10456	1576	6.04	6.365
6.8	-	25	0.004	48	10658	1587	5.48	6.807
2.4	-	25	0.004	48	11123	1567	7.55	8.562
6.8	10	25	0.004	48	10611	1592	5.49	6.710
6.8	2	25	0.004	48	10648	1590	5.48	6.787
5.0	2	25	0.004	48	10801	1567	5.75	7.254

Table 6.5. Chosen parameter values for future climate prediction.

Ad ($\times 10^{-15}$)	As ($\times 10^{-15}$)	Ac	MF	a ($\times 10^{-6}$)
6.8	2	25	0.004	48



a)



b)

Figure 6.3. Modelled ice surface using parameters in Table 6.5.; a) 1956; b) present (2000).

Simulation of Historic Record

The evolution of the ice field volume over the last century (Fig. 6.3 and 6.4), indicates that the ice volume remained relatively stable up till the mid 1950s, after which the volume steadily falls. This is consistent with the temperature record (Fig. 1.1a)) where the warming trend appears to start in the mid 1930s. There are also small increases in ice volume in the late 1960s, early 1970s and late 1980s. These confirm the high sensitivity of the ice field to short term temperature trends (both warming and cooling), and are consistent with phases of advance observed in Potter Cove in these periods (Park et al. 1998), providing independent model corroboration.

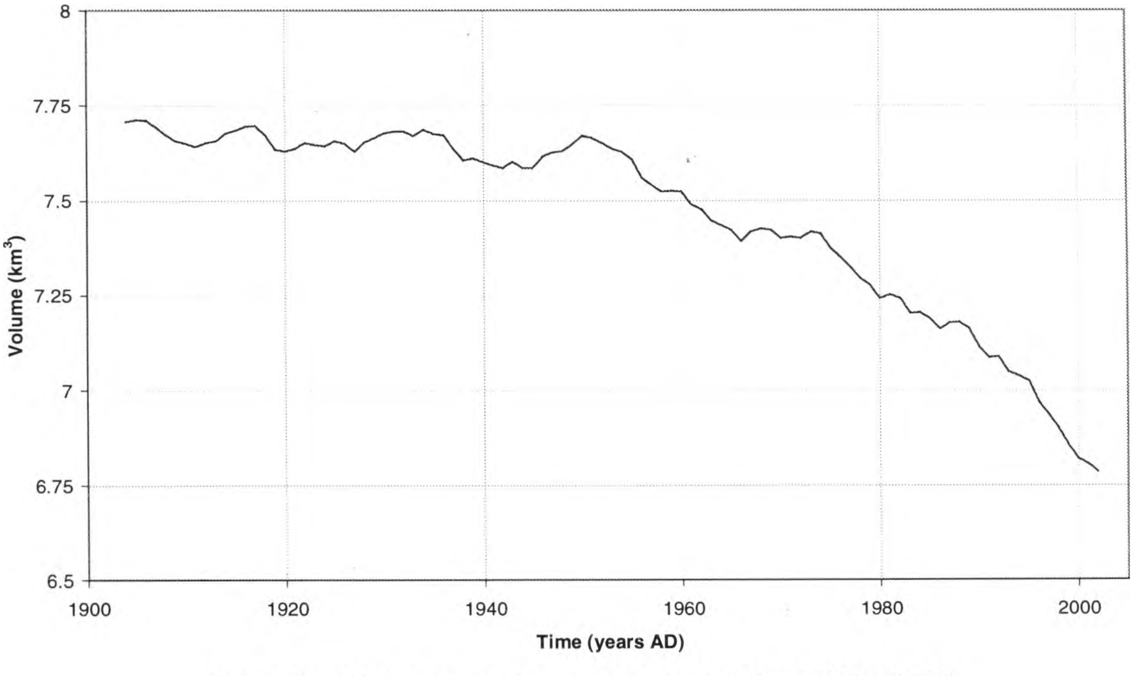


Figure 6.4. Volume evolution over the last century (1904-2002)

Future Climate Scenario Simulation

The calibrated model was then applied to the scenarios outlined in section 4. The temperature increase was applied to the last decade of temperature measurements in order to introduce the natural variability of the climate (Fig. 7.1.). The actual present day ice thickness was used as the starting condition. Table

7.1 and Fig. 7.2. show the predictions of ice volume and extent in 2100 for each scenario. For the worst case scenario with a warming of 4°C over the next century and no precipitation increase, the modelled ice sheet is only 1.1% of its present volume remaining above elevations of ~400m by 2100 (Fig. 7.3.). With a warming of only 1°C and an increase in precipitation of 10%, volume reduces by a relatively small factor of 33.8%. Ice is present at sea level in places with high slope, but generally only above ~200m with ice thickness increasing at higher elevations (Fig. 7.4.). With no further warming applied to the last ten years of temperature data, the ice field loses only 17.3% of its present volume.

These results correspond well with Knap et al.'s (1996) predictions, suggesting that 5°C warming would be enough to cause the King George Island icecap to disappear completely. With only a 4°C warming, ice is still present above elevations of 400m, and therefore by extrapolation ice would still exist at the higher elevations across the rest of King George Island.

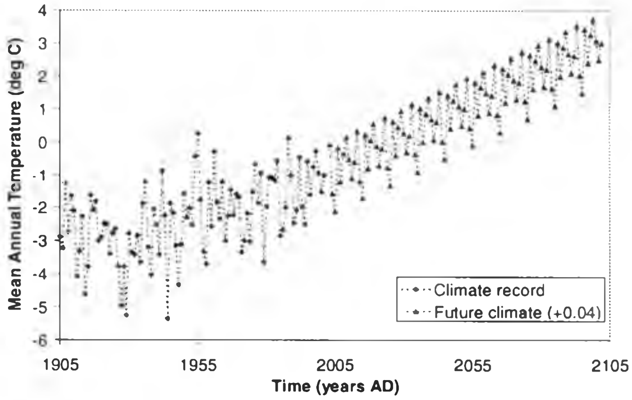


Figure 7.1. Mean annual temperature with 'worst case' warming scenario (0.04 °C a^{-1}).

Table 7.1 Ice volume in 2100 (compared to present) for climate scenarios.

Warming rate °C a^{-1}	Change in precipitation % K^{-1}	Volume in 2100 km^3	Volume in 2100 % of present	Area in 2100 km^2	Area in 2100 % of present
0	0	6.04	82.7	105.92	83.6
0.01	0	4.32	59.2	83.04	65.6
0.01	+ 10	4.84	66.2	89.30	70.4
0.02	0	2.11	28.8	49.03	38.7
0.02	+ 10	2.86	39.1	61.64	48.6
0.04	0	0.08	1.1	4.29	3.4
0.04	+ 10	0.31	4.2	11.55	9.1

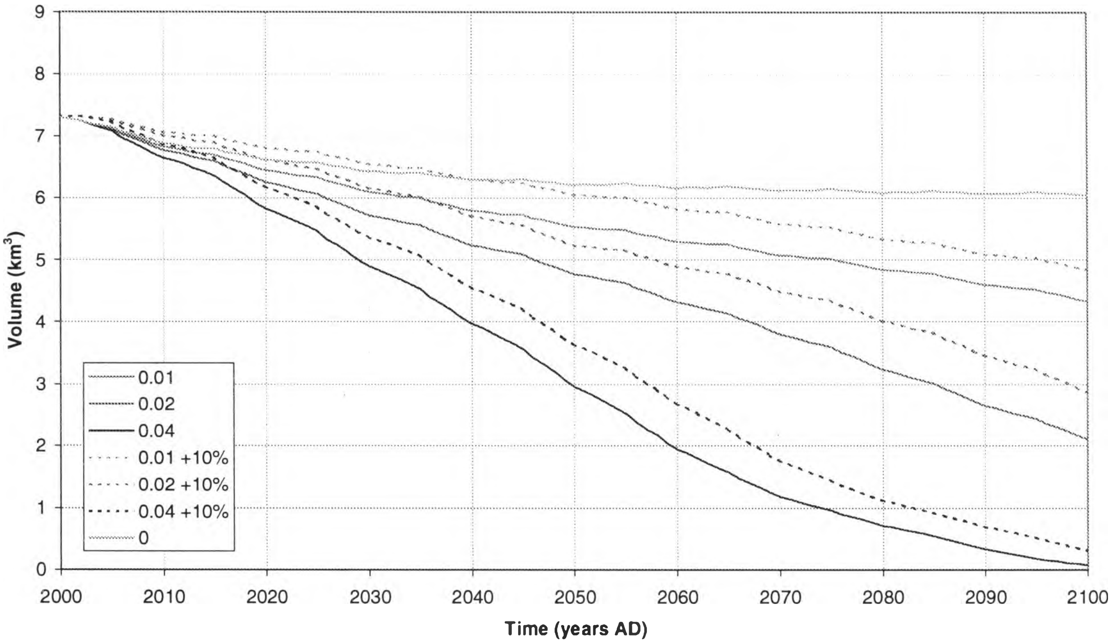


Figure 7.2. Volume evolution over time from actual (present surface) with different scenarios (°C per year, % increase in accumulation per°C)

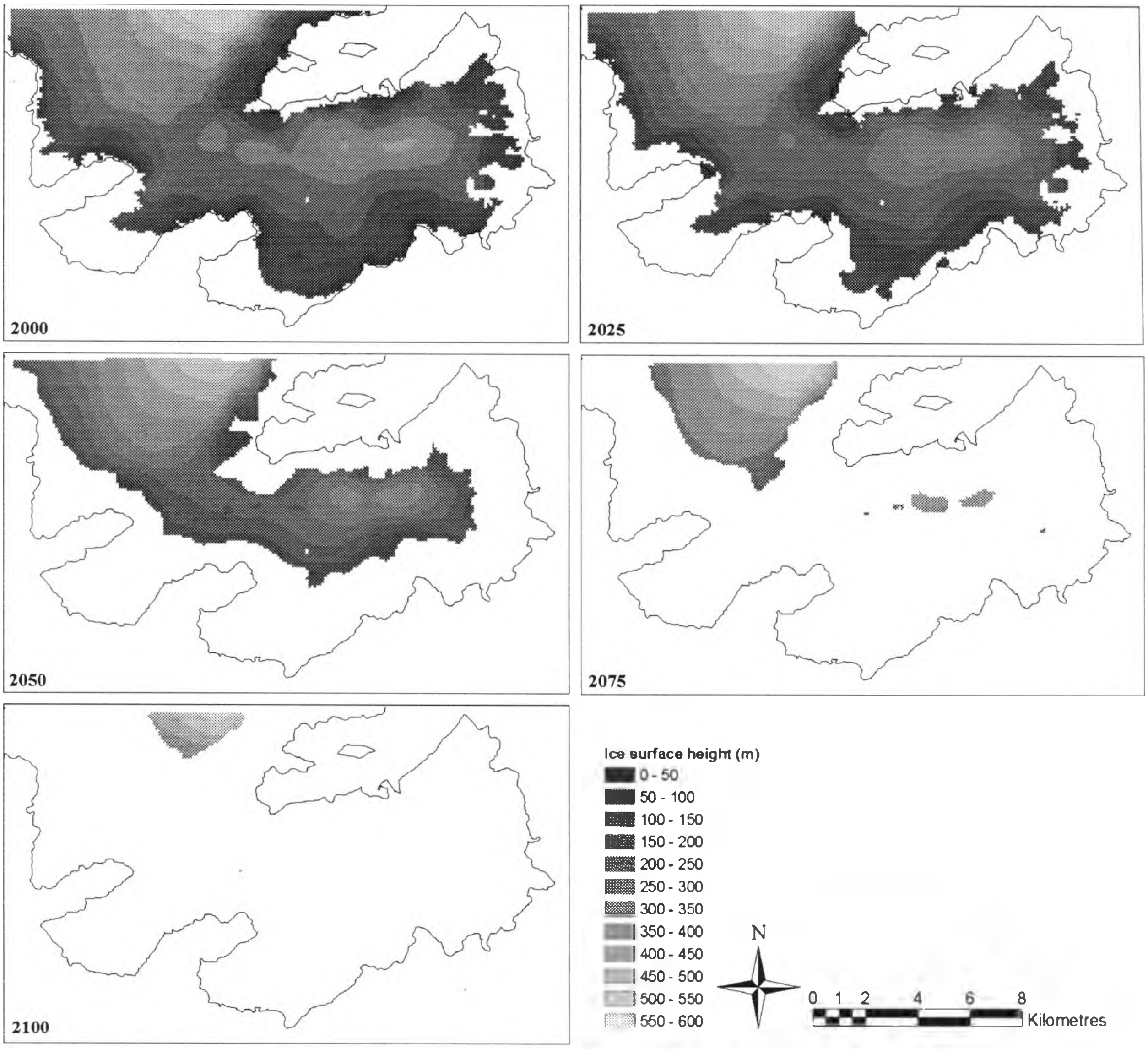


Figure 7.3. Ice surface prediction: 0.04 °C a^{-1} with no increase in accumulation.

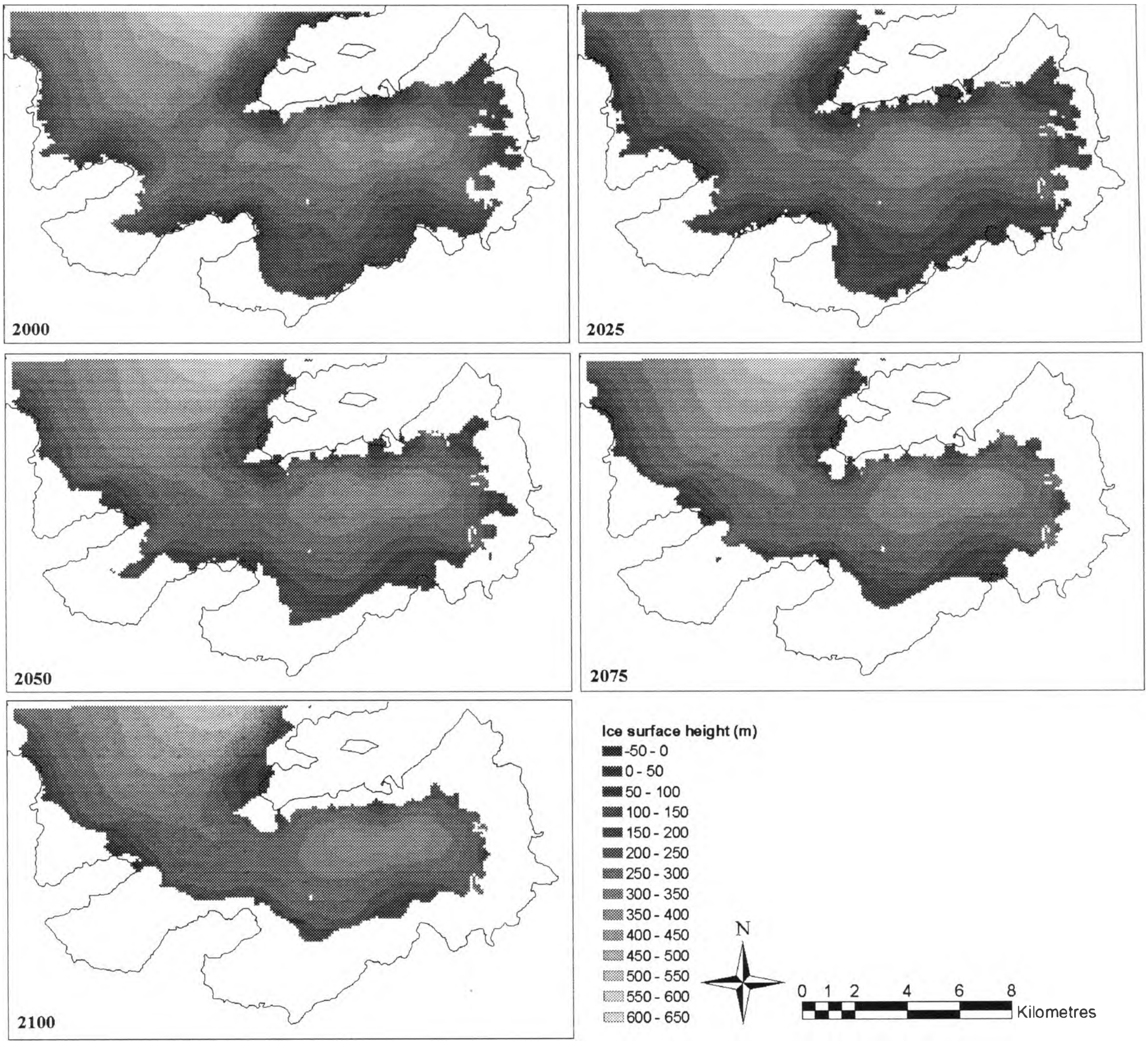


Figure 7.4. Ice surface prediction: 0.01 °C a^{-1} with a 10% increase accumulation.

Discussion

Model Evaluation

Overall the model appears to perform well. Ice field extent is on the whole well predicted, but could be further improved by consideration of additional factors affecting mass balance at this scale, such as wind re-distribution (see section 5.5.). The volume is slightly under-predicted due mainly to the extent under-prediction, rather than any particular systematic error in the thickness. The shape (i.e. modelled surface slope) is generally very good but there was considerable uncertainty in the choice of appropriate values for the flow and sliding parameters, with different values being chosen in sections 5 and 6. Significantly greater confidence in these parameters could be gained through direct comparison with field velocity measurements, allowing a better evaluation of the ice dynamics aspect of the model, which would yield improved volume and shape simulation. Given the lack of constraining field data in mass balance and parameterisation, there remains uncertainty attached to the predictions in section 7 (see Le Brocq, 2003 for further analysis). Although, the results are relatively robust in terms of changes in the internal flow parameters, others, especially those concerning the DDM, if given a different value could significantly alter the model predictions. The question remains whether or not these parameters remain constant through time, and especially into the future under possibly very different climate regimes from that experienced today. They may become invalidated when applied to situations outside that which they were initially calibrated for. However some confidence can be gained in the parameters chosen and their ability to predict the response of the ice field in the future from the degree of correspondence between the present and modelled ice distribution.

Dynamic Calibration and Simulation of the Historic Record

Dynamic calibration should allow more confidence in the parameterisation of the model. The ice sheet was not assumed to be at a steady state and the problem of defining a reference climate related to the ice state was removed. A different set of parameters was chosen using dynamic calibration, with basal sliding having a reduced contribution to the velocity. However this may be due to the improved parameterisation of the mass balance, rather than the use of dynamic calibration. Increased basal sliding improved the extent prediction, but did not improve the surface prediction, therefore it may have been used as a 'replacement' process for mass balance considerations. A higher value of MF was also chosen in the dynamic calibration compared to steady state calibration. This suggests that the 'current' climate chosen (mean of 1977-2000) was not representative of the current ice sheet state. Section 5.3 indicates a response time of 40-60 years or more, therefore the present ice sheet is still a function of cooler temperatures pre-1950s, and as result a higher melt factor may be needed to replicate the present extent.

Dynamic calibration also allows the reconstruction of the ice sheet history. Section 6 showed that the ice sheet was relatively stable until the mid 1950s when it began a more dramatic retreat. Further consideration of the Orcadas temperature record shows that the warming may have only started in the mid 1930s, suggesting ~20 year delay in the response of the ice field..

King George Island - The Future?

With a continuation of the current warming trend (~4°C per century) the future is bleak for ice masses on King George Island. For the Warszawa ice cap it means a reduction in volume of 98.9%, equivalent to 7.22 km^3 of ice, and removal of ice below an elevation of 400m. A projected increased precipitation would slow this retreat, but the reduction in ice is still significant. The general applicability of these results from a small, case study area such as the Warszawa ice sheet to the rest of the Antarctic Peninsula is difficult, since neither climate, glacier regime or warming conditions are constant in space nor time across the Peninsula. However the trends observed in Fig. 1.1.a) show that temperatures observed at Faraday are presently ~5°C warmer than those at King George Island. Therefore there must be enhanced melting occurring along the west coast of the Antarctic Peninsula at least down to this point. The recent collapse of the Larson B ice shelf and the current destabilisation of the Larson C ice shelf indicates that the January 0°C isotherm is rapidly migrating southwards as temperatures rise, leading to the question of whether these changes may eventually reach the bulk of the West Antarctic ice sheet. Therefore further investigation into the sensitivity of other ice masses on the Antarctic Peninsula is recommended in order to quantify the possible effects on these ice masses and global sea level rise.

Conclusions

- A coupled high resolution ice flow/mass balance model was applied to the Warszawa ice sheet. The model performed well, although more consideration needs to be given to the factors affecting mass balance distribution. There was also some uncertainty in the choice of the flow and sliding parameters.

- A modified degree day model (including aspect considerations) was incorporated to represent ablation and allow dynamic calibration of the model. This led to improvements in the extent prediction and the choice of a different parameter set compared to steady-state calibration.

- Simulation of the historic record showed that the ice sheet was in a relatively steady-state until the mid 1950s, after this there has been a steady retreat.

- The model showed that the Warszawa ice field is highly sensitive to future climate warming. Raising the ELA by 100m led to a 30% reduction in ice volume, with a response time of the order of 40-60 years..

- With a continuation of the current warming, the simulated volume of the Warszawa ice field is reduced considerably. Given that January temperatures further south of King George Island are already above 0°C (e.g. Faraday Base, ~65°S), this indicates that small ice masses on the west side of the Antarctic Peninsula are highly sensitive to potential climate warming. This is confirmed by the recent retreat of glaciers and collapse of ice shelves along the Peninsula.

References

Bintjana, R. 1995. The local surface energy balance of the Ecology Glacier, King George Island, Antarctica: measurements and modelling. Antarctic Science **7** (3), 315-325.

Braun, M. 2001. Ablation on the ice cap of King George Island (Antarctica) - an approach from field measurements, modelling and remote sensing. Unpublished PhD Thesis (University of Freiburg).

Braun, M., Saurer, H., Vogt, S., Simões, J. C. and Gosmann, H. 2001a. The influence of large-scale atmospheric circulation on the surface energy balance of the King George Island ice cap. International Journal of Climatology **21**, 21-36.

Braun, M., Simões, J. C., Vogt, S., Bremer, U. F., Blindow, N., Pfender, M., Saurer, H., Aquino, F. E. and Ferron, F. A. 2001b. An Improved Topographic Database for King George Island. Compilation, Application and Outlook. Antarctic Science **13** (1), 41-52.

De Angelis H and Skvarca P. 2003. Glacier surge after ice shelf collapse. Science **299** (5612), 1560-1562.

Glen, J.W. 1958. The flow law of ice. International Association of Scientific Hydrology Publication **47** (Symposium at Chamonix 1958-Physics of the movement of Ice), 171-183

Hock, R. 1999. A distributed temperature-index ice- and snowmelt model including potential direct solar radiation. Journal of Glaciology **45** (149), 101-111.

Hock, R., Johansson, M., Jansson, P. and Bärring, L. 2002. Modeling climate conditions required for glacier formation in cirques of the Rassepautasjtjakka Massif, Northern Sweden. Arctic, Antarctic, and Alpine Research **34** (1), 3-11.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van den Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A. 2001. Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge.

Hubbard, A. 1999. High-resolution modeling of the advance of the Younger Dryas ice sheet and its climate in Scotland. Quaternary Research **52**, 27-43.

Jones, P. D. 1990. Antarctic temperatures over the present century – a study from early expedition records. Journal of Climate **3**, 1193-1203.

King, J. C. 1994. Recent climate variability in the vicinity of the Antarctic Peninsula. International Journal of Climatology **14**, 357-369.

Knap, W. H., Oerlemans, J. and Cadee, M 1996. Climate sensitivity of the ice cap of King George Island, South Shetland Islands, Antarctica. Annals of Glaciology **23**, 154-159.

Le Brocq, A. 2003. Modelling fluctuations of the Warzawa Icecap, King George Island, Antarctica to climate change over the next century: Technical Paper. Unpublished MSc Thesis (University of Edinburgh)

Noble, H. M. 1965. Glaciological observations at Admiralty Bay, King George Island, in 1957-58. British Antarctic Survey Bulletin **5** (41), 1-11.

Oerlemans, J. 1997. A flow-line model for Nigardsbreen: projection of future glacier length based on dynamic calibration with the historic record. Annals of Glaciology **24**, (382-389).

Oerlemans, J., Anderson, B., Hubbard, A., Huybrechts, P., Johannesson, T., Knap, W. H., Schmeits, M., Stroeven, A. P., Van De Wal, R. S. W., Wallinga, J. and Zuo, Z. 1998. Modelling the response of glaciers to climate warming. Climate Dynamics **14**, 267-274.

Park, B.-K., Chang, S.-K., Yoon, H. I. and Chung, H. 1998. Recent retreat of ice cliffs, King George Island, South Shetland Islands, Antarctic Peninsula. Annals of Glaciology **27**, 633-635.

Parkinson, C. L. 2002. Trends in the length of the Southern Ocean sea ice season, 1979-1999. Annals of Glaciology **34**, 435-440.

Paterson, W. S. B. 1994. The physics of glaciers. Third edition. Pergamon, Oxford.

Reynolds, J. M. 1981. The distribution of mean annual temperatures in the Antarctic Peninsula. British Antarctic Survey Bulletin **54**, 123-133.

Skvarca, P., Rack, W., Rott, H. and Ibarzabal Y Donangelo, T. 1998. Evidence of recent climatic warming on the eastern Antarctic Peninsula. Annals of Glaciology **27**, 628-632.

Smith, R., Ainley, D., Baker, K., Domack, E., Emslie, S., Fraser, B., Kennett, J., Leventer, A., Mosley-Thompson, E., Stammerjohn, S., and Vernet, M. 1999. Marine ecosystem sensitivity to climate change - historical observations and paleoecological records reveal ecological transitions in the Antarctic Peninsula region. Bioscience **40**, 393-404.

Splettstoesser, J. 1992. Antarctic Global Warming? Nature **355**, 503.

Stark, P. 1994. Climatic warming in the central Antarctic Peninsula area. Weather **49**, 215-220.

van der Veen, C.J., 1999. Fundamentals of Glacier Dynamics. A.A. Balkema, Brookfield.

Vaughan, D. G. & Doake, C. S. M. 1996. Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. Nature **379**, 328-331.

Vaughan D.G., Marshall G.J., Connolley, W.M., Parkinson, C., Mulvaney, R., Hodgson, D.A., King, J.C., Pudsey, C.J. and Turner, J. in press. Recent rapid regional climate warming on the Antarctic Peninsula.

Vieli, A., Funk, M. and Blatter, H. (2001) Flow dynamics of tidewater glaciers: a numerical modelling approach. Journal of Glaciology **47** (159), 595-605.

Wen, J., Kang, J., Han, J., Xie, Z., Liu, L. & Wang, D. 1998. Glaciological studies on King George Island ice cap, South Shetland Islands, Antarctica. Annals of Glaciology **27**, 105-109.

Röthlisberger, H. and H. Lang (1987). Glacial Hydrology. A. M. Gurnell and M. J. Clark. Glacio-Fluvial Sediment Transfer: An Alpine Perspective. Chichester, John Wiley & Sons. 207-284.

Sharp, M., M. Tranter, G. H. Brown and M. Skidmore (1995a). "Rates of Chemical Denudation and CO_2 Drawdown in a Glacier-Covered Alpine Catchment." Geology **23**(1): 61-64.

Tranter, M., G. Brown, R. Raiswell, M. Sharp and A. Gurnell (1993). "A Conceptual-Model of Solute Acquisition By Alpine Glacial Meltwaters." Journal of Glaciology **39**(133): 573-581.

Tranter, M., G. H. Brown, A. J. Hodson and A. M. Gurnell (1996). "Hydrochemistry as an indicator of subglacial drainage system structure: A comparison of Alpine and sub-polar environments." Hydrological Processes **10**(4): 541-556.

Van der Broeke (2000) On the interpretation of Antarctic temperature trends. Journal of Climate **13**(21): 3885-3889.

Watson, A.J., Bakker, D.C.E., Ridgwell, A.J. Boyd, P.W. & Law, C.S. (2000) Effect of iron supply on Southern Ocean CO_2 uptake and implications for glacial atmospheric CO_2. Nature **407**: 730-733.