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Critical Literature Review

(ANTA602)

The Potential Hazard of Antarctic Ice Shelf Carving in New Zealand Territorial Waters.

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Abstract:

The Antarctic Peninsula is the one region of the Southern Ocean that has experienced large temperature changes over the past century resulting in the release of large ice bergs into the Southern Ocean. The glacial calving process is based on glacier ice flow dynamics as breaking rates are controlled by ice velocity changes and retreat. With increased continental warming and consequently melting there will be an increase in ice-berg calving frequency and movement from the Antarctic continent. GIS satellite monitoring of the Antarctic has provided useful images of the migration of icebergs. Recent advances in the use of geographic information systems and the ability to monitor the movement of icebergs and changes in ice sheets makes the potential for predicting the impacts on the Southern Ocean easier. This literature review considers the question – with increased iceberg frequency what are the potential impacts of ice-berg migration on Southern Ocean logistics.

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Introduction

In a warming world, Polar Regions have been experiencing dramatic changes in atmospheric temperatures. Over the past century the Arctic has experienced temperature increases by 10 degree Centigrade which has loosened large amounts of permanent sea ice cover. The Antarctic Peninsula is the one region of the Southern Ocean that has experienced large temperature changes over the same time, but it is likely the rest of continental Antarctic will experience large temperature changes over the next half century. As Antarctic temperatures increased in the peninsular in 2010 the Larsen ice shelf saw rapid calving of the floating portion of the ice-shelf over 6 months. Ice calving has also releases icebergs that ravage the near shore sea floor of the Antarctic coast. With increased continental warming and consequently melting there will be an increase in ice-berg calving frequency and movement from the Antarctic continent.

There are many implications from the carving of large ice masses off the Antarctic Coast amongst which are the direction and speed with which they can move on the ocean currents crossing shipping lanes or encountering New Zealand landforms like the Chathams Rise and the Sub Antarctic islands. Literature on the movement of icebergs have been built up over the last 150 years, however the use of geographical information system provides a better understanding of the origin, frequency and distribution of icebergs in the southern oceans.

This literature review considers the question – with increased iceberg frequency what are the potential impacts of ice-berg migration on Southern Ocean logistics. The review covers literature describing the ice berg formation, calving and monitoring of icebergs in the Southern Ocean from spatial distribution data from the source of the Ice-berg to decay, and the potential benefits and disadvantages of ice-berg migration.

Antarctic Glacier Processes

Ice calving is a critical part of a glacier's mass balance system. Ice calving is part of the ablation of a glacier and is controlled by positive and negative changes to the glaciers mass balance. Mass balance of a glacier in the simplest form is the total accumulation (A_c) subtracted by total Ablation (A_t). The result gives B the annual Mass balance of a given glacier $B = A_c - At$

The formula $b(x) = \int_{t_1}^{t_2} \dot{b}(x,t)dt.$

Is used to measure the specific balance rate, which is defined as the rate at which mass added to, or removed from a glacier.

b The specific net balance is evaluated as the integral of $\dot{b}(x,t)$ over the time interval of t_1 and t_2 for winter and summer mass balance. dt is the representation of change in time, x is the position vector($x = (x,y,z)$), $\dot{b}$ is the specific mass balance rate (kgm^{-2} a^{-1}) (Luthi, 2013).

In the East Antarctic ice shelf the mass accumulation of ice may have taken up to 3,500 years (Bennett et al 2009). Accumulation rates, ice velocity and shear, and stress rates of glacial ice results in the increase or decrease of calving rates at the mouth of a glacier. Ice calving ablation on glaciers is limited to glaciers where the tongue (end) of the glacier is floating in water - whether it is a glacial lake or coastal waters. Ice calving typically occurs in Polar Regions where precipitation rates are higher and melting across the glacier is low which produces longer glaciers that can flow down from the accumulation zones to the coast.

On the Eastern Antarctic the glaciers are mostly Ice sheet fed, where ice mass balance is calculated from the accumulation of ice from several sources by precipitation, drifting snow, solid deposition from water vapour, subsurface accumulation and basal accretion (Mayewaski *et al*,2009). The ablation processes of ice mass loss are ice calving, surface sublimation, basal melting and surface melting.

Ice Mass balance over the East Antarctic ice sheet results as reported in Rigno et al. (2008) showed a near-zero mass balance for East Antarctic of -4 ± 61Gt/a. This suggested that the negative mass balances in coastal areas are larger than any mass increase in the interior, as seen in a significantly negative mass balance from the Totten and Cook glaciers (Mayewaski *et al*, 2009). However, the East Antarctic interior with the use of proxy data hasn't show any major changes in the last 200 years and isn't like to have rapid change.

The smaller West Antarctic Ice sheet is understood to be losing mass, primarily as a result of mass loss by glaciers draining into the Asmundsen Sea. Research in the last decade shows ice sheet mass loss increased from 1996 -2006 by approximately 59%, 132 ± 60 Gt/a in 2006 (Mayewaski et al, 2009). The two largest glaciers draining into the Amundsen Sea, the Pine Island and Thwaites glaciers have been retreating, accelerating and thinning since the 1990s. The Antarctic Peninsula has experienced the greatest warming on the continent which is reflected by 87% of glaciers retreating and the rapid ice shelf collapse of Larsen B and Larsen A in 2002. (Mayewaski *et al,* 2009).

Current state of Calving Processes

The glacial calving process is based on glacier ice flow dynamics as breaking rates are controlled by ice velocity changes and retreat. Deformation of ice is caused by stress and tension throughout the Ice sheet. Stress is caused by spatial difference in velocity. This can be caused by friction between the ground and bottom ice leaving the top ice unaffected. Frictional stresses is caused by rapid drops in elevation and changes in the direction of ice flow (Knight, 2013).

Within ice calving there is probability of large calving events between 20-48 years of crevassing that produce Giant tabular Icebergs usually ranging from 5-12km in longitudinal length. Kenneally and Hughes (2006) explain the processes that could theoretically produce giant icebergs off the main ice shelves. The paper theorises three types of crack propagation along an ice shelf that will produce longitudinal movement to transit transverse crevasses at 45 degrees, a result of shear pressure and tension caused by spatial variation in the velocity across the ice shelf.

Basal or surface crevasses located near the calving front can be hundreds of kilometres long laterally with little or no depth, so ice overburden pressure is not a critical variable in determining the speed or length of their propagation. The second type is the propagation of surface or basal crevasse that are parallel to ice flow near the calving front. These crevasses typically open when the calving front extends beyond an embayment or basal pinning points that confined the ice shelf laterally, consequently it can spread both as a longitudinal and transverse extension. The third type of crevasse propagation is vertically downward from the top surface or vertically upward from the bottom surface. Downward propagation will encounter increasing pressure from the ice overburden, unless surface melt water fills the top crevasses, whereas the ice overburden pressure is always exceeded by water pressure in the bottom crevasses that propagate upwards, until they reach sea level (Kenneally & Hughes, 2006).

Kenneally and Hughes (2006) also explain the crevasse area process in terms of elastic, ductile and dislocation fracture mechanics. Both basal crevasses and surface crevasses will have greatly enhanced penetration rates which can cause an ice shelf collapse as seen by Larsen B Ice Shelf (Macayeal & Sergienko, 2005).

$$Uc = u_t - \frac{dL}{dt}$$

A simple equation for calving rates of a glacier, where Calving rate is Uc, is usually defined as the difference between ice velocity at the glacier terminus and glacier length over time: where u_t is the vertically-averaged glacier velocity, dL is the length of the glacier and dt is time (Benn, 2007).

Implications and Effects of Icebergs in the Southern Ocean

Ice bergs in the Southern Ocean have a range of effects and impacts to the Southern Ocean current circulations and on-going affects. A major concern for scientists is the implications of increased ice calving into the Southern Ocean and how the increased fresh water will affect Southern ocean currents.

The Iceberg sequences of B-15, C-16 and C-19 were shown in Arrigo and Dijken (2003) and Drucker, Kwok and Martin (2007) to have a major effect on the sea ice production and percentage of open water during summer which showed extremely low production of phytoplankton and krill. These two species are the primary food source for all consumers in the Ross Sea and the lack of food source will negatively affect high predators such as Antarctic Tooth fish (Petrov & Tatarnikov, 2009), the primary fishery in the Ross Sea, and Adelie penguins (Dunn, 2008). A study done by Cefarelli et al (2011) tracked iceberg C-18a free-drifting in the North West Weddell Sea during March and April 2009, tracking and monitoring of export fluxes in organic carbon in a 30km radius of C-18a, found a 46% increase in organ carbon.

The physical presence of icebergs in the Southern Ocean has impeded logistical support to McMurdo station, where both the American and New Zealand Antarctic program are supplied from. Icebergs designated as B-15 (2000), C-16 (2001) and C-19 in September 2002 moved across Scott Island (Arrigo & Dijken, 2003). This series of events also prevented scientific research as by the summer of 2002-03 production was reduced by approximately 86% relative to normal sea ice year (Arrigo & Dijken, 2003), (Drucker, Kwok, & Martin, 2007). Long and Stuart (2011) state that icebergs are a hazard to shipping lanes and given New Zealand's location to Antarctic simultaneously affect logistical support to the New Zealand and American Ross Sea Bases.

An ice shelf interacts with both the atmosphere and ocean; hence they are heavily influenced by changes in established environmental conditions (Holland& Walker, 2007). As seen in multiple sources the Southern Ocean circulation is showing evidence of warming or freshening within the sea water, (Hellmer, 2004), (Bindschandier et al, 2009), (Holland & Walker, 2007), (Hattermann &

Levermann, 2009). The Antarctic Circumpolar current (ACC) has increased 2°C at depths between 700m – 1100m since the 1950s (Mayewaski *et al*, 2009) and a strengthening ACC South towards low attitudes (Hattermann & Levermann, 2009; Hellmer, 2004), Antarctic bottom water (ABW), Circumpolar deep water (CPW), High saline shelf water (HSSW), (Mayewaski *et al*, 2009) and Warm Deep Water (WDW) in the Weddell Sea by 0.3°C.

The increased basal melting of the ice shelf consequently increases calving and ablation rates and the rate of fresh water entering the Southern Ocean. Mayewaski *et al* (2009) explains that glacier retreat on the Antarctic Peninsula is directly linked to warming of nearby ocean waters. This supports Hattermann and Levermann (2009) that warming of Southern Ocean circulations primary ACC does enhance Ice Shelf Melting (ISM), where a possible positive feedback loop may occur. All ocean currents are driven by gradients of thermohaline circulations and gradients in salinity.

Ice bergs have been responsible for over 3739 record shipping deaths in the Northern Hemisphere prior to 1619 but according to (Whiteman, 2011) the last recorded death was in 1975. Since 1975 there have been no record deaths, this is largely because of increased ship design, technology and ships avoiding high active iceberg routes.

Ice berg scouring of the sea bed will cut deep pipelines and communication cables if exposed on the seas floor, although this hasn't yet been an issue for the Southern Hemisphere (Whiteman, 2011). Scouring of the sea floor will destroy the benthic organism ecosystem along the iceberg's path (Whiteman, 2011). Ice scouring was found to be catastrophic with scour assemblages showing 95% lower in mean macro faunal abundance and 76% lower in species richness than the undisturbed areas.

Iceberg drift in the Southern Ocean

Ice berg drift in the southern ocean is a measure of strength and consistence of Katabatic winds blowing off the Antarctica interior (Arrigo & Dijken, 2003). Tidal forces, Ocean surface current (ACC) and the corillis force all direct icebergs trajectory (Bertino et al, 2008) but an iceberg will usual drift Northward to the equator until it decays.

GIS tracking of Ice Bergs in the Southern Ocean

Since the 1980s Satellites have been used to track and model migration of icebergs in the Southern Ocean. Satellite monitoring of the Antarctic has provided useful images of the Antarctic surface, means to measure mass balance and track Icebergs.

The National Ice Centre (NIC) in Washington DC has been monitoring icebergs since 1977 (Bigg & Gladstone, 2002) and continues to track icebergs with satellite imagery (Long & Stuart, 2011). Tracking icebergs with Synthetic Aperture Radar (SAR) has been most successful (Bigg & Gladstone, 2002) with an 12.5m pixel size. The recent C-19 and B-15 icebergs that impeded on New Zealand activities in the Ross Sea were mapped by RADARSAT ScanSAR image (Drucker, Kwok, & Martin, 2007).

In 1987 major open crevasses in the Ross Ice Shelf calved an iceberg of 154 x 25 km (designated as "B9") after it broke off the Ross Ice Shelf; it was tracked using LANSAT4, NOAA-10 and DMSP satellites (Barnett, Jacobs, & Keys, 1990). B-9 was tracked 2010km until 1991 when the iceberg became trapped in the shallow waters below the coast of West Antarctic, described by Krajick (2001) as an "iceberg graveyard". B-9 continued to decay over the next decade. Another piece of B-9 that broke off in the Ross Sea (Barnett, Jacobs, & Keys, 1990) was tracked and found after a journey of 10,000m west of Antarctic (Krajick, 2001). B-9 was successful tracked into New Zealand waters and strayed into the Tasman Sea for over 10 years before completely melting. B-9 did not have impact on New Zealand but this shows that ocean circulation and atmospheric winds will drive Icebergs into New Zealand waters.

Satellite monitoring of Ice shelves and icebergs has allowed for greater understanding of ice calving processes in the Southern Ocean. The infamous example of the Larsen A and B ice shelf's rapid and dramatic collapse was recorded over 1995-2002. Satellite imagery captured the complete processes of the collapse as well as evidence of the unique way it collapsed. Larsen A, an area of ~1910 km^3 of ice, collapsed in 1995 with no really warning (Krajick, 2001). Larsen B, 3250km^3 of ice, collapsed over several months over the summer of 2001 and 2002 but has been intensely studied. Larsen B collapse was prone to high percentage of water filled crevassing where by 2000, 5% of the visible surface was crevasses that could be seen from satellite imagery, the surface crevasses of Larsen B filled with melt water that penetrated deep into the ice shelf base. Heat generation and solar radiation is not all absorbed by the contact surface of ice but solar light penetrates into the ice to be absorbed by subsurface firm and ice. (Macayeal & Sergienko, 2005) found that from November 2001 – February 2002 Larsen B surface ablation over 4 months was 20 ± 10cm, twice the amount needed to fill the crevasses. Penetration rates followed Darcey's Law (Macayeal & Sergienko, 2005).

Changes in Ice Calving mechanics and Affects in the Near future

Mayewaski et al, (2009) records that the Antarctic troposphere has been warming during winter but the stratosphere has cooled year round. CO_2 in the atmosphere has recently reached above 380ppm in the atmosphere where in the past 800,000 years concentrations have ranged from 180-300ppm (Mayewaski et al, 2009). Ice sheets and shelves interact with atmospheric conditions (Holland& Walker, 2007) and responses to those changes. Solomon et al, (2007) predicts an increase in surface water temperatures between 2-6^{o}C by 2100 and both the atmosphere and oceans warming will increase ablation processes in Antarctic (Bindschandier et al 2009). This agrees with Mayewaski *et al* (2009) that retreat of glaciers in the Antarctic Peninsular was caused by effects of warming oceans and Hattermann and Levermann (2009) shows that increasing ocean temperature increases ice sheet melting.

Pleistocene sediments show Ice sheet calving rates as evidence and measurement of retreat or advance of a glacier. Ice shelves can undergo rapid changes in mass loss if conditions change that would increase melting or limit accumulation. During the last glaciations major abrupt climate events known as a Heinrich event (Benn, 2007), (Jongma et al, 2013) were associated with iceberg armadas into the Atlantic Ocean which freshened the top layers of the ocean. It is not known what caused this event but it is possible that the Collapse of the West Antarctic Ice Sheet could have similar effects.

Icebergs negatively affecting New Zealand's Interests in the Southern Ocean

The Antarctic Circumpolar Current is balanced by pressure gradients from surface displacement (barotropic), as well as from the internal density distribution (baroclinic). A rapid freshening of any layer of the ACC can re-distribute and alter the established system (Hattermann, 2009). Hattermann suggest that varying saltwater fluxes in the Southern Ocean may have caused significant changes in the global ocean circulation in the past. Therefore where there is melting of the warming West Antarctic Ice sheet this could change saltwater concentrations in the ocean with ice calving off the Ice Sheet. With this comes the possibility of altering the internal feedback mechanisms that influence the global climate system as a whole.

As Ice calving is a reflection of the state of retreat or advance of the glacier system, combined with the likelihood of increased warming in the Antarctic regions, it is expected that most of the floating ice would be removed or significantly reduced in the next 100 years. The removal of Antarctic Ice shelves is considered to influence the flow speed of adjacent continental ice, where with the removal of the ice shelf the adjacent ice would like experience increased flow rates (Hattermann, 2009).

Conclusion

The Southern Ocean is a unique region of the world in close proximity to New Zealand where Weather and ocean currents interact with New Zealand continental shelf. With increased warming of atmosphere and Surface Ocean temperatures globally projected by the international science community and the IPPC 2007 it is highly likely that ablation rates will increase and with it the calving rates of iceberg. The effect on New Zealand's interest in the Southern Ocean Scott base, Scientific research and Antarctic toothfish fisheries have yet to be explored. Recent advances in the use of geographic information systems and the ability to monitor the movement of icebergs and changes in ice sheets makes the potential for predicting the impacts on the Southern Ocean easier. This is an area that needs more research so that policymakers and the New Zealand government can prepare, minimize and mitigate against potential threats to New Zealand's interest in the Southern Ocean.

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