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A Review of Remote Sensing techniques used in the Monitoring of Ice Calving in Antarctica

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Abstract

Antarctica Ice sheets drain to the coast where the ice flows into ice shelves and glacier tongues therefore the stability of the Antarctic ice sheet is closely connected with the mass balance of the ice shelves. Climatic predictions from IPCC 2013 expect global surface temperatures to continue to warm. As a consequence the Antarctic continent will experience increasing air and ocean temperatures which affect the stability of glacial systems and the rate of calving of ice bergs. This paper reviews the use of high altitude remote sensing techniques in monitoring ice berg calving and drift in Antarctica. Recent literature was used to consider advantages and limitations in remote sensing techniques and the satellite, software and hardware used in the monitoring of iceberg processes in Antarctica. The results showed that the main limitation of remote sensing is the time between ground tracking and the repeat cycle. This means that the system is not responsive enough to track small or complex iceberg situations.

Introduction

The Antarctic ice sheet covers an impressive area of 1.4 x 10^7 km2 (twice the size of Australia) of which 10 percent consists of floating ice shelves (Kristensen, 1983). Antarctica Ice sheets drain to the coast where the ice flows into ice shelves and glacier tongues therefore the stability of the Antarctic ice sheet is closely connected with the mass balance of the ice shelves. The current climatic and mass balance monitoring suggests that the Antarctic ice might be stable, however climatic predictions from IPCC 2013 expect global surface temperatures to continue to warm (Vaughan, 2013). As a consequence the Antarctic continent will experience increasing air temperatures which result in surface ice melting and basal melting affecting the stability of glacial systems. Rising ocean temperatures will result in further fracturing of ice shelves, causing an increasing rate of iceberg calving. Should a rapid deterioration take place, the subsequent rise in sea level of up to 55m would constitute a major catastrophe for coastal regions across the globe, as many of the world's capital cities and a substantial part of the agricultural area could be submerged and the mass balance of the Antarctic ice contribution to the generation of global weather systems would be altered (Kristensen, 1983). Although ice shelves don't add to sea level rise as they are already floating (Armstrong, 2014), an ice shelf restricts the speed of inland glaciers ice flow. In 2002 after the Larsen B collapsed the Drygalski, Sjogren and Boydell glaciers feeding into the Larsen B ice flow significantly accelerated as the ice shelf had been holding back the ice flow (Rott, 2002). The consequence of this event is that long term further ice calving is likely to increase. The projected effects of warming in the South Ocean are similar to warming of glaciers in the rest of the world where there is an expected increase in ablation processes.

The annual mass balance of the Antarctic ice sheet can be described by

$$B = A_C - A_B$$

Which is the difference between the total amount of accumulation (A_C) by snow or mass added to the ice sheet within one year minus ablation rates (A_B), the loss of mass from the ice sheet provides the total mass gained or lost (B). A negative result shows that the ice sheet is retreating or losing mass and positive equation is the ice sheet is advancing. The Antarctic mainland is a desert with virtually no melting and only snow transportation by wind for ablation processes at the ice surface. The most important ablation mechanism is at present calving of icebergs from the margins (Kristensen, 1983). As ablation rates are the primary sign of ice sheet stability increased ice calving would be seen during ice shelf disintegration, so long term monitoring of ice calving shows if the ice sheet is become unstable or unchanged. The release of frozen fresh water in the form of icebergs into the Southern Ocean will have negative impacts on the ocean circulation currents and of particular concern is the production of Antarctic Bottom Water (AABW) (Gordon, 2001). Key regions of the Antarctica Coast produces these waters that transport cold water through-out the world's oceans. The AABW works as part of the Global Conveyor Belt by pressure gradients in the salinity of the water. The higher salinity content in the ocean water the heavier the water is. In Antarctic super saline (34.6 to 34.7psu) and cold waters (-1.0°C to 2°C) are produced that feed the current across the world (Gordon, 2001). Injection of fresh water from ice shelf calving is thought to have negative impacts upon the balance of this system. (The effects of added fresh melt water to the current are not well understood but are expected to have negative impacts). So it is vital that we understand and monitor the mechanical processes of the Ice calving in Antarctica.

Iceberg Variability

There are a number of high dynamic environmental factors that determine the drift of tabular icebergs. These include the forces of wind, hydrodynamic effects, inertia and effects resulting from the earth's rotation and action of waves. In addition, factors such as a sea ice cover may modify the drift pattern. The shape and surface structure of the individual iceberg will determine the relative magnitudes of the forces. As these factors can change daily or hourly, predicting ice berg direction and speed can be extremely hard. Remote sensing has allowed iceberg monitoring and tracking to improve models and predictions of icebergs and have become widely used.

Iceberg size is also a key variable that affects remote sensing ability to track and monitor ice bergs as finer/higher resolution images are needed for identifying and tracking the smaller ice bergs (Figure 1) (Navcen, 2014). Often large icebergs shelter small icebergs that will eventually break away from the large iceberg in a different direction and speed (Figure 2). Although classification of size varied between sources for large and medium icebergs, small icebergs are classified as 15-60 metres long and 5-15metres in height (International Sky Patrol), large enough to do major damage to ships and small enough to get close to shore. As small icebergs are hard to track but not impossible, the data gathered from ice movements needs time to process to determine the presence of smaller icebergs. Studies done by (Tournadre, 2012) on small ice berg tracking uses data from data bases and archives and are thus historical. Few studies are done from data retrieved in the same month. (Tournadre, 2012) used the Jason-1 archive of satellite data and was able to map small iceberg distribution from 2002-2010. (Tournadre, 2012) also estimated the mean annual volume of in the Southern Ocean at 400Gt (25-30% uncertainty), this represents 35% of the volume of large tabular icebergs and thus play a significant role in the injection of melt water in the ocean. Being able to track smaller icebergs while they pose a hazard or before they melt to determine the amount of fresh water released would be desirable.

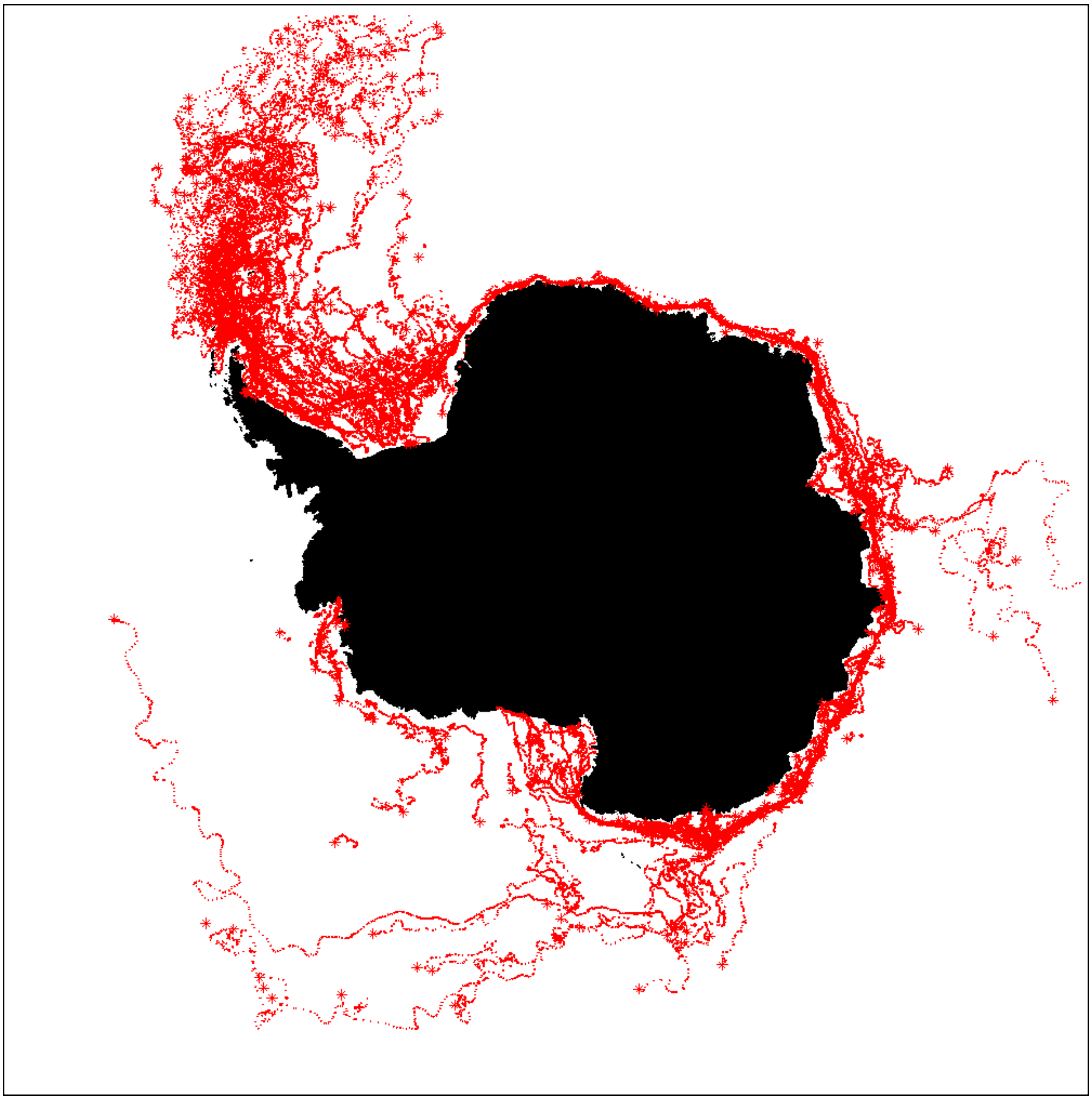

Figure 1: Large iceberg tracks from 1999-2010 from data from Seasat, NSACT, ERS-1/2, QuikSACT, ASCAT and OSCAT from 1992-2010 from Bringham Young University (BYU) database.

Figure 2: Image of larger icebergs sheltering small ice bergs that would remain undetected by satellite

Background

Icebergs drift though 20% of the oceans, mostly around the polar regions of the earth meaning untracked icebergs are a major issue for shipping lanes, coastal activities, the private sector, and government bodies as icebergs can cause loss of life, environmental damage and economic damage. Aerial photography was the first form of remote sensing to occur in response to need to monitor icebergs in the Canadian Arctic and by 1957 the Canadian government had set up radar studies to map the North Canada with similar techniques. The Canadian federal government alone spends millions in launching satellites to track and monitor iceberg calving in both the North and South hemisphere (Agency, 2012)

The IPCC 2007 and IPCC 2013 environmental reports predicts several potential surface temperatures changes on the earth ranging from an increase of 1.5°C to 4.0°C surface temperature by 2100. The affects of warming will be felt the most at the Polar Regions of the Northern Hemisphere and the Antarctic Peninsula. Here the temperature rise is expected to increase ablation processes and lower the net mass balance of the ice sheet. Most of ablation increase is expected from an increase in the rate of ice calving. This will cause iceberg movements to become a greater hazard for activities in the Southern Ocean and fresh water input into the surrounding oceans to increase.

The average rate of ice loss from glaciers around the world, excluding glaciers on the periphery of the ice sheet was estimated to be from 226 [91 to 361] GT yr-1 over the period 1971 to 2009, with a possible high of 275 [140 to 410] Gt yr-1 over the period. This figure also shows the great variation of ice loss from glaciers and the difficulty of annual and seasonal monitoring of a large ice mass.

Ice sheets are in contact with the ocean waters exchanging energy by conduction. Melting occurs on the bottom up of the ice sheet and can create basal factures. In turn these fractures increase melting. In the IPCC 2013 report Ocean Surface temperatures worldwide have warmed an average of 0.13°C largely at the upper layers, there is also increasing amounts of energy storage in the water layers. Icebergs moving over warmer seas are likely to melt rapidly putting a large amount of fresh water into the system and altering the energy balance.

Remote Sensing Techniques

Canadian Space Agency (CSA) plans to launch the RADARSAT Constellation that is currently under development in 2018. The RADARSAT Constellation is the evolution of the RADARSAT program with the objective to provide continuous data coverage on improved operational use of Synthetic Aperture Radar (SAR) (Vachon, 2012) . There will be three satellite configurations providing complete coverage of the globe while eliminating inaccuracy caused by gaps in coverage. Although this program doesn't plan to cover the Antarctica at this present time this configuration of satellites could provide greater coverage of Antarctic monitoring programs.

Satellite and remote sensing techniques have been used to great effect since the 1970s starting with Landsat-1. Satellites are now used to monitor ice calving and drift of large tabular icebergs to great affect but improvements on future tracking and understanding of the limitations of the techniques is required. This paper considers the advantages and limitations of high altitude remote sensing.

Remote Sensing Background capabilities of techniques

Monitoring of the size and thickness of the ice and ice bergs is needed to be able to determine the mass of the fresh water that could be released into the Southern Oceans.

Synthetic Aperture Radars (SAR) are the only imaging radars that are capable of penetrating heavy cloud cover around the planet, day or night but the imagery is limited to lower resolutions. SAR software is now attached to nearly every earth environment monitoring satellite. Sounding radar uses low-frequency ground-penetrating radars that are used to retrieve data from the sub-surface of earth. Their low operating frequency allows them to penetrate hundreds of metre below the ground while synthetic aperture radar is usually reduced to the surface layer. This is because of the low operating frequency and small allowable antenna dimension, thus the beam is very wide and much less powerful.

On 27th July 1991 the European Space Agency's first earth observing satellite (ERS-1) was launched in a sun-synchronous polar orbit. ERS-1 was to provide environmental monitoring with SAR, ATSR-1 and RA. ESR-1 was later replaced by ERS-2 (launched 21st April 1995) that improved on the software of ERS-1 including new ATSR-2 and GOME (Global Ozone Monitoring Experiment) instruments. It depleted all fuel by 5th September 2011 and ended service. The Larsen A retreat in 2002 was well captured by ERS (Rott et al. 1996). The successor of ERS-2 is Envisat which was launched on the 1st March 2002 on a synchronous polar orbit. Envisat mapped the most well know extreme Antarctic ice calving event of 2002 - The collapse of Larsen B - in moderate resolution imaging Spectroradiameter (MODIS) imagery and contained improved versions of many of the instruments on-board ESR-2 (Online, 2014). Larsen B ice shelf was the most rapid collapse seen of an ice shelf and showed that that ice shelves are highly dynamic with this event releasing 3250km^2 (at 220m height) of ice bergs into the Southern Ocean. Larsen B was later found to have been stable for at least 12,000 years. Envisat's mission ended on 9th May 2012.

Satellite used for ice monitoring in the Southern Ocean

Launched in November 1995, RADARSAT-1 provided Canada and the world with an operational radar satellite system capable of timely delivery of large amounts of data. Equipped with powerful synthetic aperture radar (SAR) instrument, it has acquired images of the earth day or night, in all weather and through varied cloud coverage, smoke and haze.

RADARSAT-1 was a Canadian led project involving the Canadian federal government, the United States and the private sector. RADARSAT-1 has provided useful information to both commercial and scientific users in such fields as ice studies, oceanography and coastal monitoring. Antarctic mapping mission (AMM) acquired images from September to October 1997 to complete the first seamless mosaic of Antarctica. The AMM was aimed at completing a high resolution map of Antarctica, 50km by 50km at 10m resolution. Such coverage was not possible with existing or previous space-borne high-resolution sensors because of their orbit inclination and /or field of view capability. On 29 March 2013 RADASAT-1 experienced a technical problem. The CSA team of engineers conducted an extensive investigation and concluded that RADARSAT-1 was no longer operational. RADARSAT-1 operated for 17 years out of its planned 5 years lifetime margin. (http://www.asc-csa.gc.ca/eng/media/news_releases/2013/0509.asp)

RADARSAT-2 was launched in December 2007 with the next generation of commercial radar satellites technical advancements to improve on the precision of SAR that RADARSAT-1 proved and following the same sun-synchronous orbit with a resolution of 1m (Agency, 2014). Thus more accurate data from the same circuit of RADARSAT-1 has been gathered since its launching.

QuikSCAT (Quick Scatterometer) is a NASA earth observation satellite carrying the SeaWinds satterometer. Its primary mission was to measure the surface wind speed and direction over the ice-free global oceans (NASA, 2014b). QuikSCAT has a wide range of applications and was used to track large icebergs in their ocean movements.

TerraSAR-X is a joint venture between German Aerospace Center(DLR) and EADS astrium. TerraSAR-X was launched June 15 2007 with high accuracy sensors TerraSAR-X can provide up to 0.25cm resolution. It covers the whole earth and follows the sun's path allowing for better image quality and more flexibility in angle adjustments to capture data.

The OSCAR satellite is a Ku-band conically scanning scatterometer system designed and built by the India Space Research Organization (ISRO)/Space Applications Centre (SAC). OSCAT was launched aboard the Oceansat-2 satellite on September 23, 2009 (Ref). OSCAT was never meant to be used to monitor iceberg in the Southern Ocean, its primary focus is surface winds and ocean conditions. As a result imaging from OSCAT has too much contrast between open water and Icebergs as well as the data band has low resolution.

The daily ice image products are generated from the OSCAR Level 1B sigma0 data provided by ISRO. The images are produced using software that was developed as part of the NASA Scatterometer Climate Record Pathfinder Project (SCP) at Brigham Young University (BYU).

The ice products contain the most recent images covering the Antarctic, the Arctic, the Ross Ice Shelf, South Georgia Island and the Weddell Sea. The Antarctic and Arctic products typically span a 24-hour data period, while the other regions span a 38-hour period. The coverage may vary due to delays in data availability or revolution reprocessing. Current products include the h-pol average, the h-pol SIR (Scatterometer Image Reconstruction) and the ocean-masked image (Wikipedia, 2014).

NASA's ICESat (Ice, Cloud, and Land Elevation Satellite) was part of NASA's Earth Observing System, its mission being the measuring of ice sheet mass balance, cloud and aerosol heights, as well topography and vegetation characteristics. Providing spatial resolution of less than 10km. ICESat was originally launched on the 13th January 2003 and recorded data from a near-polar orbit at an approximate altitude of 600km. It operated for seven years until its payload shut down and engineers were unable to restart it in February of 2010 (NASA, 2014a). ICESat-2 will be the successor but it is still currently being planned but is scheduled to be launched in 2016

All the remote sensing techniques discussed have limited lives and capabilities. NASA's LANDSat is the longest running series of satellite imagery of earth. Established on 23th July, 1972 and most recently Landsat 8 was launched on the 11th February 2013 (Table 1). Table 1 indicates the limited life of Landsat satellites.

Satellite	Launch/termination
Landsat-1	23rd July 1972 – 6th January 1978
Landsat-2	22nd January 1975 - 22nd January 1981
Landsat-3	5th March 1978 – 31st March 1983
Landsat-4	16th July 1982 - 1993
Landsat-5	1st March 1984 – Decommissioned 5th June 2013
Landsat-6	5ht October 1993 – Failed to reach Orbit
Landsat-7	15th April 1999 – Functioning with faults
Landsat-8	11th February 2013 - Functioning

Table 1: Table of Launch and termination dates of Landsat satellites from 1972 to 2014

Discussion

Characteristics of mechanical forces and links to problems encountered with various technologies

Author	Techniques	**Purpose**	**Advantages and Limitations**
(Weshe, 2013)	-Mosaic of 3000 Radarsat-2 Images. -Antarctic Mapping Mission (AMM) - SAR 100m pixel size imagery	- Use Remote Sensing data to monitor and determine Iceberg classifications	-SAR imagery was coarse resolution and identifying single types specificity of detail was difficult and instead uses genetic terms of “surface structure” or “Surface feature”
(Jansen, 2007)	-United States National Ice Centre Database -ICESat -ERS SAR -ScanSAR	Modelling changes in iceberg drift and melt rates with change of enviroment	-Had a range of Satellite Images for identification and estimating height of icebergs.
(Luckman, 2010)	-Time average series of SAR images between 2005-2007 - ERS-1 SAR -Envisat ASAR Wide Swath Mode -ICESat	-To identify grounded icebergs in western Weddell Sea	-ASAR backscattering increase from firm layers -Study tracked Large Icebergs -Wide swath mode has 150m resolution

(Tournadre, 2012)	-Reprocessed Jason-1 satellite imagery from 2002-2010	- Antarctic iceberg distribution focusing on small icebergs	-Jason-1 tracks from 66°S to 66°N not covering regions of the Weddell Sea and Ross Sea. -Large data set - Able to track small icebergs 400-800m
(Evers, 2013)	-The International Monitoring System, Comprehensive Nuclear-Test-Ban Treaty (IMS CTBT), Contains hydro acoustic stations to monitor the oceans	-Remote hydro acoustic sensing of large icebergs in the Southern Indian Ocean.	-Stations can detect and track Large Icebergs thousands of Kilometres away from its location. -Hydro acoustic localization is not affected by meteorological phenomena. -Icebergs were located in the Antarctic Circumpolar Current (ACC). Technique was not test closer to the Antarctic continent -Acoustic sound increases with icebergs collision.
(Scambos, 2008)	-ICESat (Freeboard measurements) - Automated Met-Ice-Geophysics Observation Stations (AMIGOS) located on Icebergs -US National Snow and Ice Data Centre -Antarctic Iceberg Tracking database using QuickSat and SeaWinds satellite.	-Examine the drift of several large tabular icebergs drifting northward towards South Georgia Islands.	-GPS co-ordinates give daily updates of location -Large tabular iceberg are easy to track with satellite -Accurate freeboard measurements

Table 2: Summary of recent studies, Techniques, Purpose and Dis/advantages that used Remote sensing as thier primary data source

Limitations of Remote Sensing

Despite its convenience remote sensing techniques do have limitations that restrict their usefulness. Such limitations are based on the orbit and hardware of most satellites. A satellite's orbit is a key defining factor to a satellite's capability. This limitation is the large spacing between ground tracks and time of repeat passes for radar altimeters. Therefore it is difficult to determine the freeboard of icebergs and therefore the thickness of the ice.

Coverage with SAR imagery is poor at the moment, the Enivsat satellite has been decommissioned but Sentinel-1 will be launched in Late 28th March 2014. Currently Southern Hemisphere countries must buy data from satellites which partially track into the hemisphere. There are a limited number of satellites in polar orbit, or orbit that crosses over the Southern Ocean. This is because of a satellite's repeating cycle - the time interval that passes before the satellite begins to repeat its series of ground tracks. (Luckman, 2010) indicates that multi passes were required by SAR imagery and altimeter data to acquire and identify tabular icebergs and estimated their drift. This complements (Jansen, 2007) that used multi-satellites to observe and measure freeboard height changes in icebergs. For near-polar orbits the repeat cycle is several days although the satellite may orbit the earth in a few hours. This is large limitation of remote sensing, although a different satellite may pass over the region a few days later its cargo maybe a different sensor, hardware and software that will produce different imagery and can produce different results.

Spatial Variations in Iceberg monitoring in the Southern Ocean

Icebergs are not evenly spatially distributed across the Southern Ocean as seen in Figure 1. Iceberg tracking shows their presence is more common in the Weddell Sea, Ross Sea and Amery ice shelf, the three regions with the largest volume of ice shelves on the continent. East Antarctica coast is highly active with icebergs as well but the West Antarctica, Bellingshausen Sea has none according the Figure 1. The lack of icebergs is not because of lack of ice shelves of glacier tongues. These gaps may result from gaps in data gathering methods, size of ice bergs or the frequency of calving in the area. (Luckman, 2010) found that in regions of iceberg grounding in the Weddell Sea that ice drift wasn't the constant Northward drift they expected.

(Weshe, 2013)found by using SAR imagery that it was possible to observe the locations of potential ice calving sites and to combine the information with known drift patterns. (Weshe, 2013) also determined that when the origin of detected icebergs is known, their thickness at the time of calving can be determined from maps of ice shelf thickness, which leads to and improved estimation of freshwater fluxes in the Southern Ocean.

Tracking Iceberg Movement - Limitations/ Advantages

SAR hardware is extremely common for environmental censoring satellite to carry as SAR software has shown its capability by even penetrating the heavy cloud cover of Venus (Meyer, 2012). Although SAR performance isn't affected by cloud cover this does affect the resolution of image by lowering the resolution as the radio waves sent to surface are spread over a wide surface area and are lower frequency making visual observations of small icebergs, Icebergs under the sea or pack ice difficult. This limitation is pushed aside by the ability for images to be captured day and night through clouds. Ground penetrating radar isn't that helpful for iceberg monitoring as cloud cover restricts the imagery, but with greater resolution available in other systems smaller icebergs can also be identified that were not visible in low resolution. In the reflection back from the surface data received will show the height of the freeboard of an iceberg that is above surrounding water; this is useful data to determine the total volume of the iceberg and helps to predict trajectory, ablation rates and fresh water added to the Southern Ocean. They are difficult to detect operationally using satellite borne sensors. Visible and infrared sensors are often blinded by clouds while low resolution microwave sensors, such as radiometers, cannot detect such small features. (Luckman, 2010) used multi-passes of SAR imagery to retrieve complete data, while (Jansen, 2007) used ICESat, MODIS sequences, ERS, RADARSAT and ASTER to achieve the desired data for modelling ice drift and decay. Multiple satellites and software has been used in these studies to gain the benefits of all satellite and software, if databases are not used.

In the paper written by (Evers, 2013) iceberg tracking is used with hardware and software from The International Monitoring System, Comprehensive Nuclear-Test-Ban Treaty (IMS CTBT); its purpose was originally to monitor the earth's oceans for nuclear testing but was used by (Evers, 2013) to successfully track large tabular icebergs with sound in the ACC, Southern Indian Ocean and through storms. However they found that this technique's accuracy would be limited by collision of icebergs causing an increase in the acoustic sound received by land based monitoring stations. This suggests that this technique would not work where collision is common in icepacks and in coastal monitoring.

Other possible courses of action

Drones and unmanned aerial vehicles (UAV) have only recently (last 5 years) (Haugen, 2011) been applied as potential environmental monitors as Lidaroptical (VNIR and TIR), Laser altimeter/scanner, Radiometer, scatterometer, Radio altimeter and SAR hardware can be equipped to the UVA. As UVA technology and interest has increasing over recent years the focus on drones development has been to increase operations over long periods of time without landing or refuelling, to withstand intensive weather conditions, and to provide Infrared and remote sensing data imagery back to data collection. UVAs are new potential technique for monitoring of icebergs in the Southern Ocean. An UVA can launch from ground sites on the continent, boats and other aircraft. They offer the possibility for lower altitude monitoring of iceberg that is not available through the current use of satellite technology.

Conclusion

Remote Sensing is an effective tool to monitoring and track some large tabular iceberg drift in the Southern Ocean. Satellites produce a wide range of instruments and data, are convenient, and provide all year coverage over a vast region of earth. The main limitation of remote sensing is the time between ground tracking of an area of interest and the repeat cycle. This means that the system is not responsive enough to track small or complex iceberg situations. While remote sensing instruments have their individual limitations the range and number of satellites covering Antarctica can be used to the researcher's advantage by using the strengths of each instrument's coverage for immediate data. There are also large databases of over 30 year's satellite imagery available to be fully utilized and new satellites are planned to continue on from failing satellites. To get more high quality and constant satellite coverage over the South Polar would require ongoing financial resources and upgrading of existing satellite hardware that currently limits the lifetime of satellites. Low level alternatives to high altitude remote sensing may offer more reliable data collection.

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