501: Literature Review

REMOTE SENSING OF ICE SHEET MASS BALANCE IN ANTARCTICA

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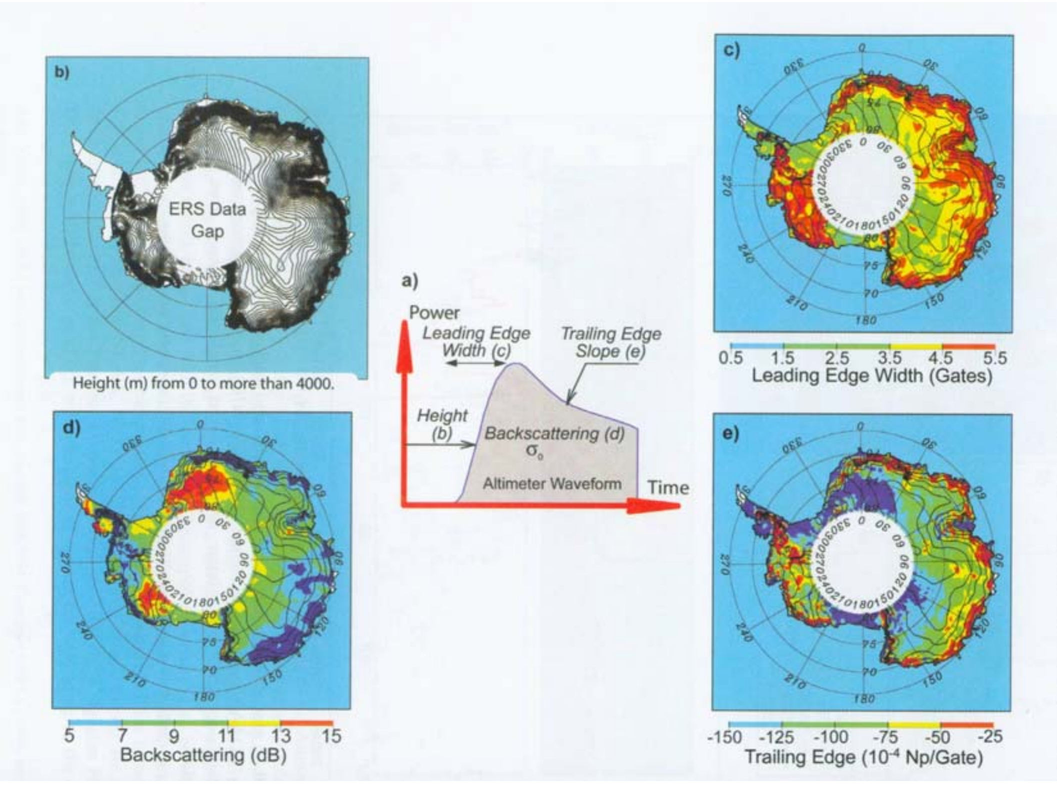

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Introduction

Technological advances in the twentieth century have enabled scientists to undertake research on virtually every location on the Earth. Parallel advances in space technology have provided a rapidly increasing number of satellite platforms that can be used to study complex physical processes in the Earth-atmosphere system. Remote sensing is the small or large-scale acquisition of information of an object or phenomenon in a given area by the use of recording devices that are not in physical contact with the object or area of interest, such as aircraft or satellite. The basis of remote sensing is the electromagnetic spectrum. Satellite remote sensing often permits real time, year round and long-term study. Remote sensing has greatly improved mass balance estimates of ice sheets and glaciers in Antarctica. Mass balance is the difference between accumulation and ablation of mass on an ice sheet or glacier over a time period.

There are three ways to measure the mass balance of an ice sheet: the mass-budget method, the volume method, and the geodetic method. The significant development of Synthetic Radar Altimetry (SAR) has allowed the measurement of surface height in the mass-budget method. The volume method uses satellite radar altimetry to measure changes in surface elevation of ice sheets. The geodetic method is an emerging approach that exploits gravity and holds huge potential for the future. This review will focus on these three methods. Although these methods have made dramatic improvements on mass balance estimates over the last decade, each method still has limitations. Mass balance products of remote sensing are important because they assist in interpretation and analysis of global change (Konig et al., 2001).

In the field of glaciology, remote sensing has proven to be a particularly useful tool because areas of interest are often inaccessible, such as those at high latitudes in Antarctica. Other physical characteristics of Antarctica that have limitations on ground based point measurements include: climatic extremes, the large spatial coverage, environmental sensitivity, the polar ‘night’ and the continent’s natural resources.

Mass Balance in Antarctica

Mass balance is the difference between accumulation and ablation on an ice sheet or glacier (figure 1). Accumulation is the gain of mass and occurs through snowfall, precipitation, avalanching and surface melt refreezing processes. Ablation is the loss of mass and results from iceberg calving, sublimation, basal or surface melting and runoff, aeolian removal of snow and evaporation processes. Ice loss in Antarctica is predominately by basal melting of ice shelves and iceberg calving (Massom and Lupin, 2006).

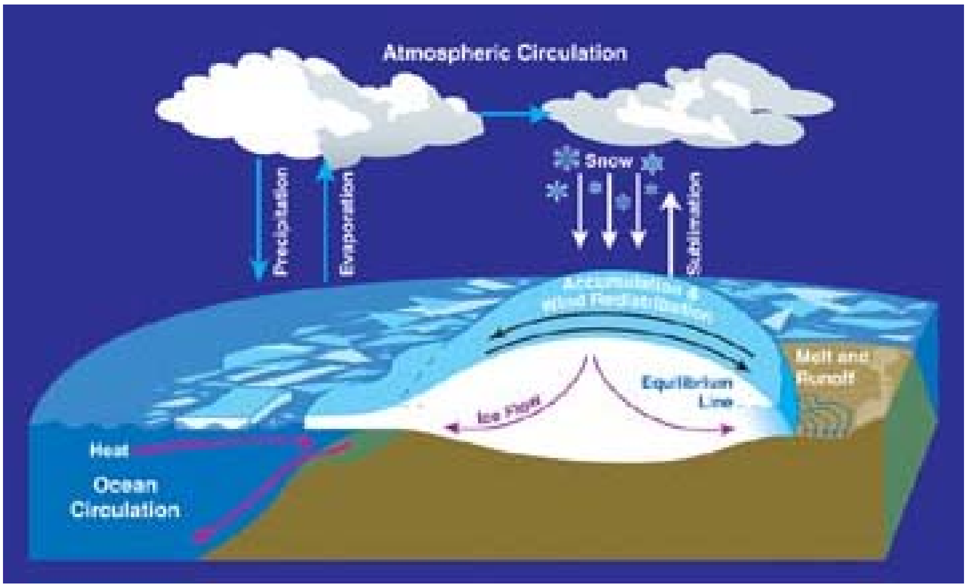

Figure 1: Schematic diagram of ice sheet ablation and accumulation fluxes. Source: Zwally et al. (2002)

A body of ice is said to be in negative mass balance if it is losing mass, and in positive mass balance if it is gaining mass. Mass balance can be established using the following formula (Massom and Lupin, 2006):

Change in surface height = Ice discharge + Accumulation

Surface height can be quantified using radar or laser altimetry; ice discharge can be determined using Antarctic Bedrock Mapping (BEDMAP); and accumulation can be measured using active or passive microwave techniques, Synthetic Aperture Radar interferometry (InSAR) or feature tracking (which compares sequences of satellite images).

Mass balance serves as a 'health' indicator of an ice sheet or glacier (Rignot and Thomas, 2002). The Antarctic ice sheet (AIS) holds 30 million cubic meters of ice representing enough water to raise global sea level by 66 meters; 60 meters in East Antarctica; and six meters in West Antarctica. Large variations in the sea level over the last million years have been controlled by ice, with rates of sea level rise at least one order of magnitude larger than at present periods of rapid deglaciation. Uncertainty in the response of the AIS to climate change represents the largest single unknown in the determination of sea level change (Massom and Lupin, 2006). Only mass balance of the grounded part of the ice sheet contributes to global sea level rise because mass changes in ice shelves have little or no direct effect on sea level as they are already floating. In order to understand past sea level change and predict future change it is essential to measure the current balance status and resolve the large uncertainties in the budget of the AIS.

The Electromagnetic spectrum

The electromagnetic spectrum is the basis for remote sensing (figure 2). Satellite sensors can see a wider spectral range than humans. Different instruments measure the different parts of the spectrum. Unlike optical and infrared imaging sensors, which are inherently passive, that is they rely on reflected or radiated energy, radar is an active sensor, which provides its own illumination in the form of microwaves.

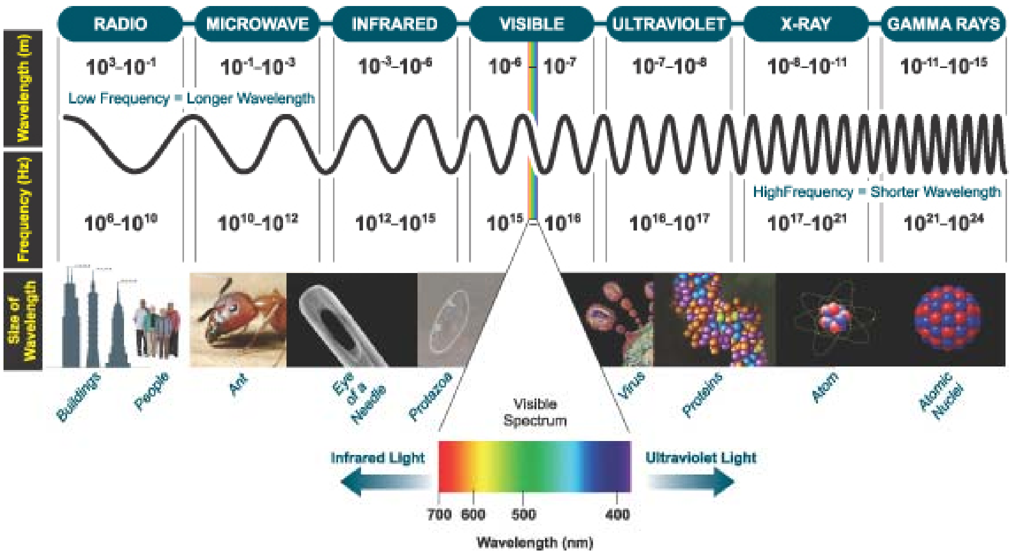

Figure 2: The electromagnetic spectrum. Source: www.andor.com/library/

Development of Remote Sensing

Over the past decade remote sensing has revolutionised glaciologist's ability to examine ice sheet processes at large scale and micro-scale (Bindschadleret al., 2001). Mass balance concepts previously held are rapidly becoming more focused and are revealing new discoveries. Hence, mass balance estimates are constantly being re-evaluated (Masson and Lupin, 2006). Recently, accurate merging of satellite data with modelled and observed atmospheric and oceanic data and further refinement of ice sheet models has led to the successful reduction of uncertainties of ice sheet mass balance and related sea level rise estimations (Houghton et al., 2001).

Satellite remote sensing will never entirely replace in situ measurements because they complement and broaden remote sensing both spatially and temporally. Surface and aircraft measurements remain essential to validate remote sensing data and also to provide information not attainable from space (Massom and Lupin, 2006). Important developments in remote sensing include: provisions of ice sheet data to constrain, run and validate models on climate change; geophysical applications of radar interferometer to measure changes on the earth's surface that have dramatically improved in the early 1990s; and the recent development of InSAR over the last decade which has had an immense impact on mass balance research. Organisations such as the NASA/US National Science Foundation West Antarctic Ice Sheet Initiative is an international research programme devoted to mass balance measurement. (WAIS, 2003: http://igloo.gsfc.nasa.gov/wais). It has also been of importance to the development of mass balance remote sensing. In addition to improved satellites and sensors and new technologies being launched, some satellites are specifically designed to measure ice sheets, for example Ice, Cloud, and Land Elevation Satellite (ICESat) and CryoSat. Although the launch of CryoSat failed in October 2005, a follow-on mission is thought to occur by Massom and Lupin (2006).

Measuring mass balance using remote sensing

There are two main types of satellites: geostationary satellites which orbit above fixed points on the Earth's surface and view limited areas constantly, and polar orbiting satellites which follow tracks that precess around the Earth in tandem with the planetary rotation, for example Landsat 7 which has a 16 day repeat cycle. Polar orbiting satellites go from north to south and are very low to the Earth's surface (8 km). However, there is a problem in that high latitudes are difficult to image and require special orbital changes. This is applicable in Antarctica.

There are also two types of satellite sensors: active and passive. Active satellite sensors provide their own energy source: both transmit and receive. The advantages are that illumination is controlled and they are not limited by clouds or darkness. Complex processing and higher power consumption are disadvantages of active satellites. Radar or lasers are used in active sensors. Examples include: Radarsat, CryoSAT and ICESat. In comparison, passive satellite sensors detect energy that is naturally available, reflected or re-emitted. Advantages of passive satellite sensors are simple interpretation, low power consumption and lower cost. Disadvantages are that the process only works during daytime and they cannot see through cloud. Optical and thermal wavelengths are used in passive sensors. For example, Landsat. There are three ways to measure the mass balance of an ice sheet using remote sensing: the mass budget method, the volume method and the geodetic method.

Mass Budget Method

The mass budget method compares losses by melting and ice discharge with total net input from snow accumulation, that is, the net difference between accumulation and ablation (Rignot and Thomas 2002). Massom and Lupin (2006) further discuss the mass budget method or what they term the 'component approach.' They define the component approach for a given region as "ice mass in minus ice mass out" (Massom and Lupin, 2006:17). Input and output fluxes are determined separately. They argue that only this method can be used to estimate present, past and future mass budgets because it observes changes in ice sheet aerial extent and thickness (H) by using the equation:

$$\partial H/\partial t = Q_a - Q_L - \nabla.\,(H\,(\bar{u}))$$

where $\partial H/\partial t$ is the surface elevation change, Q_a is the net accumulation rate, Q_L is the net mass loss rate and ($\bar{u}$) is the depth-averaged velocity (ice flux F-H ($\bar{u}$)). Ideally these measurements should be carried out around the perimeter of the ice sheet, as this area is most dynamic. This approach has fewer uncertainties than the integrated approach (discussed in the volume method section) however, it is more susceptible to errors associated with the uncertainty of ice thickness and velocity and accumulation rates (Massom and Lupin, 2006). These errors are being reduced through the use of InSAR.

Accurate knowledge of patterns of accumulation and their variability across the ice sheet surface are essential for the understanding of mass balance dynamics. Current uncertainties of accumulation rates represent a primary error source in estimates of mass balance. Net accumulation rates derived from recent estimates for Antarctica range from 2020 Gt per annum (Giovinetto and Zwally, 2000) to 2288 Gt per annum (Vaughan et al., 1999). Net accumulation is currently inferred primarily from ice-core measurements but there is no present technique to derive accumulation from satellite data. However, satellite microwave techniques are being investigated along with satellite InSAR for future accumulation measurements in Antarctica (Massom and Lupin, 2006). Accumulation measurements can be validated with ground measurements such as snow pits and stakes. On 15 June 2007 Terra SAR was launched. One of its roles is to measure snow accumulation, but also measures surface height and ice discharge (Eineder et al., 2004). This will improve accumulation inputs into mass balance models.

Ablation is inferred through ice thickness and velocity, which are measured by feature tracking InSAR at the terminus of the glacier. Losses by melting are more complex because of meltwater refreezing after it drains into near-surface snow. Melt rates are commonly estimated from positive degree-day models. Although large uncertainties suggest that accurate mass balance determination for an entire ice sheet is difficult by the mass budget method, it can be achieved by using Global Positioning Satellites (GPS) over large regions and InSAR data (Rignot and Thomas, 2002).

SAR uses the component approach to improve mass balance estimates and reduce the uncertainty in projections of likely future sea level rise (Thomas and Rignot, 2002). Figure 4 highlights how the InSAR process measures surface height. Repeated imaging of the same location from two slightly different angles occurs as two SARs fly on parallel rackets to view the surface. With accurate information on the two slant ranges r_i and r_j and the sensor/satellite orbital location, the elevation of points on the Earth's surface can be mapped from the images back into space by geometric triangulation (Massom and Lupin, 2006). Using this data an inferogram, which is a mixture of motion and elevation, contours can be produced, that is, InSAR.

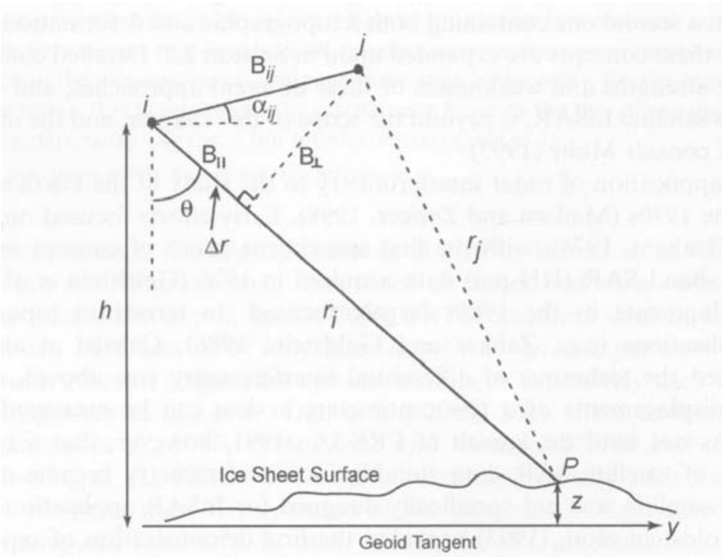

Figure 4: The repeat pass InSAR process that measures surface elevation. The spatial baseline B_{ij} created between the *i*th and *j*th repeat SAR observations of the same surface point *P*. At a virtually identical look angleθ, the differential range to point *P* is given by the interferometric phase. Source: Massom and Lupin (2006)

SAR can measure height within meters. Although this is not as precise as other techniques such as laser altimetry, a major strength of SAR is its unique ability to simultaneously measure both ice motion and elevation. Furthermore, SAR can acquire data over large regions irrespective of cloud cover and solar illumination conditions and at a high horizontal resolution. SARs produce all season, day and night maps of radar reflectivity of illuminated scenes on the Earth's surface, that is they use the information contained in the amplitude of the backscattered energy (Rotschyy et al., 2006).

An example of the use of SAR in Antarctica is by Rotschky et al. (2006) who combined satellite radar technique, low-resolution C-/Ku-band scatterometer and high resolution C-band SAR to estimate the AIS mass balance. The result was the first high-resolution map based on SAR data (figure 5). Their study focused on the area of Dronning Maud Land and they found that SAR data can be used to map mass balance changes but only within limited areas. This method requires accurate ground truth data for calibration and additional information on mean air temperature or elevation.

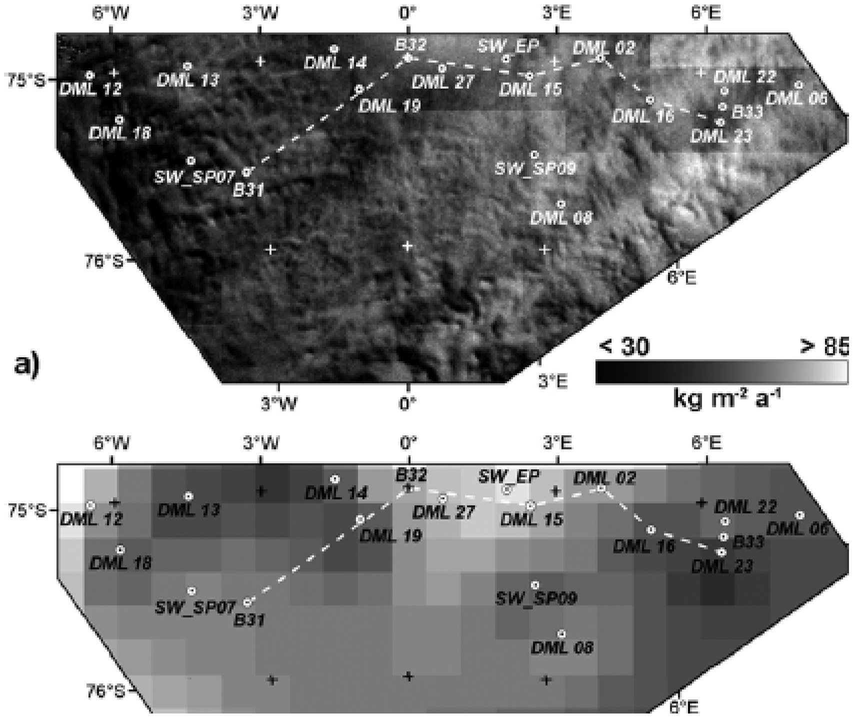

Figure 5: Accumulation maps based on a) SAR data and b) interpolation from point records. Source: Rotschky et al. (2006)

Volume method

The volume method (Rignot and Thomas, 2002) or integrated approach (Massom and Lupin, 2006) measures surface elevation change over time using satellite altimeters. Radar altimeters are non-imaging, nadir-viewing sensors that exploit the ranging capability of radar to determine the topographic profiles of the surface along the satellite ground track (Massom and Lupin, 2006). This concept is based on the relationship between changes in elevation and changes in thickness and thus, volume (Zwally, 1989). Surface elevation changes are equivalent to ice thickness changes minus the vertical motion of the underlying bedrock (Rignot and Thomas, 2002). Satellite radar altimeters such as Seasat, Geosat, and European Remote Sensing Satellites ERS-1 and -2, have been used to infer elevation change rates over Antarctica since 1978 (Davis et al., 2001). Ice sheet satellite radar altimeter has evolved to find regional changes in surface elevation that can be inferred with an accuracy on the order of a few centimetres per annum.

New and improved estimates of surface elevation are resulting from processing of Environment Research Satellite (ERS) radar altimetry data. An example of this is the production of a spatial plot of elevation change for a large part of the AIS over June 1995 to April 2000 by Davis and Ferguson (2004) (figure 6). The continent displays a trend in surface elevation of 0.4+/-0.4 cm per annum, however there is significant regional variability. The trend over East Antarctica is -3.6+/-0.6 cm per annum, while the trend in West Antarctica is -3.6+/-1.0 cm per annum. Pine Island and Thwaites Glacier show trends of -135+/-10 cm per annum and -31.6+/-5.2cm per annum respectively. One the other hand, Wingham et al. (1998) produced a similar map covering the period 1992 to 1996 that detected thinning of -11.7+/-1.0 cm per annum over Pine Island Glacier and Thwaites Glacier using ERS-1 and ERS-2 data (figure 7). This area is of particular concern because it drains a large part of the West Antarctic Ice Sheet (WAIS).

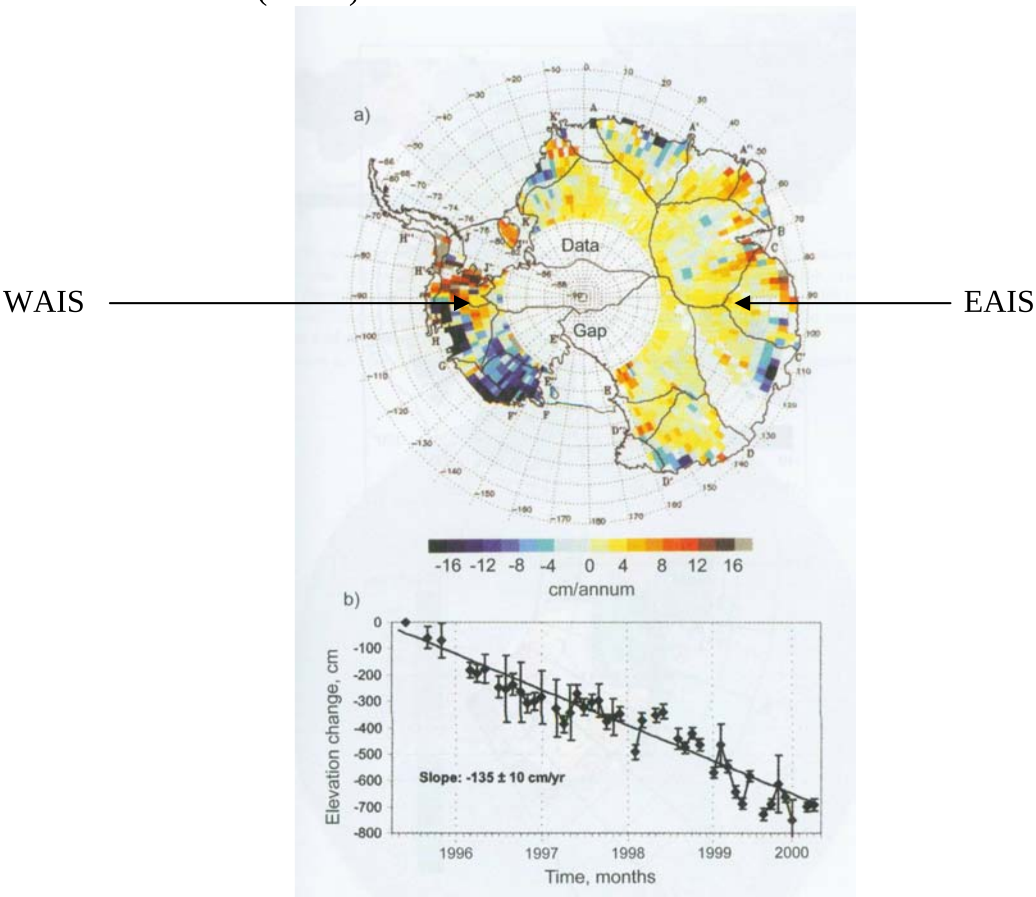

Figure 6: a) A spatial plot of the trend in *∂H/∂t* over the AIS for the period June 1995 to April 2000, derived from ERS-2 radar altimeter data (123 million elevation change measurements) and after adjustment for variations in the backscattered power of the radar signal returns. Elevation change time series were computed for 1° x 2° (latitude x longitude) regions north of 81° S and 0.6° x 2.0° for the most southerly data between 81° and 81.6°. Major drainage basin divides are marked. b) The corresponding elevation change time series for a circular region centred around the outlet of the Pine Island Glacier. Source: Davis and Ferguson (2004)

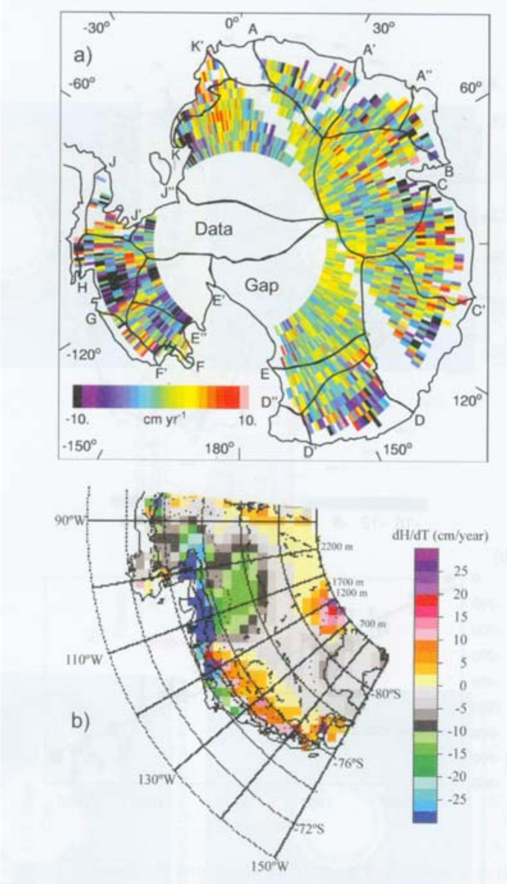

Figure 7: a) Elevation change (in cm per annum) of the AIS from 1992 to 1996 for 63% of the grounded AIS, measured by radar altimeters onboard ERS-1 and -2. Dark lies are boundaries of the major drainage basins. b) Map of elevation change of part of the WAIS, derived from ERS-1 and -2 radar altimeter data (1992-1999). Source: Massom and Lupin (2006)

Limitations exist when using satellite radar altimetry to calculate mass balance in Antarctica. Challenges exist in determining long-term variability or trends because of the need to account for seasonal variations in elevation caused by variations in snowfall, firn compaction or ‘densification’ and melting, that is, a change in surface height could be a result of a change in density and not a change in volume (Davis and Ferguson, 2004). This problem has the potential to become exacerbated within areas of warming because as temperature increases, snow becomes more compact and hence the satellite measurement will be distorted. This is significant as it is the long-term changes that are linked to climate change and global sea level rise (Massom and Lupin, 2006). Moreover, satellite coverage is limited to the interior regions of the ice sheet, where surface slopes are low. They do not perform successfully well in marginal outer regions, where slopes are greater and undulations are more prominent (Davis and Ferguson, 2004). Improved measurement of outer ice sheet margins is critical given that they are the most dynamic part of an ice sheet and are exposed to global atmospheric and oceanic forcing. They also exhibit high variability in accumulation. While the first generation satellite radar altimeters provide sufficient measurement accuracy to constrain mass balance calculations over five to ten year intervals, accuracies are still insufficient over shorter time periods (Massom and Lupin, 2006).

The need for higher resolution measurements to overcome these limitations has led to the development of ICESat and CryoSat. They both carry altimetry technologies specifically for the measurement of ice masses and will improve estimations of mass balance and reduce the uncertainties to only a few centimetres (CryoSat Science Report, 2003). The launch of CryoSat in October 2006 failed but it is expected that it will be relaunched in 2009/2010. CryoSat will incorporate altimeter measurements of ice sheet inland regions, steeper ice sheet margins and ice shelves as well as ice sheet thickness. Ground measurements, such as snow pits, ice cores, stake measurements and density profiles, will be compared with aircraft radar altimeter measurements and these measurements will be compared to satellites to validate the data (CryoSat Science Report, 2003).

Geodetic method

The geodetic method is an emergent approach which estimates mass balance through the weighting of ice sheets using mass signals from the new satellite-derived measurements of changes in the Earth's gravity (Rignot and Thomas, 2002). NASA's Gravity Recovery and Climate Experiment (GRACE), launched in March 2002 by the joint German and US Gravity Recovery and Climate Experiment, is the first in a series of satellite missions devoted to measurement of the Earth's time-variant gravity field. With GRACE, two identical satellites, separated by 220 km, circle the Earth in the same orbital plane. GRACE measures the gravity field to a precision 100-1000 times greater than previously possible and at a spatial resolution of 100 km. Data from GRACE has been used to create new global maps of the mean gravity field and high-resolution maps of the monthly average gravity field. Temporal variations in the distribution of surface mass can be detected from these. Ramillien et al. (2006) proposes an estimate of mass balance from GRACE geoid solutions over the period July 2002 to March 2005. After correcting for land hydrology contamination and glacial isostatic adjustment, GRACE volume rates are -107+/-23 cu km/yr for West Antarctica and +67+/-28 cu km/yr for East Antarctica (figure 8). For the AIS a bimodal behaviour is apparent, with volume loss in the west and gain in the east. The total Antarctic contribution to sea level over this short time span is slightly positive +0.11+/-0.09 mm/yr. These results are in qualitative agreement with recent mass balance estimates based upon other remote sensing observations.

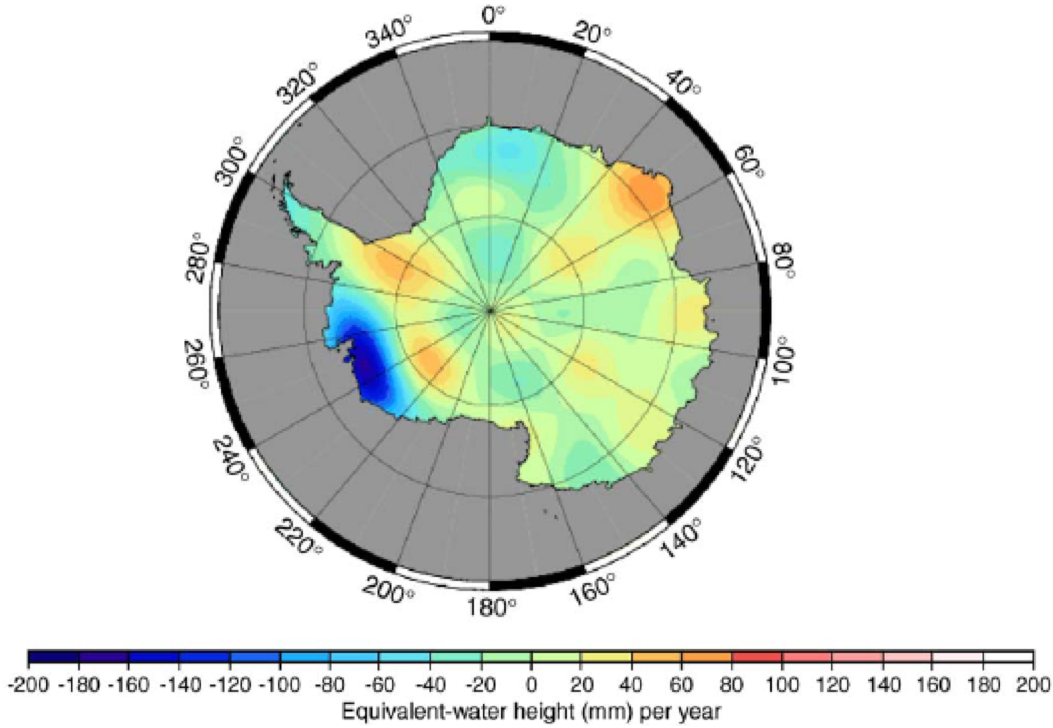

Figure 8: Map of ice volume change over Antarctica computed from the 10 day GRACE solution period August 2002 to March 2005. Source: Ramillien at al. (2006)

Discussion

Trends of global warming indicate an increase in accumulation processes in Antarctica which suggests a positive mass balance. However, the literature highlights that regional patterns of mass balance are spatially diverse. Recent advances in the determination of the mass balance show that the WAIS is thickening in the west and thinning in the north with thinning overall to be most likely. The mass imbalance in the East Antarctic Ice Sheet (EAIS) is likely to be small, but even its sign cannot be determined. The most current estimate of mass balance is by Shepard and Wingham (2007) using a survey period from 1992 to 2005. They use a combination of all three methods to estimate the current mass balance in Antarctica. They estimate the EAIS to be gaining mass -1 to +67 Gt per year, the WAIS to be losing mass -136 to -47 Gt per year and the overall AIS to be -139 to +42 Gt per year. This estimate still has large error margins. West Antarctica is a marine ice sheet with its bed below sea level, thus concerns exist over its stability in the face of climate change. The numerous studies on mass balance in Antarctica highlight that estimates are continuously improving and will persist in the future with the development of more accurate remote sensing applications.

Over the last decade, glaciologist's understanding of the AIS has improved dramatically with the availability of improved data sets from satellite's remote sensing. The success of measuring specific properties from satellites is closely linked to the development of new technologies and satellite sensors. SAR sensors have been a huge advance as they provide high-resolution images unaffected by cloud cover and have resulted in new techniques such as SAR inferometry. The full potential of SAR is yet to be completely explored. More accurate estimations of mass inputs and outputs enable a refinement of mass balance estimations and the understanding of complex processes and feedbacks involved in ice sheets. However, limitations still exist in remote sensing in Antarctica. Satellite coverage does not extend to the area of central East Antarctica and the short time period of large-scale. Furthermore, the relevance of satellite-derived observation relative to the long response time of ice sheets needs to be put in perspective. Poor knowledge of accumulation rates undermines the ability to accurately establish the mean annual input into the ice sheet. The combination of poor knowledge of ice thickness and large errors measured in ablation rates creates the greatest uncertainty in mass balance using the component approach. Mass balance is poorly known in areas around ice sheet margins and where surface slopes are steeper. New technology and more robust alogrithms are likely to be developed in the future which will not rely on assumptions and external information.

Conclusion

Over the last few decades the use of satellite remotely sensed data has revolutionised. However, the methods presented still need to account for the limitations of present satellite sensors that introduce uncertainties in mass balance estimates. Ground truth data is still crucial for precise interpretation of remotely sensed data. Although the component approach has fewer uncertainties associated with it's mass balance measurements than the integrated approach, it is more susceptible to errors associated with the uncertainty of ice thickness and velocity and accumulation rates. The emerging geodetic method is remarkable and holds much potential to overcome these uncertainties in the future. Understanding the role of mass balance in the earth-atmosphere system in the future is invaluable considering the response to current global warming trends and the role satellites play is immensely important to the creation of that knowledge. Major challenges remain but the incentive to accurately model mass balances and there contribution to global climate change are compelling.

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