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Recommendations for the collection and synthesis of Antarctic Ice Sheet mass balance data

The ISMASS Committee[1],*

Abstract

Recent unexpected changes in the Antarctic Ice Sheet, including ice sheet thinning, ice shelf collapse and changes in ice velocities, along with the recent realization that as much as one third of ice shelf mass loss is due to bottom melt, place a new urgency on understanding the processes involved in these changes. Technological advances, including very new or forthcoming satellite-based (e.g. ICESat, CryoSat) remote sensing missions, will improve our ability to make meaningful determinations of changes in Antarctic Ice Sheet mass balance.

This paper is the result of a workshop held to develop a strategy for international collaboration aimed at the collection and synthesis of Antarctic Ice Sheet mass balance data, and at understanding the processes involved so that we might predict future change. Nine sets of recommendations are made, concerning the most important and sensitive measurements, temporal ranges and study areas. A final tenth recommendation calls for increased synthesis of ice sheet data and communication between the field measurement, satellite observation and modelling communities.
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Keywords: Antarctica; Ice sheet; Ice shelf; Ice mass balance; Remote sensing

1. Introduction

The determination of growth or shrinkage of the great ice sheets is a longstanding unsolved scientific problem concerning the Earth's polar regions. Today, the issue of ice sheet mass balance has renewed urgency because of the role of grounded ice in sea level change. In fact, the significant variations in sea level over the past million years have been controlled by ice, and it is clear that the response of the ice sheets to climate change in the immediate future could raise, or in the short term even lower, global sea level (e.g. Fairbanks, 1989). Climate variability and sensitivity in Antarctica is a complex issue. Current patterns of temperature trend in Antarctica are hard to reconcile and to simply relate with global climate change.

The study of ice sheet mass balance is especially relevant at this time because the prediction of global sea level change is of practical concern. Recent

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observations of the Antarctic Ice Sheet have revealed unexpected changes in ice stream velocities (Stephenson and Bindschadler, 1988; Joughin et al., 2002; Rignot et al., 2002), including complete shutdown (Retzlaff and Bentley, 1993), as well as glacier retreat and ice shelf collapse (Skvarca, 1993, 1994; Rott et al., 1996, 1998, 2002; Rignot, 1998, 2001; Skvarca et al., 1999). Analyses of ice sheet response to climate change have indicated a wide range of outcomes on different time scales under different climate change scenarios (e.g. Hughes, 1981; Whillans, 1981; Alley and Whillans, 1984; Sugden, 1992; Bentley, 1997; Warner and Budd, 1998). Observations show that the interactions between surface wind and subtle variations of surface slope have a considerable impact on the spatial distribution of snow at short and long spatial scales (Gow and Rowland, 1965; Whillans, 1975; Frezzotti et al., 2002). New technologies, e.g. Satellite Radar (SAR) interferometry (Goldstein et al., 1993), Lidar and airborne coherent Ground Penetrating Radar (GPR), and remote sensing campaigns (Jezek, 1999, 2002) have resulted in a significant increase in our ability to observe and model ice sheet properties and processes. Recognizing the potential for ice sheet change, the Scientific Committee for Antarctic Research (SCAR) established the Ice Sheet Mass Balance and Sea Level (ISMASS) project to examine and report on the study of the ice mass balance of Antarctica. This paper addresses a strategy for ISMASS to result in a meaningful international scientific approach to understanding and predicting Antarctic Ice Sheet mass balance.

In the last decade, our picture of a slowly changing Antarctic ice sheet has radically altered. Rignot and Thomas (2002) estimate the net gain of ice from the East Antarctic Ice Sheet to be 22 km^3 $year^{-1}$ (433 km^3 $year^{-1}$ accumulation minus 411 km^3 $year^{-1}$ outflow at the grounding-line). They estimate the net loss from the West Antarctic Ice Sheet to be 48 km^3 $year^{-1}$ (381 km^3 $year^{-1}$ accumulation minus 429 km^3 $year^{-1}$ outflow). It is now realized that ice shelf basal melting may account for up to one third of the loss from the floating ice (Jacobs et al., 1996). Extensive, rapid thinning is occurring in several sections of the West Antarctic Ice Sheet interior (Wingham et al., 1998; Rignot, 1998; Shepherd et al., 2001; Zwally et al., 2002b) and in the Amundsen Sea sector including Pine Island and Thwaites glaciers

(Rignot and Thomas, 2002; Shepherd et al., 2002). The collapse of the Antarctic Peninsula ice shelves is associated with, and probably causing acceleration of grounded ice discharge (Rott et al., 2002; De Angelis and Skvarca, 2003; Zwally et al., 2002a). In addition, significant deceleration (23%) has been observed for Whillans Ice Stream on the Siple Coast and the region is thickening substantially, largely in response to the shutdown of Ice Stream C (Retzlaff and Bentley, 1993; Joughin and Tulaczyk, 2002). These discoveries inject a new sense of urgency into gaining a better understanding of the evolution of the ice sheet. Will the expected warming of the ocean adjacent to the ice shelves alter the basal melting rates, and what is the consequence for the ice sheet grounded below sea level? Is the thinning observed in the Pine Island and Thwaites glacier regions of West Antarctica a sign of its continued deglaciation? If so, will the thinning accelerate? It is important to understand the sensitivity of numerical deglaciation models to the treatment of the grounding line. Assuming the present thinning is a deglaciation signal, how confident can we be that today's numerical models can capture the future evolution of the ice sheet in this region?

The latest IPCC estimate of the Antarctic contribution to 20th century sea level rise (Church and Gregory, 2001) is − 0.2 to 0.0 mm $year^{-1}$. Atmospheric warming in the coming century may lock up as much as 10 cm of ocean volume due to increased precipitation over the ice sheets (Budd and Smith, 1985; Polar Research Board, 1985; Giovinetto and Bentley, 1985; Robin, 1986; van der Veen, 1988; Fortuin and Orlemans, 1990; Warrick and Orlemans, 1990; van Lipzig et al., 2002). On the other hand, Kapsner et al. (1995) and Cuffey and Clow (1997) document situations in which warming does not lead to higher accumulation. It is expected in addition that higher accumulation may largely be counterbalanced by increased ice shelf bottom-melting. Evidence for the acceleration and deceleration of the low driving stress Ross Sea ice streams has demonstrated the potential for variability in West Antarctic ice flow (Fahnestock et al., 2000; Conway et al., 2002; Joughin et al., 2002). This is confirmed in the larger and more extensive inland thinning and acceleration seen in the high stress, high velocity flows of the Pine Island and Thwaites glaciers

(Schmeltz et al., 2001; Rignot et al., 2002; Zwally et al., 2002a). Satellite interferometry has now also demonstrated that the numerous grounded glaciers of the Antarctic Peninsula have accelerated in response to the collapse of the Prince Gustav Channel and Larsen Ice Shelves (Rott et al., 2002). In summary, the 20th century Antarctic mass imbalance seems near to zero or slightly negative—easing the problem of closing the 20th century sea level budget—and the newly recognised importance of ice shelf melting now emphasises mechanisms that may offset the 21st century expected growth due to global warming.

While ice shelf melting is important for considerations of the ice sheet mass balance, it does need to be noted that ice shelf melt has no direct effect on sea level since the ice is already floating. Furthermore, floating ice eventually has to melt or calve, so the realization melt is important does not necessarily mean any departure from a steady state ice shelf. Instead, the significance of the role of the oceans through melt could be important in a warming climate. If melt rates pick up due to ocean warming, this could have an indirect but significant affect on ice discharge, leading to sea level rise.

This new picture makes it timely to reconsider research priorities into the mass imbalance of the ice sheet. The largest observed changes so far are taking place in the Ross ice streams, the Pine Island and Thwaites glacier basins and the Antarctic Peninsula. In East Antarctica, a new importance is placed on research at or near the coast because the expected increase in accumulation will occur at low elevations, and because bottom-melting of floating ice fed by outlet glaciers has a newly recognised importance. A detailed field investigation of these regions may require a geographical redistribution of the present scientific resource. These ice sheet changes are observed mainly with satellite radar interferometry and radar altimetry. In situ measurements are required to reduce geophysical uncertainties arising, for example, from the poor state of velocity control, ice shelf tides or recent accumulation rate fluctuations. Spatial and temporal uncertainty in accumulation rate and ice thickness data sparsity are the biggest issues for estimating mass balance. The present portfolio of field observations and programmes may require modification to ensure the provision of these measurements. It

remains the case that we lack a clear consensus on how to treat the ice stream-ice shelf boundary in numerical models of deglaciation. Focused field programs may allow us to achieve a usefully satisfactory representation of this critical interface. Finally, the community should address the question of whether data and numerical models are being properly used to provide a clear prescription for an effective set of field observations.

To consider these questions, 32 scientists from 11 countries met on 10–14 June 2001 in Annapolis, MD, USA. Their objectives were: (1) to examine the processes involved in determining the state of the Antarctic mass balance by field, remote-sensing and modelling approaches; (2) to assess the certainties and uncertainties in each of these approaches; and (3) to evaluate methods of combining the three approaches.

There are two basic approaches to measuring the mass balance of the ice sheet. One is an integrated approach, i.e. a measurement of its mass changes without separately determining the input and output fluxes. The other is a component (or flux) approach in which the input and output fluxes are individually measured or estimated; this approach is particularly important when applied to individual drainage systems within the ice sheet. Both approaches are important for obtaining a measurement of mass change, but only the second approach moves towards an understanding of what is causing that change. The two approaches are largely independent and thus complement each other.

For the integrated approach, changes in the volume and mass of the ice sheets can be determined by satellite measurements of changes in ice-sheet surface elevation, after correction for vertical motion of the underlying bed and for variations in near-surface firn density. Vertical motion of the bedrock, which is largely due to adjustments of the lithosphere to changes in ice loading, is estimated from coupled models of the ice dynamics and lithosphere flexure (Le Meur and Huybrechts, 1996; Zweck, 1998). Measurements of changes in the Earth's gravity field, from observed perturbations on satellite orbits, can be related to changes in the mass of ice (averaged over a large area under the satellite) and also provide information on the bedrock motion correction (Bentley and Wahr, 1998).

Ice-sheet mass balance, ice volume, and surface elevation all change continually in response to daily and seasonal variations in snowfall, snow drift, temperature, and other meteorological and climate forcings. An understanding of the changes in surface elevation, concurrent with the changes in the climate forcings on seasonal to interannual time scales, is essential for predicting changes in mass balance. For this purpose, continuous observation of ice sheet elevations using satellite altimeters provides time series of surface elevation on seasonal time scales and spatial scales of about 40 km. Associated measurements of temperature, snow accumulation, wind and other parameters from networks of automatic weather station (AWS), results from General Circulation Models (GCM) and other atmospheric models, and from reanalysis products, provide information on the relevant climate forcings.

For the component or flux approach, a similar set of observations is required along with detailed information on ice thickness and ice velocity. Essentially, the change in ice thickness averaged over a volume is computed by differencing the flux into the volume (from ice advection, surface accumulation/ablation and basal accretion/melting) with the ice discharged from the volume. This approach suffers less from uncertainties in near surface processes (such as firn compaction) but is more susceptible to errors in ice thickness and velocity, which are still little known across large parts of the ice sheet.

2. Surface mass balance

The input component to ice sheet mass balance is the net accumulation of snow at the surface. Accumulation rates are most commonly obtained from ice core stratigraphy, but because of large gaps in the observation coverage, any estimate of the current mass input has a large error. Major gaps in our knowledge of processes that determine the magnitude of the temporal and spatial variability prevent us from making best use of advances in technology and model capability to produce a reliable estimate of current mass input, and prediction of its future trend. Improvement of climate and meteorological models requires an iterative process of field survey, model adjustment and verification.

Information about snow surface processes is essential not only for the input term of the mass balance but also for interpreting surface elevation change signals from altimeters and for improving climate and meteorological models.

What is the mean annual input to the Antarctic Ice Sheet and how is it distributed over drainage basins? In spite of significant improvement in spatial coverage of ice cores in recent years, large regions remain unsurveyed. A number of existing measurements must be re-analysed on the basis of improved understanding of redistribution processes. The potential for exploiting spaceborne techniques needs further validation (Bolzan and Jezek, 1999; Winebrenner et al., 2001), and new techniques like GPR profiling of firn stratigraphy, coupled with precise Global Positioning System (GPS) positioning and GPS ''coffee can'' accumulation measurements (Hamilton et al., 1998), need to be applied over wider regions. The International Trans-Antarctic Scientific Expedition (ITASE) (Mayewski and Goodwin, 1997) is an ideal venue for this type of work. Consistency analysis and synthesis of surface mass balance reconstructions from field activity, satellite information, meteorological analyses and climate models must be carried out for optimal spatial coverage and integration.

Time variability shorter than 1 year must be assessed at selected sites. Observations of temporal variability of snow accumulation, e.g. utilising stake farms (e.g. Mosley-Thompson et al., 1999) and AWS, are needed to improve atmospheric models and the interpretation of satellite altimetry. Observations and models on an interannual to centennial time scale (e.g. ice/firn cores and meteorological time series) are important to detect current and predict future changes.

Surface mass balance is known to vary substantially in space. To interpolate data for satellite ground truthing, it is important to understand local (<10 km) redistribution processes and to determine how representative point observations are. A knowledge of precipitation distribution and redistribution processes at scales >10 km is required to build the high-resolution continental-scale surface mass balance map necessary for atmospheric and ice sheet modelling.

Post-depositional processes resulting from the interaction between the surface layers of atmosphere and snow affect the distribution of accumulation and

the satellite signal. Redistribution transport, sublimation, densification and metamorphism of snow require specific field experiments and modelling.

Ultimately, mass balance and sea level change in response to climate change needs to be predicted. Climate models are required to predict surface mass balance change, but these models must be physically based using field measurements.

2.1. Recommendations

Continent-wide surface accumulation values at spatial (10 km) and multi-annual (5–20 years) resolution are required through a variety of different approaches (e.g. traverse and airborne GPR and GPS "coffee can" surveys, firn cores, satellite-based remote sensing, numerical simulation, re-analysis of previous snow accumulation data). Data on the trend of snow accumulation at centennial scales (200–500 years) at selected sites are required.

To characterise spatial and temporal variability and covariance, comparisons are required over local (<10 km) and seasonal (<1 year) scales at selected sites, of precipitation estimates from atmospheric models, field measurements (AWS+stake farms) and remote sensing observations.

Field observations and modelling of atmosphere/cryosphere processes are required to estimate snow redistribution and export to the ocean, sublimation, densification, and metamorphism processes.

3. Mass output (ice dynamics, fluxes, melt/freeze, calving)

New satellite remote sensing data have led to major advances in our current knowledge of grounding zone definition (e.g. Rignot, 2002), ice flow dynamics (e.g. Young and Hyland, 2002), coastal fluxes, and inferred ice shelf bottom-melting. From these data, we have learned that major changes are taking place at specific locations in the Antarctic on much shorter time scales than previously anticipated.

3.1. Recent advances

There have been several major advances in recent years towards more accurate estimation of

ice sheet mass output. These have included continental-scale mapping of balance velocity and surface and bedrock topography (Budd and Warner, 1996; Liu et al., 1999; Lythe and Vaughan, 2001) and observations and estimates of ice velocity (e.g. Fig. 1) on large outlet glaciers and Siple Coast ice
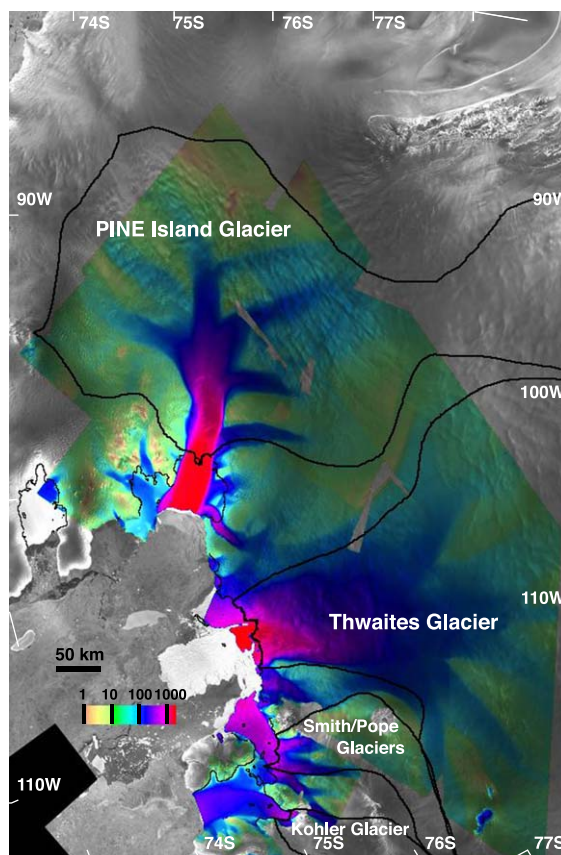

Fig. 1. Velocity of outlet glaciers and ice streams discharging into Pine Island Bay, in the Amundsen Sea Sector of West Antarctica derived from ERS-1/2 radar interferometry, from work by E. Rignot. Velocity is shown on a logarithmic scale between 0 and 3500 m year^{-1}, overlaying the Radarsat RAMP mosaic. Grounding line positions, where the ice detaches from its bed and becomes afloat in the ocean, are shown in thin black lines. Drainage basin boundaries of Pine Island, Thwaites, Smith and Kohler Glaciers are shown in thick black lines. In this region, radar interferometry shows a systematic retreat of the glacier grounding lines; ice discharge is accelerating; the glacier mass budgets are negative; and radar altimetry shows a systematic thinning of the glaciers and ice shelves.

streams (Joughin et al., 1999; Bamber et al., 2000; Rignot, 2002). In addition, there have been some remarkable events highlighting the potential of the Antarctic Ice Sheet for rapid change. These include ice-shelf disintegration and outlet glacier acceleration in the Antarctic Peninsula (Rott et al., 2002) as well as flow acceleration of Pine Island Glacier, flow widening of Thwaites Glacier and resultant strongly negative mass balance of the Pine Island and Thwaites glacier basins (Wingham et al., 1998; Zwally et al., 2002a) and large diurnal swings in velocity in some ice streams (Anandakrishnan et al., 2003; Bindschadler et al., 2003).

Earlier estimates of large positive mass balance for Pine Island Glacier and the Lambert Glacier Basin (Allison, 1979) have not been confirmed by recent studies, either because data have improved or because the mass balance has changed over time, and current estimates of the mass balance of the whole Antarctic Ice Sheet are nearer to zero or perhaps even negative. Likewise, in some areas where negative imbalances were previously found (Shabtaie and Bentley, 1987), new results suggest thickening instead (Joughin and Tulaczyk, 2002). Substantial basal melting inferred near the grounding zones of some glacier systems, e.g. Pine Island and Lambert glacier basins, dominates the mass budget of the ice shelves and a new emphasis is required to study this phenomenon.

3.2. The future

Data to become available in the near future include: (1) Interferometric Synthetic Aperture Radar (InSAR) mapping of ice velocity with Radarsat AMM-2, and ERS-1/2 as far south as $80°$; (2) observations of ice-shelf mass balance from ICESat and better definition of ice-shelf topography to improve grounding-line flux estimates; and (3) improved understanding of ice dynamics from numerical models that incorporate unprecedented, detailed remote sensing data.

3.3. Major gaps

Data collection required to fill crucial gaps in our knowledge includes: (1) ice thickness across the whole Antarctic Ice Sheet, and particularly along the coast and over specific basins, including the major outlet glacier basins; (2) continuation of InSAR missions beyond ERS, Radarsat and EnviSAT to map ice velocity changes and fill in gaps in past InSAR coverage; (3) direct measurements of basal melt, and its spatial and temporal variability, underneath floating ice shelves; (4) collection of GPS velocity data and continued collection of ice velocities using feature tracking on visible satellite imagery for augmentation where InSAR is not viable due to lack of coverage or de-correlation; and (5) characterization of bed conditions, ice temperature, ice crystal orientation fabrics, etc. to constrain ice flow models.

3.3.1. Recommendations

Focused research is required on the large outlet glaciers draining West and East Antarctica and the Antarctic Peninsula, in particular the rapidly changing sectors of the Pine Island and Thwaites Glaciers, but also the David, Mertz, Totten, Lambert, Shirase and Jutulstraumen Glaciers. Specific requirements are for:

– Detailed measurements of ice thickness near the grounding zones, which have now been identified with InSAR.
– Observations of ice-shelf bottom-melting, especially in the proximity of grounding zones, and investigations of whether basal melting may be changing with time in response to changes in ocean conditions.
– Measurements, using InSAR and ICESat, of changes in ice velocity and elevation of the glacier surface.

4. Surface elevation change ($\partial h/\partial t$)

4.1. Observation of surface elevation change

The best currently available time series of surface elevation change ($\partial h/\partial t$) for the Antarctic Ice Sheet (1991–2001) comes from ERS-1 and ERS-2 satellite radar altimetry. Future satellite radar (ENVISAT and CryoSat) and laser altimeter (GLAS/ICESat) missions will extend this time series for another decade. Increased spatial coverage of ICESat and CryoSat

(both due to extended latitudinal coverage and improved tracking/technology) will provide $\partial h/\partial t$ information in the regions where the ice surface is changing the most (fast flowing outlet glaciers and ice margins). Recent results (Wingham et al., 1998; Shepherd et al., 2002; Zwally et al., 2002a) from analysis of ERS-1 and ERS-2 altimeter heights at orbit crossovers show that the portion of the grounded ice sheet upstream of the Pine Island and Thwaites Glaciers has thinned by up to 30 cm year^{-1} over the past decade (Fig. 2).

Validation of satellite altimeter observations requires complementary datasets to be collected in the field. For example, in order to correctly interpret the $\partial h/\partial t$ time series, we need to understand the signal contributed by snow accumulation, firn compaction and post-glacial rebound (PGR) of the underlying lithosphere.

Knowledge of snow accumulation and its spatial and temporal covariance can only be achieved through well-planned field surveys in coordination with satellite altimeter results. Improvements in the permanent GPS network on ice and bedrock surrounding the continent are required to improve estimates of compaction rate and the current PGR signal. To improve models of snow accumulation, there is a need for an expanded network of AWS-based sonic ranging measurements (short time-scales) and permanent GPS "coffee can" sites (Hamilton et al., 1998) (long time-scales). Firn compaction models (e.g. Li and Zwally, 2002) require improved monthly surface temperature maps.

The Earth's response to past and present ice mass changes includes three-dimensional crustal motion and changes to sea level, the gravitational field, and mantle and lithospheric stress. In turn, ice sheet growth and stability is affected by the Earth's response because crustal subsidence affects the location of the grounding line and the height of the ice sheet. Gravity data from the GRACE mission may be combined with GLAS data to partially remove the PGR contribution (Wahr et al., 2000). PGR models will be improved through GPS point calibrations on bedrock. Over the ice shelves, most of the high-frequency $\partial h/\partial t$ signal comes from ocean tides. Linking of this high-frequency variability into the frequency range sampled by the satellites can inhibit the detection of true ice shelf changes on seasonal to multi-year time scales. Therefore, to properly interpret satellite data collected over ice shelves, the high-frequency height variability (primarily tides) should be removed. Tide models in the ice shelf regions need to be improved before this can be done to the required accuracy (Padman et al., 2002).

4.2. Modelling of surface elevation change

The existing time series of $\partial h/\partial t$ from satellite altimetry provides information that can be assimilated into present ice sheet models. None of the current ice sheet models predicted the large changes observed in the Pine Island and Thwaites glacier basins or in the Siple Coast area over the past 10 years. The new time series provides an interesting opportunity to investigate why current models do not capture these changes, and highlights the need for large-scale and regional models to help understand causes of observed changes. Improved parameterisation of ice stream flow and ice-shelf interactions needs to be included in those models.

4.2.1. Recommendations

There is a requirement for the separation of short-term (<30 years) vs. long-term (>30 years) surface elevation change; this requires knowledge of firn compaction processes and the accumulation rate, or failing this, a statistical characterisation of its covariance function over the last 10 years and a knowledge of how that relates to the long-term trend.

An understanding is required through field experiments, particularly in West Antarctica, of how much of the $\partial h/\partial t$ signal measured by satellite altimeters is related to the compaction of the firn, for annual and longer time scales.

Determination is required, by a continuously occupied field experiment in central East Antarctica, of the extent to which the $\partial h/\partial t$ signal measured by radar altimeters is affected by interactions of the microwave pulse with variations in the near surface layers.

A very long-term site is required in a region of ongoing surface elevation change, where firn conditions are reasonably typical, and where continuous measurements will allow the temporal variation to be examined on seasonal and longer time scales.
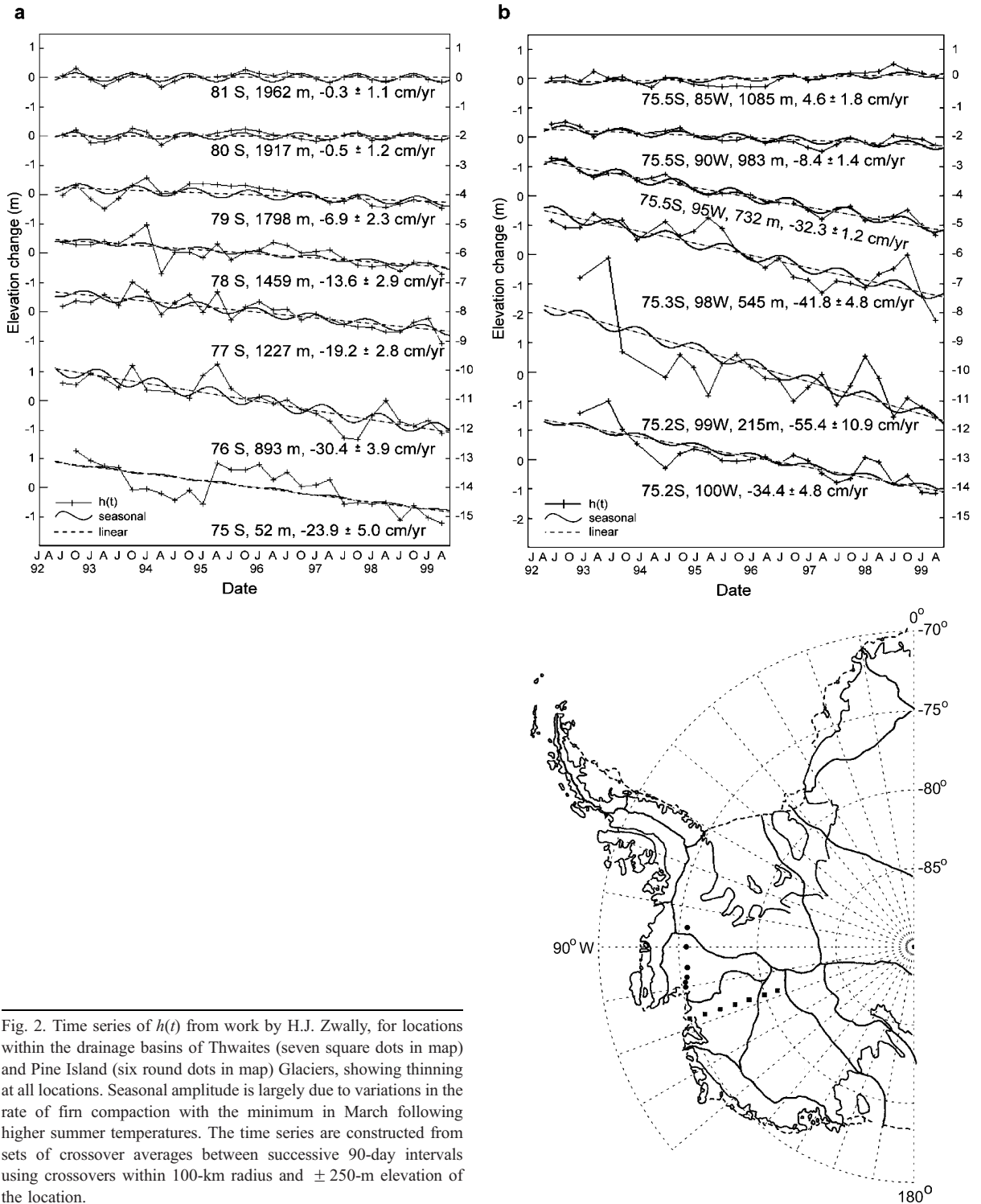
Fig. 2. Time series of *h*(*t*) from work by H.J. Zwally, for locations within the drainage basins of Thwaites (seven square dots in map) and Pine Island (six round dots in map) Glaciers, showing thinning at all locations. Seasonal amplitude is largely due to variations in the rate of firn compaction with the minimum in March following higher summer temperatures. The time series are constructed from sets of crossover averages between successive 90-day intervals using crossovers within 100-km radius and ± 250-m elevation of the location.

5. Deglaciation

An accurate understanding of the deglaciation of Antarctica since the Last Glacial Maximum (LGM) is important for a variety of reasons. While some computer modelling suggests the ice sheet has largely responded to changes in sea-level and global climate associated with the transition to the present Holocene climate from the LGM, even the sign of present ice volume change remains a matter for debate.

The ice sheet retreat in the Ross Embayment was almost entirely independent of sea level rise beforehand (Conway et al., 1999), and Parizek et al. (2002, 2003) have used models of West Antarctic ice streams to argue that it was the penetration of surface warmth to the beds increasing melt water lubrication that triggered the retreat.

The ice sheet geometry is sensitive to the slowly evolving temperatures deep within the ice sheet, to poorly characterised rates of isostatic motion of the underlying bedrock and to the deformation rate of the ice. The geological record gives indications of the past extent and thickness of the ice sheet, while glaciological studies can provide evidence of past ice accumulation rates and present ice motion. Some observations (particularly from West Antarctica) are claimed to reflect a continuing process of deglaciation, independent of any recent climate change, leading to suggestions that the decay of the West Antarctic Ice Sheet would occur under "present" conditions over the next 10,000 years (Bindschadler, 1998). Conversely, some marked localised imbalances have been observed in the Pine Island/Thwaites glacier region in West Antarctica, which appear unlikely to be persistent features of a gradual steady deglaciation process. It remains unresolved whether they are responses to long-term natural climate variability, responses to changing climate, or simply transient encounters with local threshold effects in the deglaciation process.

It is important that more evidence is gathered to describe the time sequence of grounding line retreat and ice sheet thinning associated with the changes in the marine based ice sheet since the LGM. As each cycle in the sequence of recent ice ages has been different, evidence from earlier stages would also help discriminate between the various influences on the Antarctic mass budget. The roles of sea-level change and changes in snow accumulation need to be resolved.

Improved numerical models need to be developed, synthesizing ice accumulation patterns, the dynamics of the ice sheet/ice shelf system, bedrock isostatic motion and the ice–ocean interaction. Models that can successfully explain the history of Antarctica through the Ice Age cycle, and particularly its recent deglaciation history, hold the best prospect of more reliable projections of the future geometry and mass budget response of the system. Before we can test models to see if they can predict deglaciation, we need a good history of the deglaciation. The recent realization that the ocean can produce substantial melting near the deep grounding lines of some major outlet glaciers and ice shelves has highlighted the possible role of interaction with ocean climate.

The investigation of Antarctic deglaciation recorded in palaeoclimate records over millennial time scales, for example from the LGM through the Holocene to the present, should illuminate the relative influences of sea level change (from Northern Hemisphere deglaciation), Antarctic climate change (the ice accumulation and temperature regime) and the Southern Ocean (ice shelf–ocean interaction).

On the time scale of centuries, the refinement of the evolving Antarctic mass budget should uncover the background trend in Antarctic contributions to observed historical sea-level change.

5.1. Observational basis

The observational basis of ice sheet change is constituted of geological and geophysical observations of former ice sheet extent, isostatic recovery, and radio-echo sounding information of ice sheet isochrone layer architecture.

The glaciation signal comprises glacial sediments and glacially moulded landforms which typically do not contain organic deposits and cannot be dated directly, although exposure age dating using cosmogenic isotopes (e.g. Stone et al., 2003; Ackert et al., 1999) is providing important constraints on ice sheet history. Material overlying glacial deposits contains organic deposits that can yield radiocarbon dates and thus minimum ages of deglaciation. Generally, these deposits are found around or below current sea level. A few exposure ages for high elevation surfaces are available. A very few raised beach sequences reveal the relative sea-level signal associated with deglaciation in Antarctica.

These data are being assembled into a database in a current British Antarctic Survey project. Data from about 150 studies have been incorporated into a form suitable for modellers, with a particular focus on error estimates useable in data assimilation schemes. Problems using this data base to constrain ice sheet models arise from the very uneven spatial coverage, and the accuracy of the radiocarbon dates. Many dates are subaerial and from the Transantarctic Mountains, while all dates are affected by poorly understood carbon reservoir effects.

Other sources of information about the palaeogeometry and dynamics of ice sheets lie in the isochrone layer architecture, ice core records and observations of current isostatic response. Isostatic response is being addressed by GRACE while layer architecture does not have a uniform or sufficiently dense coverage. GPS is extremely important in determining isostatic crustal motion. It augments GRACE by providing some 'ground-truthing' and is entirely independent of it.

5.2.1. Recommendations

Additional dated retreat sequences are required from the continental shelf, including sub-ice shelf regions, especially in areas exhibiting current rapid change. To improve dating, more research is needed on the spatial and temporal variations of the radiocarbon reservoir in Antarctica. Surface exposure studies will provide important information on ice sheet history in subaerial regions where organic deposits are scarce or lacking. Further systematic deployment of radio-echo sounding is encouraged to obtain ice sheet layer architecture for understanding ice sheet history and constraining models of the evolution of the Antarctic Ice Sheet.

Further collection of sea-level and crustal motion (primarily GPS) observations is encouraged, to better determine the Antarctic glacio-isostatic response. Glacio-isostatic modelling is needed to link the observations to ice sheet history and Earth rheology.

6. Ice sheet modelling

6.1. Model inter-comparison

How can we improve our understanding of why deglaciation occurred in Antarctica? Inter-compari-

sons, in particular under the EISMINT banner (Huybrechts et al., 1996; Payne et al., 2000), of ice sheet models have been carried out in recent years and there are now several models of marine ice sheets, but with no standardized method of treating grounding line retreat. The differences in formulation and performance need to be evaluated to understand physical mechanisms behind deglaciation. It is not clear that current models represent the stability of marine ice sheets properly, and there are fundamental methodological issues involved in using numerical techniques to define the stability of dynamical systems. Modelling provides the framework that uses the geological data to estimate the expected current deglaciation signal. Up to now ice sheet models have been driven by sea level change and mass balance change. Sea level changes are reasonably well known. Mass balance changes are inferred from ice core records. Individual ice cores provide a proxy for temperature deviations. Assuming accumulation to be limited by saturation vapour pressure, these temperature deviations can yield proportionate changes in the accumulation rates. However, we know that the distribution of accumulation changes is far more complicated. Recently developed higher resolution mesoscale atmospheric models can contribute to our understanding of why deglaciation occurred. Both sea level change and mass balance change are important and both produce a set of responses that operate over a variety of time scales, sometimes cancelling each other, sometimes not.

6.1.1. Recommendation

Inter-comparisons are required of existing models of Antarctica that focus on grounding line retreat. Investigations of stability issues are required by analytical techniques and by use of models with simplified boundary conditions. Development is required of models that can assimilate geological and dynamical data; and investigations are required that couple ice sheet models with high-resolution atmosphere and ocean models.

6.2. Physical basis of models

What should be done to improve the physical basis of ice sheet models?

Until recently ice sheet numerical models have assumed isotropic crystal structure, utilising a creep power law with exponent 3 (Glen, 1958) to relate stress to strain rate. It is now clear that ice flow is highly dependent on crystal structure. Laboratory and field studies show crystal anisotropy can modify flow rates by a factor of up to 10 depending on the relationship between the stress pattern within the ice and the crystal orientation pattern (e.g. Budd and Jacka, 1989; Warner et al., 1999). Significant improvements have been achieved in the accuracy of ice flow models to simulate deformation (as measured in boreholes), by incorporation of anisotropy into the models (e.g. Wang et al., 2002).

Model studies suggest that the present-day imbalance is very sensitive to the choice of bed parameters. This implies that it is crucial to validate bed properties by field measurements. It is also known that the West and East Antarctic plates have different properties. Therefore, work is needed to improve the geodynamical properties of the ice sheet models. By doing this, we will discriminate whether the observed change in West Antarctica is a result of the deglaciation or due to short term processes, e.g. tidal affects on basal seismicity (Anandakrishnan and Alley, 1997; Anandakrishnan et al., 2003).

It is most unlikely that the Antarctic Ice Sheet has reached thermal equilibrium following the warming at the end of the LGM. This means the viscosity and areas where sliding occurs are changing. A few temperature fields are available from boreholes already drilled. Radar reflections can show which areas are warm-based, while the possibility is emerging of using hot water drilling and drilling technologies originally developed for oil exploration (Tulaczyk et al., 2003).

6.2.1. Recommendation

To substantially improve the physical basis of models of past and future deglaciation, there is a requirement for: (1) incorporation into the models of the effects of ice crystal anisotropy; (2) validation of geodynamical parameters; (3) mapping of the basal interface character (warm/cold; till/rock; geothermal heat flux); (4) use of natural high-frequency forcing (e.g. tidal forcing of water pressure and ice motion) to test hypotheses about basal processes; (5) measurement of internal temperature fields using drill holes or

remote probes; and (6) continuing efforts in laboratory ice mechanics and geotechnical experiments at temperatures close to pressure melting point, and for ice containing substantial impurities.

7. Special areas

Satellite remote sensing and the much-improved logistic support provided by the national Antarctic operators have allowed investigators to access much of the Antarctic continent during the last decade and this coverage should continue in the future to provide direct support of mass balance calculations. There are, however, several areas that for different reasons require increased attention.

7.1. Amundsen sea embayment

Altimetric measurements from the ERS satellites have highlighted only one region of the continental ice sheet of Antarctica that appears to be significantly out of balance. This part of the ice sheet, flowing into the Amundsen Sea embayment, includes Pine Island and Thwaites glaciers, both of which are thinning. There are, however, only a few field measurements from this area. The thickness of the ice sheet is poorly known. There is only a rough understanding of the rate of surface accumulation, and there are no measurements in this area of possible recent changes in accumulation rate. Without substantially improved measurements, we cannot predict the future of the observed thinning because we do not understand the processes that are driving it. In addition to continued monitoring from space, field observations in this area are required to improve the basis for ice-sheet modelling, specifically so that we can unravel the cause and likely future of the present change. The distribution of these studies should be specifically designed to validate the results of remote sensing studies and to provide an optimal basis for predictive ice sheet modelling.

7.1.1. Recommendation

A programme of field work is required in the part of the West Antarctic Ice Sheet draining into the Amundsen Sea. Over the ice sheet, this fieldwork must include measurement of fluctuations in recent

accumulation rates, measurement of ice thickness and a characterisation of sub-glacial conditions and ice flow velocities. In addition, detailed observations of ocean circulation and physical characteristics beneath the floating glacier tongues are needed.

7.2. Antarctic Peninsula

In contrast to the continuous and relatively homogeneous ice sheet that covers the rest of the continent, the Antarctic Peninsula ice sheet comprises ice caps, mountain glaciers and ice shelves in a complex system in which each component, or the total, may respond to evolving climate. Climatically, the Antarctic Peninsula is also distinct from the rest of Antarctica. There, surface air temperatures have risen over the past 50 years more rapidly than most other areas of Antarctica, and perhaps more rapidly than anywhere else in the Southern Hemisphere. The Larsen A and B ice shelves have collapsed (Skvarca, 1993, 1994; Rott et al., 1996, 1998, 2002; Skvarca et al., 1999), and many studies show that other glaciers and ice shelves in this region are rapidly retreating. There is evidence from some locations that the rate of retreat and inland flow has accelerated dramatically in the last decade (De Angelis and Skvarca, 2003).

Predicting the present and future mass balance of the Antarctic Peninsula ice sheet as a direct contribution to global sea level change requires a specific programme. To account for the contribution of the Antarctic Peninsula ice sheet to sea level, we require a continued programme of satellite based and field measurements.

7.2.1. Recommendation

Field monitoring is required of climate, ice caps, glaciers and ice shelves, and an investigation is especially required of the grounded glaciers and ice caps affected by loss of ice shelves in the Antarctic Peninsula. We recommend continued monitoring by remote sensing and the initiation of modelling studies at a variety of spatial scales.

7.3. Coastal Antarctica

The present generation of satellite altimeters has proven to be largely unsuccessful in measuring ice sheet elevation change around the coastal annulus of Antarctica where surface slopes are relatively steep.

For this reason, the present mass balance in these coastal areas is not well known. In addition, since air temperatures are higher and accumulation rates in the coastal areas are substantially greater than in the interior, climate change has the potential to alter mass balance in the coastal areas more rapidly than inland. While ice cores from the interior of Antarctica show the purest climate signals, ice cores from the margin of the continent can better provide a record of the progress and process of deglaciation. There are currently, however, only a few ice cores from coastal sites that record Holocene and recent climate change, or recent retreat of the ice sheet. Climate and accumulation histories from coastal sites are essential to constrain numerical modelling of deglaciation and for direct estimation of the likelihood that local change in climate will cause rapid basin-scale change in ice sheet mass balance.

7.3.1. Recommendation

Ice cores covering late-glacial to decadal timescales are required from Antarctica, particularly from coastal sites. These will provide Holocene histories of accumulation rates, constraints on deglaciation, and an envelope for future variability of accumulation and dynamic changes in these sensitive areas.

8. Conclusions

The aim of SCAR ISMASS is to develop a revitalized approach towards the assessment of methods and uncertainties in the estimation of Antarctic Ice Sheet mass balance. This new approach is in response to the "Summary of the SCAR Global Change Program Achievements 1995–1999 and Recommendations for the Future" (Goodwin, 1999 unpublished report to SCAR Executive), and to the recommendations of the World Climate Research Programme (WCRP) Climate and Cryosphere (CLIC) Project (Dick et al., 2000; Allison et al., 2001).

The primary issue regarding the role of the cryosphere on sea level is the past, present and future contribution of land ice to sea level change, yet the largest unknown in the determination of future sea level change is due to uncertainty in the response of the large ice sheets, particularly the Antarctic Ice Sheet. In order to understand past sea level change and to predict future change, it is essential to measure and explain the

current state of balance of glaciers and ice sheets, and especially to resolve the large uncertainties in the mass budgets of the Greenland and Antarctic ice sheets. Even though the current state of balance of ice sheets is not well known, the sensitivity of the volume of ice stored in glaciers and ice sheets to climate change can and must be studied.

The emphasis should be on a co-ordinated program including collection of critical new data, and modelling. For the data collection, many new remote sensing tools are becoming available for ice sheet studies, but in-situ observations are also required for validation. Field process studies are also needed to improve the ice-sheet models and the high latitude performance of atmospheric models.

Estimates of the modern state of mass balance will be improved by internationally planned fieldwork, advances in satellite altimetry measurements of ice sheet surface changes, and advances in ice-sheet and atmospheric modelling.

Despite national and multinational research activity aimed at measuring the mass balance of Antarctica, and despite some excellent steps to close the gaps, (e.g. the US WAIS project), there remain weaknesses in data synthesis between the field glaciology, remote sensing and modelling communities. A priority for ISMASS therefore is to develop a framework for maximizing the synthesis of field, remotely sensed and modelled information, and to develop innovative approaches to the problem. This requires input from all interested researchers and organizations, along with awareness by proponents of the different techniques, to acknowledge both the strengths and weaknesses in their techniques.

8.1. Concluding recommendation

We recommend increased synthesis of data and communication between the field, satellite observation and modelling groups.

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