A REVIEW OF THE CAUSES AND MECHANISMS THAT MAY LEAD TO GLOBALLY SIGNIFICANT CHANGE IN THE ANTARCTIC ICE SHEET

A preparatory review prepared by D.G Vaughan, NERC British Antarctic Survey in conjunction with Det Norske Veritas under contract to the UK Dept. of Environment Transport and the Regions.

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SUMMARY

An idea that has come to pervade environmental science and sections of the popular media over the past two decades, is that the West Antarctic ice sheet (WAIS, Figure 1) is unstable and its collapse may lead to a substantial (perhaps 6 m) rise in global eustatic sea level within human time-scales. Many glaciologists now believe that complete collapse of WAIS is unlikely on these time-scales (Bentley, 1998; Oppenheimer, 1998) and that only a small fractional change in the volume of WAIS is likely. Such a change would, however, augment sea level rise from the wastage of mountain glaciers and thermal expansion of the oceans and changes in groundwater. Our current "best-estimates" for sea level rise over the coming century are an order of magnitude lower than that which would result from complete collapse of WAIS and are based on individual estimates of each of the possible contributing factors. The contribution of the Antarctic Ice Sheet is the greatest uncertainty in our predictions. Concern, however, continues to increase as we now understand that sea level rise of just a few tens of centimetres would have substantial social and financial implications. In addition, the simple hypothesis of WAIS instability has been joined in the literature by other hypotheses of ice-sheet change, these have their root-cause in climate change and internal ice-sheet instabilities. This review aims to give an overview of the present state of the Antarctic Ice Sheet and a summary of the hypotheses that have been proposed in the literature that might lead to globally significant change in the Antarctic Ice Sheet. It is intended that this study will underpin panel discussions that will lead to an assessment of the uncertainty and risk of globally significant change in the Antarctic Ice Sheet.

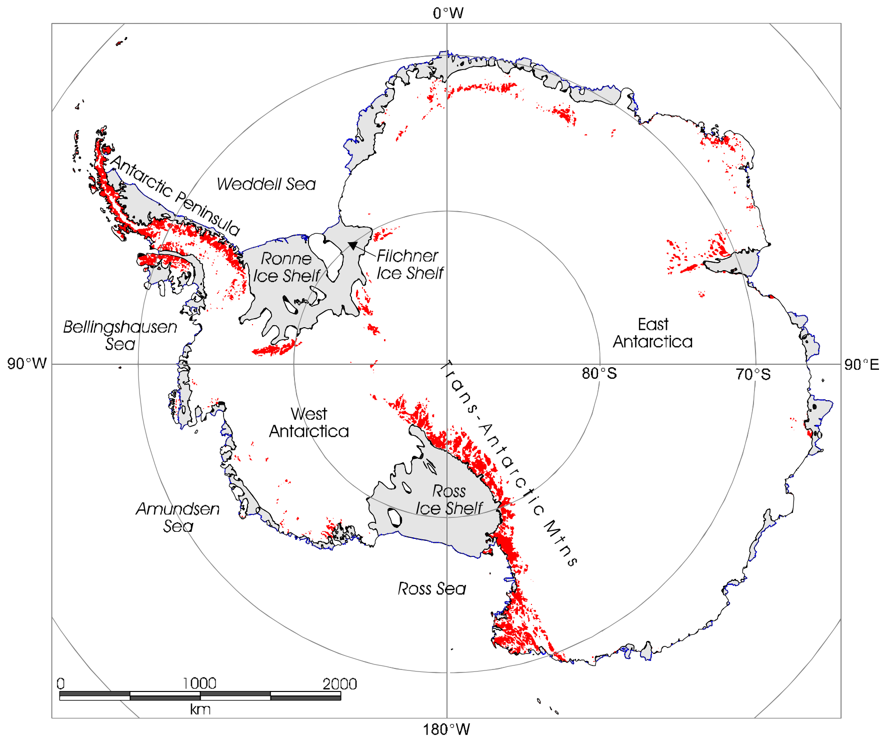

Figure 1 – The Antarctic continent. The shaded areas show where rock protrudes through the ice sheet.

CONTENTS

INTRODUCTION TO THE APPROACH

There have been many studies which, at least in passing, have discussed the likely evolution of the Antarctic Ice Sheet over the coming centuries. Most authors, however, being specialists, have concentrated on one particular cause or mechanism of change, for which that author appears to be either a proponent or a detractor. I do not mean to reproach previous authors, only to point out that individual papers tend to focus on particular mechanisms without consideration of the wider picture. For example; Titus and Narayanan (Titus & Narayanan, 1995; Titus & Narayanan, 1996) considered the problem of sea level rise but concentrated only on the likelihood of raised ocean temperatures causing collapse of the West Antarctic Ice Sheet (See Appendix 1 – Summary of Titus and Narayanan, 1995/6) but they did not consider the other forces on the ice sheet, such as internal instabilities or long-term readjustments continuing since the end of the last glacial period. Indeed, few reviews of the entire picture exist. To a non-specialist - here I include, journalists, governments, and scientists from other disciplines - the literature must appear to be compartmentalized, and to lack any clear conclusion about the likely fate of the Antarctic Ice Sheet.

In this review I attempt to consider all the likely routes and mechanisms discussed in the scientific literature, whereby globally significant change might take place in the Antarctic Ice Sheet. I consider these in parallel and attempt to prepare the ground for an assessment of their relative likelihood and our scientific uncertainty of each occurring on human time-scales. Little new analysis has been completed within the course of this review but I hope that the it will be of value in clearing the waters and providing a framework for panel discussions that will work towards an assessment our present uncertainty and the risk of globally significant change occurring in the Antarctic Ice Sheet. (For further background on the approach see; Appendix 2 – A Scientific approach to Risk Assessment, Appendix 3 – Probability Vs. Uncertainty).

Part One – Review of Understanding

1. A SHORT PRIMER ON THE DYNAMICS OF THE ANTARCTIC ICE SHEET

The following section is intended as a brief introduction to the important components and mechanisms of the Antarctic Ice Sheet. For a more complete description I refer the reader to more comprehensive reviews (Doake, 1987).

1.1 The ice sheet

The Antarctic Ice Sheet is the most massive single mass of ice on Earth. It covers almost 14 million km^2 and contains 30 million km^3 of ice. Around 90% of the fresh water on the Earth's surface is held in the ice sheet, an amount equivalent to around 70 m of water in the world's oceans. In East Antarctica the ice sheet rests on a major land mass, but in West Antarctica the bed is in places more than 2500 m below sea level. It would be seabed if the ice sheet were not there.

Even in summer Antarctic temperatures are below 0EC and so frost and snow crystals that gather on the surface of the ice sheet do not melt but accumulate year-by-year. As these crystals are buried the weight of the crystals above presses them together. Eventually, they are transformed into dense and impermeable *glacial ice* (See Appendix 4 – Glossary).

Glacial ice seems solid but under the tremendous pressures it experiences in the ice sheet, it flows like a viscous liquid. This means that the ice sheet does not continue to get thicker as new snow falls but, under the action of gravity, flows over and around obstacles toward the sea. The ice sheet acts like a conveyor belt, taking ice from the atmosphere and delivering it back to the sea. Whether the mass of ice entering balances the amount leaving is the subject of considerable research and has a direct effect on world sea level.

1.2 The ice streams

Although the surface is cold, the base of the ice sheet is generally warmer, in places it melts and the melt-water lubricates the ice sheet so that it flows more rapidly. This process produces fast-flowing channels in the ice sheet - these are *ice streams* (see Appendix 5 – Notes on nomenclature).

Although they account for only 10 per cent of the volume of the ice sheet, ice streams are sizeable features, up to 50 km wide, 2000 m thick and hundreds of km long. Some flow at speeds of over 1000 m per year and most of the ice leaving the ice sheet passes through them. Ice Streams are the a key component in the dynamics of the ice sheet and thought by many to be the "bottleneck" which controls the output from the ice sheet.

Ice streams generally form where water is present to lubricate the flow, but other factors also control their velocity, in particular whether the ice stream rests on hard rock or soft, deformable sediments. At the edges of ice stream deformation can cause ice to recrystallise making it softer and concentrating the deformation into narrow bands or *shear margins*. *Crevasses*, cracks in the ice, result from rapid deformation and are common in shear margins.

1.3 The ice shelves

Ice is less dense than water and as it nears the coast resting on a bed below sea level, there comes a point where it begins to float – this is the *grounding line* (Figure 2). Beyond the grounding line, ice floats in hydrostatic equilibrium and either it stays attached to the ice sheet as an *ice shelf*, or breaks away as an *iceberg*. Being afloat, ice shelves experience no friction under them, so they tend to flow even more rapidly than ice streams, up to 3 km per year. Ice shelves fringe much of Antarctica. Ross and Ronne-Filchner ice shelves each have an area greater than the British Isles.

Across the base of ice shelves seawater and ice come into contact. Where this seawater is warm enough, the ice shelf will melt, adding cold fresh water to the sea. This diluted seawater eventually helps to form an oceanographic water mass called *Antarctic Bottom Water* (AABW) which is present in many of the deepest parts of the ocean.

Eventually ice breaks off the ice shelves to form icebergs that melt back into the ocean along their drift-tracks.

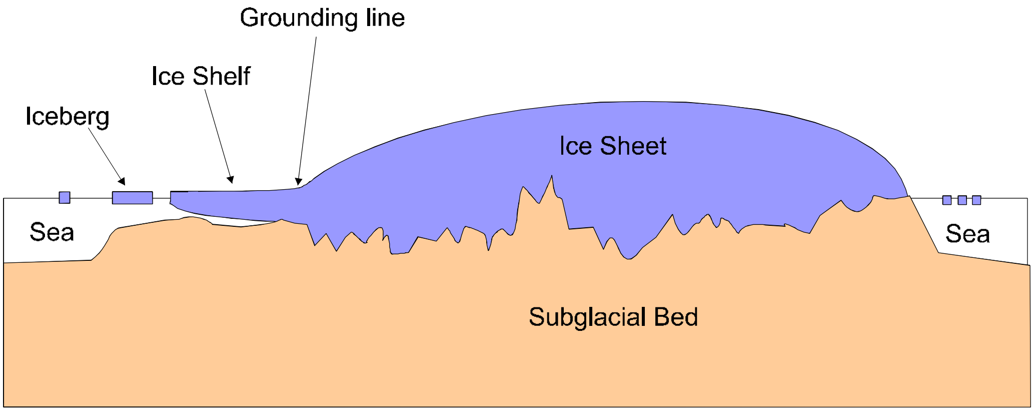

Figure 2. A schematic diagram of the Antarctic Ice Sheet. Note the parabolic profile of the ice sheet which provides the driving force that keeps the ice moving from the interior towards the grounding line.

1.4 Ice-drainage basin dynamics

The Antarctic Ice Sheet can be considered as a system that incorporate distinct ice-drainage basins, each with a different dynamic character and with some potential to alter in isolation from its neighbours. Many ice-drainage basins are associated with a particular glacier, while some do not seem to have a well-developed glacier system at all. Figure 3 shows a delineation of around 70 of the major ice-drainage basins in Antarctica. I have used a 5-km resolution ERS-1-derived digital elevation model (DEM) (Bamber & Bindschadler, 1997) to delineate the major ice-drainage basins in Antarctica using methods that were described in detail by (Vaughan *et al.*, 1999). In summary; I identified segments of grounding line where identifiable glaciers go afloat, then mapped the basins that feed these sections of grounding line by tracing the line of steepest ascent inland to the ice divide. This procedure assumes that ice flow is parallel to the surface slope, which is reasonable only over grounded ice and so ice shelves were excluded from the analysis.

Using an equal area projection I measured the area of each basin together with a grid representing the mean annual surface balance over Antarctica (Vaughan *et al.*, 1999), I have estimated the mass of snow accumulating in each ice-drainage basin (Table 3.). This is equivalent to the mass of ice that must leave the basin for it to be maintained in its present state – this is often termed the balance flux (McIntyre, 1987; McIntyre, 1987).

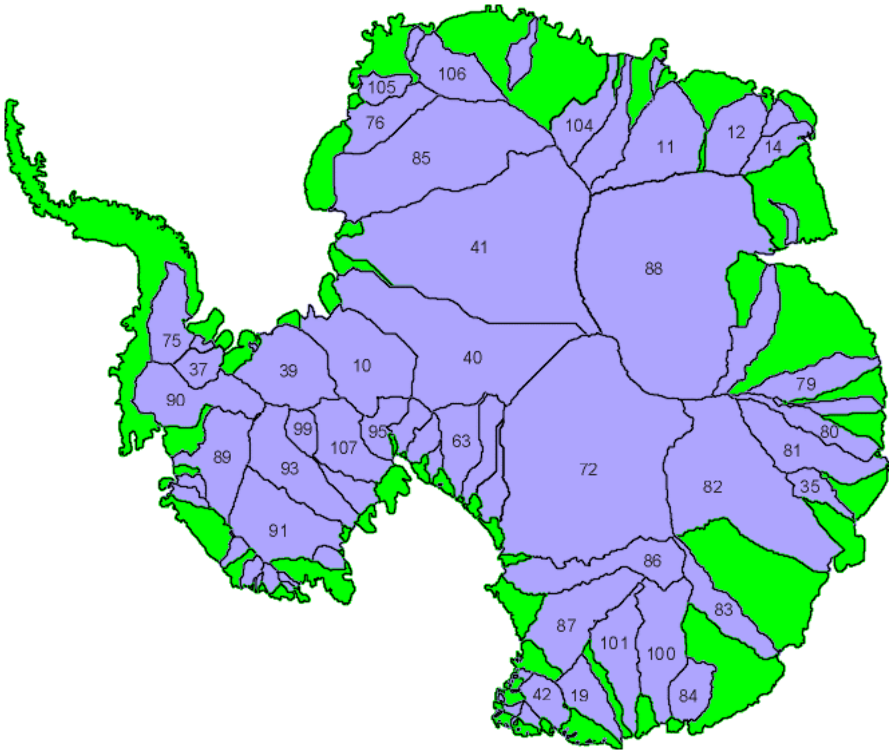

Figure 3 – A delineation of ice-drainage basin based on a DEM (for orientation and scale see Figure 1) Ice-drainage basins shaded purple are drained by major ice streams and outlet glaciers, while those shaded green are drained largely by slow-flowing ice sheet.. Ice-drainage basins are identified by their "Basin-id" numbers listed in Table 1.

As shown in Table 1. I find that in terms of balance flux, Totten Glacier, EAIS Antarctica is the most active in Antarctica, a balance flux of around 75 Gta^{-1}; and Pine Island Glacier is the most active in the WAIS. Outside Antarctica, the most active glacier is Jacobshavns Isbrae, Greenland which supports about half this flux (Bindschadler, 1984).

It has been an often-repeated maxim that around 90% of outflow from the Antarctic Ice Sheet passes through ice streams (McIntyre, 1985a). The provenance of the statement is unclear, but it perhaps was originated by Morgan et al. (Morgan *et al.*, 1982) who actually studied only a small section of East Antarctica. The analysis summarised in Table 3. allows us to update this figure. Assuming for the present that the term *ice streams* means ice streams and outlet glaciers (See Appendix 5) and that balance fluxes reflect outflow, I find that

- 85 largest ice streams drain 77% of the continental area and transport 57% of out-going ice
- 40 largest ice streams drain 73% of the continental area and transport 53% of out-going ice
- The "Top-10" ice streams drain 43% of the continental area and transport 27% of the out-going ice.

Glacier Name	Ice Sheet	Basin Id	Area of basin / 1000 km^3	Balance flux / Gt a^{-1}
Totten Gl.	EAIS	82	531	74.6
Pine Island Gl.	WAIS	90	176	69.7
Lambert Gl.	EAIS	88	1060	59.7
Byrd Gl.	EAIS	72	1101	56.6
Thwaites Gl.	WAIS	89	154	52.4
Recovery Gl.	EAIS	41	976	48.0
Evans Ice Stream	WAIS	75	108	41.8
Scott Gl. (Wilkes Land)	EAIS	81	165	41.6
Slessor/Bailey Gl.	EAIS	85	519	38.1
Support-Force Gl.	EAIS	40	548	35.0
Institute Ice Stream	WAIS	39	201	34.3
Moller / Foundation Ice Stream	WAIS	10	254	30.0
Denman Gl.	EAIS	80	79	28.0
Ice Stream E	WAIS	91	215	27.1
Ice Stream D	WAIS	93	194	27.0
Ninnis Gl.	EAIS	100	185	22.5
Frost Gl.	EAIS	83	107	21.6
Shirase Gl.	EAIS	11	217	18.9
Rutford Ice Stream	WAIS	37	49	18.7
Rayner/Thyer Gl.	EAIS	12	117	18.5
Phillipi Gl.	EAIS	79	105	18.0
Unnamed Gl. Feeding Cook IS	EAIS	101	140	17.8
Mertz Gl.	EAIS	84	70	17.5
Ice Stream B	WAIS	107	137	17.0
Stancomb-Wills Gl.	EAIS	76	107	16.9
David Gl.	EAIS	87	192	16.5
Jutulstramen	EAIS	106	124	16.3
Feeding Cook IS	EAIS	19	80	15.4
Underwood Gl.	EAIS	35	46	15.1
Skelton / Mullock Gl.	EAIS	86	183	14.4
Downer Gl. (etc)	EAIS	14	56	11.3
Ice Stream C	WAIS	99	86	10.5
Rennick Gl.	EAIS	42	56	9.2
Gl. feeding Princess Ragnild Coast	EAIS	104	102	9.1
WAIS Stream	EAIS	105	41	9.1
Ice Stream A	WAIS	95	61	8.6
Beardmore Gl.	EAIS	63	104	8.0

Table 1. Results of ice-drainage basin analysis (see Figure 6 for a key to the ice-drainage basins)

1.5 Sea ice

Beyond the ice shelves are the narrow continental shelf seas and beyond them the Southern Ocean. The sea itself can freeze and when it does, it forms a salty type of ice, *sea ice*. The area covered by sea ice varies with the seasons, around 3 million km^2 in February, around 20 million km^2 in October. Sea ice is not strictly part of the Antarctic Ice Sheet and so beyond the scope of this review but its effect, especially on climate, should not be underestimated. Although only a few metres thick, sea ice insulates the sea, preventing heat to escape to the air above, and limiting the amount of sunlight reaching the sea. Lack of light limits growth of phytoplankton in the sea water, though algae do sometimes multiply in the sea ice. The insulation effect reduces heat transfer between ocean and atmosphere, keeping the air cold and dry. Finally, when sea ice melts it cools both ocean and atmosphere. Controlling energy transfer, the extent and variability of sea ice also controls the climate of the Southern

Hemisphere. For more details I refer the reader to the body of literature which address changing sea ice coverage directly (Jacobs & Comiso, 1993; Jacobs & Comiso, 1997; Jacka & Budd, 1998).

2. GLOBAL IMPACTS OF CHANGE IN THE ANTARCTIC ICE SHEET

There are two primary impacts on the Earth system of alterations in the Antarctic Ice Sheet, change in global sea level and modifications in the global thermohaline circulation.

2.1 Sea-level rise

BAS is currently attempting new calculations of the volume of ice within the Antarctic Ice Sheet and the sea-level-rise potentials associated with each of the major ice drainage basins in Antarctica. For the present, however, it is sufficient to assume that the total loss of the Antarctic ice sheet would raise sea level by around 70 m and the loss of WAIS alone would raise sea level by around 6 m. Even individual ice-drainage basins could have a significant impact - the Pine Island Glacier ice-drainage basin, on its own, has the potential to raise global sea level by 0.6 m.

It is seductive to view the issue of sea level change as a subsidiary issue to that of anthropogenic climate change. Climate change and sea level rise may, however, occur together or separately. Some mechanisms; thermal expansion related to historic ocean warming, beach subsidence and displacement of ground water, surface-water and biomass, and perhaps changes in the Antarctic Ice Sheet will continue to alter apparent sea level, no matter whether climate change continues. To view sea level rise and climate change as inextricably linked is to disregard the potential, economic and human, costs that may result from sea level rise during next century, and which may be unrelated to the future rate of greenhouse gas emissions.

This point is highlighted by studies which seek to distinguish between the effects of sea level rise and of climate change. For example; Zhang et al., (1997) investigated hourly tide gauge data from Atlantic City, USA and Charleston, USA. Studying records of storm surges during this century they found, “large inter-annual and inter-decadal variability, but no discernible trend in storminess [which might have been related to climate change]. However, coastal development, sea level rise, and continuing beach erosion over the last century have exacerbated the flood damage from storms that would have caused relatively minor or inconsequential damage a century ago.”

2.1.1 Sea level rise…over the last 10 000 years

Global sea level has risen by around 120 m since the end of the last glacial period around 12 thousand years before the present (Fairbanks, 1989) a mean rate of 1 m per century (Figure 4). Although the recent rate of rise is twice the mean rate for the last 6 thousand years, it is 10 times slower than during two 1000-yr periods of rapid deglaciations in the Northern Hemisphere 12 and 9.5 thousand years ago. Clearly, when they are in full retreat ice sheets are a major cause of extremely rapid sea level rise.

Periods of deglaciation in the Northern Hemisphere are also thought to be the causes of the Heinrich Events, which left layers of ice-rafted debris across the seabed of the North Atlantic, when Armadas of icebergs floated out into the North Atlantic from the Laurentide Ice Sheet (Bond *et al.*, 1992; Bond & Lotti, 1995).

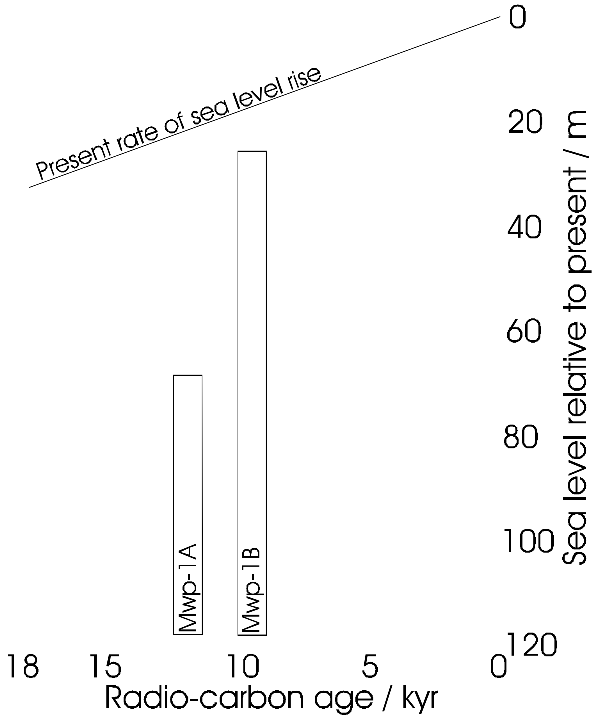

Figure 4. A reconstruction of sea level since the last glacial period derived from coral reef studies by Fairbanks (1989). The 20th Century rate of sea level rise is shown, together with the timing of melt-water pulses (1A and 1B) believed to coincide with rapid retreat of the Laurentide Ice Sheet.

2.1.2…during the previous interglacial

During the last interglacial it is thought that sea levels were 6 m higher than today and this has lead to speculation that during the previous interglacial WAIS collapsed entirely. Bindschadler et al., (Bindschadler & The SeaRISE Group, 1990) noted this saying “The assertion that the 6-meter rise in sea level during the last major interglacial was caused by the disappearance of the West Antarctic ice sheet has been repeated so often that many believe it has been established. It has not.” Unsurprisingly, this problem has become the focus of considerable research interest and while there claimed to be geologic evidence that WAIS has collapsed at some time in the last 600 000 yr (Scherer, 1991), this is disputed (Burckle, 1993).

Either way, the sea level record alone suggests that the process of deglaciation does not always end in the same ice-sheet configuration and our failure to understand the process of deglaciation and what brings it to a halt is a significant problem when it comes to predicting the future configuration of WAIS.

2.1.3… in the 20th Century

The measurement of contemporary sea level rise, a prerequisite to reliable predictions, is an extremely difficult exercise. It requires a co-ordinated global approach and so a global network of tide gauges provide the basis for the measurement, which has been well-reviewed as part of the IPCC’s second assessment of Climate Change (Warrick *et al.*, 1996). For prediction, however, no less important is a satisfactory attribution of the observed sea level rise to its contributing sources; as understanding how these sources are likely to change in future must form the basis for predictions. Table 2. shows Warrick et al.’s summary of contemporary sea level rise.

Component Contributions	Low	Middle	High
Thermal expansion of the oceans	2	4	7
Glaciers/small ice caps	2	3.5	5
Greenland Ice Sheet	-4	0	4
Antarctic Ice Sheet	-14	0	14
Surface water and ground water storage	-5	0.5	7
TOTAL [Contributions]	-19	8	37
OBSERVED [Sea level rise]	10	18	25

Table 2. Summary of the estimates of observed sea level rise and its contributions during the 20th Century from Warrick et al. (1996).

Greatest among the unknowns are the 20th Century contributions from the two remaining great ice sheets, Greenland and Antarctica. Warrick et al., suggest that Greenland contributed 0±4 cm, and Antarctica contributed 0±14 cm. However, Warrick et al., noted that these contributions “should be interpreted as a reflection of the current poor state of knowledge, rather than as an estimate of the current state of balance.” And so, while the estimates of uncertainty allow that Antarctica may have made the largest single contribution to sea level rise during the 20th Century, we cannot at present be sure if its contribution was positive, negative or negligible

Paterson (Paterson, 1993) took a different approach. Attributing the measured rate of the sea level rise (1.8"0.5 mm a^{-1}) to well-known sources, he determined that the Antarctic contribution to sea level over the last Century was (0.65"0.61) mm a^{-1}. He interpreted this to mean that the Antarctic was contributing to sea level rise at a rate of 235 Gt a^{-1}. Each millimetre of sea-level rise is roughly equivalent to the addition of 360 Gt of water to the world’s oceans (Jacobs *et al.*, 1992). This result does not, however, agree well with the observation that over the period 1992-1996, most of Antarctica contributed only (60"76) Gt a^{-1} (Wingham *et al.*, 1998) (See 3.1.3).

From this confused picture, I conclude that the problem of sea level rise attribution is far from solved. If Antarctica and Greenland have made little contribution in the last century then the best-estimates of contributions given by Warrick et al. do not add up to give the observed sea level rise.

2.1.4…In the coming century

In the coming century global sea levels will almost certainly continue to rise as the aggregate for contributions from mechanisms that have already been active 20th Century. The uncertainty of the contribution of the Antarctic Ice Sheet of the last century is mirrored in our uncertainty over its future contribution. At present it holds the greatest potential to raise sea level but may also be a major mitigator of sea level rise if precipitation increases over Antarctica. (See Appendix 6 – What is the gobal hazard associated with sea level rise?)

2.1.5 Steric contributions to sea level rise

Projections of sea level usually consider what is known as, *eustatic* sea level, i.e. the level rise caused by changes of the mass of water in the oceans. However, the hazard presented to any section of coastline results from a change in *Relative* sea level change, which takes account both of eustatic sea level rise and beach subsidence or uplift etc. These are local issues and do not concern us here, but there is another secondary effect of melting of the Antarctic Ice Sheet, or portions of it, which will freshen and cool the oceans. This will cause a *steric* change in sea level resulting from changed density of the oceans. Steric changes can be transiently regional and are related to changing oceanography.

While it has generally been assumed that the steric effect of changes in the Antarctic Ice Sheet are insignificant, I have found no clear assessment of the effect and so Table 3. shows the results of a box model in which I considered the steric increase in sea level resulting from the melting of various components of the Antarctic Ice Sheet into various oceans. The calculation was performed using the standard formulae for calculating seawater density used throughout the marine research community (Fofonoff & Millard, 1983).

	Larsen Ice Shelf - A	Ronne iceberg	All ice shelves	West Antarctic Ice Sheet
Weddell Sea	0.5	15	*	*
Southern Ocean (south of polar front)	-0	0.4	43	*
All oceans in the S. Hemisphere	-0	-0	8.2	36
World's oceans	-0	-0	4.0	18

Table 3. Steric sea level rise contributions (in cm) from the melting of various portions of the Antarctic Ice Sheet melting into, and completely mixing with, different oceans. Note: that Ronne Iceberg represents the iceberg that is expected to calve from the Ronne Ice Shelf in the near future to move the ice front back to its 1940s ice front position. A similar-sized iceberg may also be expected to eventually calve from Ross Ice Shelf (Keys et al., 1998).

The results show that while the recent loss of ice shelves on the Antarctic Peninsula (Vaughan & Doake, 1996) will have had no measurable steric effect on sea level. The melting of the iceberg likely to be produced soon from Ronne Ice Shelf or Ross Ice Shelf, would have a measurable effect only if its melt was confined in the Weddell Sea (which is probably unrealistic). The melting of all ice shelves around Antarctic would, however, have a measurable effect on Southern Hemisphere oceans or even the entire world oceans. While melting of WAIS appears to have a substantial, perhaps catastrophic, steric effect on sea level this is actually dwarfed by the effect such an event would have on eustatic sea level. I thus conclude that, while theoretically measurable, the steric contribution from the loss of Antarctic Ice Shelves will give only a small contribution to sea level rise in the next centuries, and since they are only likely to occur after considerable change in the ice sheet it is unlikely that they will be a noticeable effect.

2.2 Thermohaline circulation and Antarctic Bottom Water formation

Almost all the water that falls as snow over the Antarctic Ice Sheet is eventually returned to the ocean, as an outflow of melt-water from the continental ice sheet, by melting from the base of ice shelves, or along the drift tracks of icebergs. Because latent heat is extracted from the ocean during the melting process, the discharge of ice is equivalent to the introduction of the same mass of melt-water at a temperature below -80EC, and so the cooling effect is very significant. Extreme temperatures can result at the base of thick ice shelves, where the elevated pressure maintains the ambient water in the liquid phase at temperatures below the surface freezing point (Doake, 1976; Robin, 1979). This has profound consequences for the oceanography of Antarctica's coastal seas and for the global oceans, through the water masses, such as oxygen-rich Antarctic Bottom Water (AABW) which are produced in Southern Ocean (Killworth, 1983). Indeed, Antarctic Bottom Water has been described at the "lungs of the ocean" because it transports oxygen and other nutrients to many the World's oceans as it mixes with other water masses (Edmond, 1975) (Figure 5).

The present geometry of the ice-sheet allows for both ice shelf cavities and broad continental shelves that act as reservoirs for the transformation of water masses. In the case of the southern Weddell and Ross seas, the open continental shelves reach to latitudes above 75ES, where exposure of the sea surface to the atmosphere stimulates intense sea-ice formation (Gill, 1973; Zwally *et al.*, 1985). Brine rejected during the process of sea-ice formation results in the production of High Salinity Shelf Water (HSSW), which sets the oceanographic regime for the largest of today's Antarctic ice shelves (Foldvick *et al.*, 1985). Melting ice mixes with HSSW to form Ice Shelf Water (ISW), which is sufficiently dense in places to descend the continental slope, ultimately to form Antarctic Bottom Water (AABW) (Foldvick *et al.*, 1985).

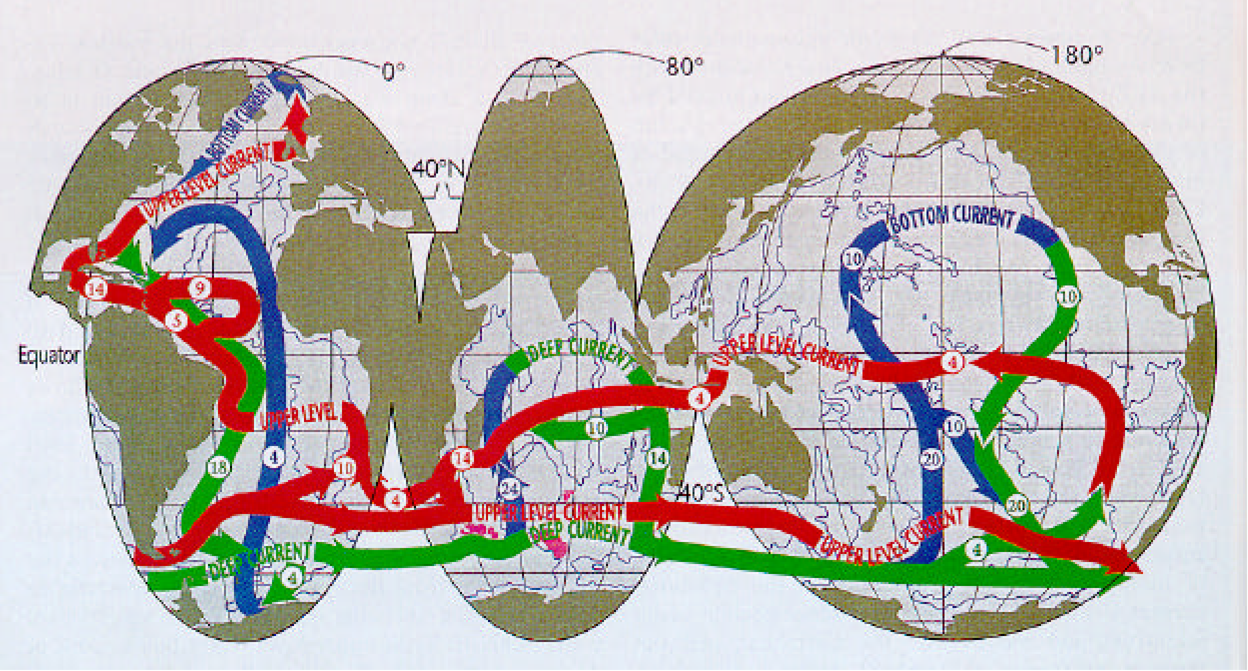

Figure 5 – Schematic of Global thermohaline circulation [Taken from (Schmitz, 1995)].

The production of HSSW not only drives the circulation beneath the ice shelves (Nicholls, 1996), it also makes a direct contribution to AABW formation via mixing processes that occur at the shelf break (Foster & Carmack, 1976). 70% Antarctic Bottom Water is formed in the Weddell Sea (Foldvick & Gammelsrod, 1988). Condtions are quite different in the eastern Pacific sector. HSSW is entirely absent and rapid melting at the base of ice shelves causes enhanced upwelling of the warmer water that occupies the continental shelf (Potter & Paren, 1985; Hellmer *et al.*, 1998).

A climatically induced change in the oceanographic regime of the Antarctic continental shelf would have dramatic consequences for the ice shelves and the products of their interaction with the ocean. On long time-scales the configuration of the continental shelves evolves with the changing geometry of the ice sheet margin. At the Last Glacial Maximum (LGM) the ice sheet is thought to have been grounded to the continental shelf break (Kellogg & Kellogg, 1987; Bentley & Anderson, 1998), thereby eliminating deep ice-shelf cavities and removing the reservoirs needed for efficient water mass transformation. The Southern Ocean might then have played a very different role in global ocean circulation, with AABW production perhaps being confined to sites of deep convection in the open ocean. Recent evidence indicates that some of the dramatic climatic variability indicated by Greenland ice core records for the last glacial period may have been initiated by changes in the Antarctic, and communicated via oceanographic, rather than atmospheric, pathways (Blunier *et al.*, 1998).

3. MEASURING THE "MASS BALANCE" OF THE ANTARCTIC ICE SHEET

The Antarctic Ice Sheet is a dynamic system, in which ice that is lost through iceberg calving or melting is largely replaced by precipitation. Thus an obvious question, and one which glaciologists have asked since the 1960s is, "What is the different between the mass of ice entering the ice sheet and the mass leaving it?" Or to use the jargon, "What is the mass balance of the ice sheet?"

In theory there are two methods for answering the mass balance question, and these can be broadly termed *the credit & debit method* and *the balance-of-account method*. I will discuss each.

3.1 The credit & debit method

The credit & debit method attempts to use measurements to quantify separately, the input flux and the output flux over some specific area and time period. Subtracting these numbers will give the mass balance. The credit & debit method usually suffers from a highly unfavourable uncertainty budget and rarely gives an answer significantly different to zero (Allison I.F., 1979; Shabtaie & Bentley, 1987; Lindstrom & Tyler, 1984; McIntyre, 1985b; McIntyre, 1987; Whillans & Bindschadler, 1988; Jacobs *et al.*, 1992; Rignot, 1998).

A recent study (Vaughan *et al.*, 1999) indicated that a total of 1811 Gt a^{-1} of ice accumulates on the coterminous grounded Antarctic Ice Sheet (i.e. the main grounded ice sheet not including ice rises and offshore islands). Over the entire ice sheet including ice shelves and embedded ice rises the accumulation is, 2288 Gt a^{-1}. This implies that the accumulation of ice falling on the grounded ice sheet is thus equivalent to 5.0 mm of sea level each year. Jacobs et al. (Jacobs *et al.*, 1992) estimated the total mass of ice lost from the ice sheet (including ice shelves) to be 2613 Gt a^{-1}; with an uncertainty of ±530 Gt a^{-1}. Jacobs et al. compared this with the total net surface mass balance for the continent (Giovinetto & Bentley, 1985; Frolich, 1992) and calculated a net imbalance of (-469 ± 639) Gt a^{-1}. Using the estimates from the recent study we can refine this estimate of net imbalance to (-325 ± 594 Gt a^{-1}). In terms of uncertainty, this is only a small improvement and realistically we are still unable to determine even the sign of the contribution of the Antarctic Ice Sheet to recent sea level change.

It is probable that credit & debit method calculations will for the foreseeable future give uncertainties so large as to have questionable value and so we should perhaps look to the balance-of-account methods to establish the mass balance of the Antarctic Ice Sheet.

3.2 The balance-of-account method

The balance-of-account method seeks to make sequential observations of the volume of ice in the ice sheet. Researchers approach this by making periodic measurements of the surface elevation of the ice sheet either by satellite (Zwally *et al.*, 1989; Lingle *et al.*, 1994; Lingle & Covey, 1998; Wingham *et al.*, 1998), from aircraft (Krabill *et al.*, 1999), or from surface stations fixed either with reference to outcropping bedrock or using GPS (Hamilton *et al.*, 1998; Morris & Mulvaney, 1995). Clearly satellite-based methods offer the best hope of wide coverage but until recently they suffered from the poor precision of the calculated orbits - these have now been significantly improved.

The major limitation with satellite radar altimetry is that in areas of steep surface gradient they fail to keep track of the surface echo. Re-acquisition of the surface is an automatic process but during the re-acquisition phase data is lost. For this reason around much of the coastal margin of the ice sheet, little or no data are available. NASA's, Ice Cloud and land Elevation Satellite (ICESat) mission begins in July 2001 when a satellite will be launched into low Earth Orbit (600 km) with an inclination of 94 degrees giving full coverage of the Antarctic. The Geoscience Laser Altimeter System (GLAS) is the sole instrument on this satellite. GLAS will transmit 4 ns pulses at two frequencies, infrared (1064 nm) and visible green (532nm), that will illuminate the earth with a footprint of 70 m diameter and sample at along-track intervals of 175 m. The infrared pulse is used for surface altimetry, and the green pulse is used for atmosphere measurement. The intrinsic precision of the GLAS will be 10 cm and over ice is designed not to suffer from the problems of tracking and volume scattering that plague radar altimeters.

In addition, a planned twin-satellite mission (GRACE) could use changes in the gravitational field over the ice sheet to infer changes in ice sheet mass (Bentley & Wahr, 1998).

3.2 The best effort so far

Perhaps the best effort so far in obtaining balance-of-account of the Antarctic Ice Sheet as a whole was that undertaken by Wingham et al. (Wingham *et al.*, 1998). Wingham et al. analysed data from the ERS-1 Satellite Altimeter for the period 1992-1996 for signs of surface elevation change. They searched for spatially and temporally coherent changes in surface elevation using data that covered most of the interior of the Antarctic Ice Sheet north 82ES (Figure 6).

Wingham et al. took pains to point out that surface elevation change could be caused either by a long-term imbalance in the ice sheet or by a short-term anomaly in the surface mass balance rate. They interpreted the mean surface elevation change in the context of the variability of the snowfall in each area. They found changes in surface elevation in various ice-drainage basins of between –11.7 and +6.7 cm a^{-1}, but in all but one basin the variability of snowfall exceeded the change in surface elevation – meaning that it was not possible to conclude whether the surface elevation change (or lack of it) was due to ice-sheet imbalance or anomalous surface balance in the period of the measurements. The exception to this was the Pine Island Glacier-Thwaites Glacier basin, where the surface elevation fell (-11.7 ± 1.0) cm a^{-1} over the period, marginally more than the likely variability in the surface mass balance, 9.3 cm a^{-1}. It is hoped that an extended analysis of ERS-1 altimetry will refine the pattern of change.

Wingham et al. concluded that, “A large century-scale imbalance for the Antarctic interior is unlikely”. This is probably a reasonable conclusion but we should note that the data were obtained over only 5 years and that such measurements may give an excellent indication of what has happened to the ice sheet over the period of measurement, but may provide only a poor basis for predicting its future behaviour.

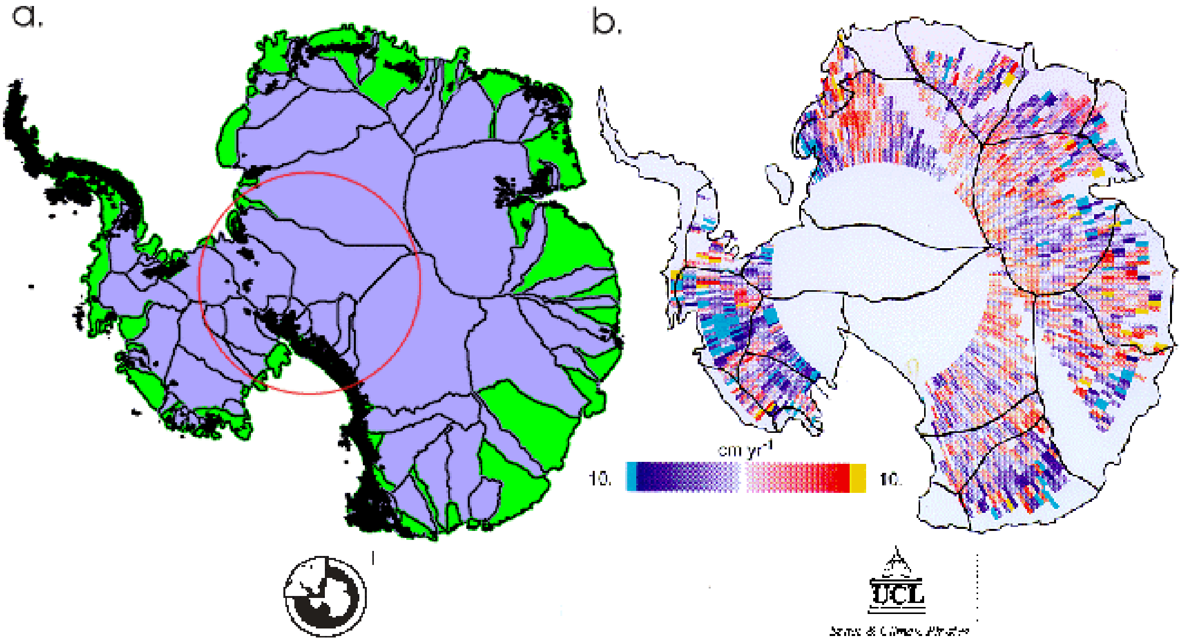

Figure 6 - (a) Map of ice-drainage basins derived from ERS-1-derived DEM (See Figure 2). Ice-drainage basins shaded purple are drained by major ice streams and outlet glaciers, while those shaded green are drained largely by slow-flowing ice sheet. (b) Changes in ice-surface elevation 1992-1996 derived by Wingham et al. (1998) from repeated ERS-1 altimetry.. Note that only spatially coherent change covers both the Pine Island Glacier and Thwaites Glacier drainage basins.

4. OBSERVED CHANGES IN POLAR ICE SHEETS

While mass balance of the Antarctic Ice Sheet is primary concern, as it shows the direct contribution to sea level change, there are other observed changes have been reported to be occurring in polar ice sheets and these must have their causes. Some can been attributed to changing climate but others are perhaps diagnostic of changes in ice dynamics. There follows short and certainly incomplete catalogues of observed changes in polar ice sheets, that have been attributed to climate change and ice dynamics.

4.1 Climate-related changes

4.1.1Greenland

- The Greenland ice sheet suffers melting in summer over much of its area. Passive microwave data has shown that the area prone to melting each summer has increased (Abdalati & Steffen, 1997) and will probably show further increases in area and duration.
- Airborne altimetric monitoring has shown that over the period 1993-1998, the Greenland ice sheet was thickening at a low rate at high elevation, whilst at lower elevations thinning (around 1 m a^{-1}) was underway (Krabill *et al.*, 1999).
- The ice sheet margin in West Greenland is known to have retreated in the last century (Weidick, 1985).

4.1.2 East Antarctic ice sheet

- The majority of the East Antarctic ice sheet appears to be close to a state of balance (Wingham *et al.*, 1998).

- Snow accumulation at South Pole has increased by around 30% since the 1960s and the net accumulation for the 30-year period, 1965-1994 was the highest 30-year average in this millennium (Mosley-Thompson *et al.*, 1999).
- Other studies have revealed temporal trends in net surface mass balance that are both positive (Petit *et al.*, 1982; Jouzel *et al.*, 1983; Goodwin, 1991; Morgan *et al.*, 1991) and negative (Isaksson *et al.*, 1996).

4.1.3 West Antarctic ice sheet

- The Thwaites and Pine Island glacier basins appear to be showing a spatially and temporally coherent trend in surface elevation (Wingham *et al.*, 1998). It is not yet known if this change was related to a change in precipitation (long-lived or transient) or due to some dynamical change in the ice sheet.

4.1.4 Antarctic Peninsula

- Over the Antarctic Ice Sheet, where only a few limited areas suffer summer melting (Zwally & Fiegles, 1994), however detailed measurements show that in some marginal areas the period of summer melt has lengthened (Ridley, 1993b; Ridley, 1993a).
- At least 5 meteorological records from the scientific stations on the Antarctic Peninsula have shown decadal warming trends (King, 1994; Harangozo *et al.*, 1997; Skvarca *et al.*, 1998).
- This atmospheric warming appears to have caused several notable changes in the ice cover of the Antarctic Peninsula, including changes in the snow elevation (Morris & Mulvaney, 1995) (Smith *et al.*, 1999)and the extent of surface snow cover (Fox & Cooper, 1998).
- Seven ice shelves on the Antarctic Peninsula have shown significant progressive and continued retreat, Wordie Ice Shelf, Müller Ice Shelf and George VI Ice Shelf and Wilkins Ice Shelf on the west coast (Vaughan & Doake, 1996; Ward, 1995; Luchitta & Rosanova, 1998); the ice shelves that occupied Prince Gustav Channel and Larsen Inlet, and Larsen Ice Shelf A on the east coast (Vaughan & Doake, 1996; Rott *et al.*, 1996; Skvarca *et al.*, 1998). Following Mercer (Mercer, 1978) Vaughan and Doake showed that the pattern of retreat could be explained by a southerly movement of the 0EC January isotherm which appears to define a limit of viability for ice shelves.
- The ~100-m thick ramp of snow and ice that formerly connected Stonnington Island to the main Antarctic Peninsula retreated and collapsed since the 1970s when the UK science station on Stonnington Island was abandoned (Splettoesser, 1992).
- Some ice-core records have shown an increase in accumulation rates (Peel, 1992).

(See Appendix 7 – Impact of climate-related changes on the Antarctic Peninsula)

4.2 Ice-dynamics related changes

4.2.1Greenland

- I am not aware of any major recent changes in the dynamics of the Greenland that have been clearly ascribed to changes in ice dynamics.

4.2.2 East Antarctic ice sheet

- There is geomorphological evidence that Law Dome has re-advanced at least once during the Holocene at around 4000 years bp. (Goodwin, 1996)
- The Mizuho Plateau which feeds Shirase Glacier appears to be thinning at a rate of 70 cm a^{-1} (Nishio *et al.*, 1989).

4.2.3 West Antarctic ice sheet

- Radar sounding data from Ice Stream C shows a buried layer of crevasses that probably show that the ice stream “switched-off” around 200 years ago (Rose, 1979; Shabtaie *et al.*, 1987; Retzlaff & Bentley, 1993).

- Presumably in response to the recent “switch-off” Ice Stream C is now thickening at around 10 cm a^{-1} (Whillans & Bindschadler, 1988)
- In contrast, the ice drainage basin of Ice Stream B is thinning at a rate of 6 cm a^{-1} (Whillans & Bindschadler, 1988)
- Crary Ice Rise, embedded within the Ross Ice Shelf appears to be migrating inland,
- Between 1974 and 1984 a portion of the grounding line of Ice Stream migrated inland around 300 m (Thomas *et al.*, 1988)
- Ice Stream B slowed by around 205 in a 10-year period between the early 1970s and early 1980s (Stephenson & Bindschadler, 1988)
- Relict flowlines on Ross Ice Shelf shows non-steady behaviour in the flow of the ice stream feeding it, perhaps 800 year ago (Cassasa *et al.*, 1991)
- There has been some evidence that the shear margins on the boundary of Rutford Ice Stream has changed in position in recent years (Frolich & Doake, 1998)
- There is evidence for the changes in configurations of ice streams on the Siple Coast perhaps 1.8 ka bp (Jacobel *et al.*, 1996)
- Internal layers indicate current migrations of the ice divides at Siple Dome ice rise (0.05-0.5m a^{-1}) (Nereson *et al.*, 1998) and Fletcher Promontory (0.5 ma^{-1}) (Vaughan *et al.*, 1999) .

4.2.4 Antarctic Peninsula

- The final stages of collapse of the Larsen Ice Shelf (A) were modelled (Doake *et al.*, 1998) and shown to be due to instability in the ice shelf.

Part Two - Modes of Change in the Antarctic Ice Sheet

It is a popular misconception that the Antarctic Ice Sheet will inevitably melt as a result of "*Global Warming*". Actually, its future is not so easy to predict; many forces, internal feedback mechanisms and outcomes have been discussed in the literature, some predicting the collapse of the ice sheet and some predicting thickening. Each has a different likelihood, time of initiation, and rate of impact, final outcome and probable implication of the rest of the Earth system. I will discuss each aspect of change in the ice sheet:

- external drivers
- internal drivers
- feedback systems that might cause amplifications of the drivers

Having discussed the aspects individually I will consider the combinations and then draw together an overall framework of probable change scenarios.

5. EXTERNAL DRIVERS OF CHANGE

The simplest cause of change in any long-lived and apparently stable system is a change in the external boundary conditions acting on that system. The grounded ice sheet is no exception and each ice-drainage basin has four boundaries across which change might be driven, these are:

- The ice sheet surface
- The ice sheet - bed interface
- The ice – ocean boundary
- The boundaries (ice divides) with neighbouring ice-drainage basins

A change in boundary conditions at any one of the boundaries will cause alteration in the mass balance of the ice-drainage basin. In theory, any mechanism that causes a change in mass flux across one of these boundaries will alter the overall mass balance of the basin and so we should consider changes at each boundary as a possible cause of change across the basin.

5.1 Sea level

While change in the Antarctic Ice Sheet is a potential cause of sea level change, sea level change is also driver of change in the ice sheet. It has long been held that the collapse of marine ice sheets was most easily triggered by a rise in eustatic sea level (Thomas & Bentley, 1978) and during rapid deglaciations this may well have been the case. However, given a specified bed topography and ice thickness, the migration of the grounding line resulting from a sea level change is easily predicted and unless some grounding line instability is triggered (see section 7.2) the retreat of the grounding line resulting from a sea level rise of the order of 1 m will be quite modest.

5.2 insolation

Budd et al., (Budd *et al.*, 1999) used GCM modelling studies to investigate the long-term changes in polar ice sheets. They wrote, "It is apparent that the Northern Hemisphere ice changes through the [last] glacial cycle can be reasonably well simulated from the orbital radiation changes plus the ice-sheet albedo feedback. This generates the global sea-level and climate changes that together with the local radiation changes drive the Antarctic ice-sheet changes." However, while changes in insolation do have a long-term effect on the climate (and thence) the ice sheet it is difficult to imagine changes that such changes could occur on century time-scales.

5.3 Atmospheric temperature

The flow of ice is strongly controlled by temperature, ice is approximately 100-times stiffer at -30EC than it is near 0EC. Thus warming of the ice would tend to promote acceleration of the flow. Ice and snow are, however, relatively poor conductors of heat and this leads to two cases.

a. In areas where summer temperature are not high enough to cause surface melt, and this includes almost all of Antarctica (Zwally & Fiegles, 1994), transport of heat is generally via conduction. The thermal conductivity of dry snow and ice is such that a yearly cycle in surface temperature will be attenuated to around 5% at 10-m depth. A 2500-year cycle in temperature would similarly penetrate only around 500 m by conduction and in this case the advection of heat, and temperature change, by the burial of snow is thus likely to be more important (Paterson, 1994). This means that on century time-scales a change in atmospheric temperature is unlikely to be an important cause of change in the mass balance of this ice sheet.

b. In areas where summer temperatures are high enough to cause surface melting, liquid water can penetrate the snow-pack and advect heat into the snow. More importantly, as the water refreezes, it releases considerable latent heat that warms the surrounding ice. This is a highly effective means of removing the “cold wave” that resulted from the previous winter, and so raise the surface layers by several EC. Since even summer temperatures, in Antarctica, are generally below zero, this mechanism acts only in a few localised areas on the margin of the ice sheet. The mechanism is, however a strong non-linearities and is believed by many to be the mechanism that caused retreat of the ice shelves around the Antarctic Peninsula in recent years (Doake & Vaughan, 1991; Vaughan & Doake, 1996; Doake *et al.*, 1998; Skvarca *et al.*, 1998).

An increase in atmospheric temperature alone is thus unlikely to cause a significant change in the mass balance of the Antarctic Ice Sheet in the next few centuries, except in areas where melting becomes usual in the summer months (See Appendix 8 – Predictions from Hadley Centre Climate Model)

5.4 Precipitation rate

The pattern of surface mass balance over the Antarctic continent has been mapped several times using in situ data (Giovinetto *et al.*, 1989) and satellite-based measurements (Zwally & Giovinetto, 1995), and most recently using a combination of both sources (Vaughan *et al.*, 1999). The pattern that has emerged is one where most of the precipitation falls near the coastline and the central plateau has only very low amounts of snowfall (Figure7)

Much play has been made of the likelihood that increased air temperature above Antarctica would allow a greater poleward transport of moisture and would increase precipitation rates over the ice sheet. This is, however, a view which grossly simplifies the situation. For example, Kapsner et al.,(Kapsner *et al.*, 1995) showed that the variations in precipitation in the GRIP core from the Greenland Ice Sheet could not simply be explained through temperature variations; the frequency, intensity and preferred track of storms also needed to be considered. For this reason, we will need to use sophisticated climate models to predict the future of precipitation over the Antarctic Ice Sheet.

Simulations of precipitation can be derived from GCMs operating in pure climate mode, i.e. spun-up and then allowed to run without re-initialisation, or from GCMs run as numerical weather prediction (NWP) models forced during the run by observational data. Both NWP and climate GCMs reproduce the pattern of surface balance reasonably well, although perhaps, surprisingly the NWP models, which have higher resolution, are not clearly better than the best climate GCMs (Genthon & Braun, 1995; Connolley & Cattle, 1994; Giovinetto *et al.*, 1989).

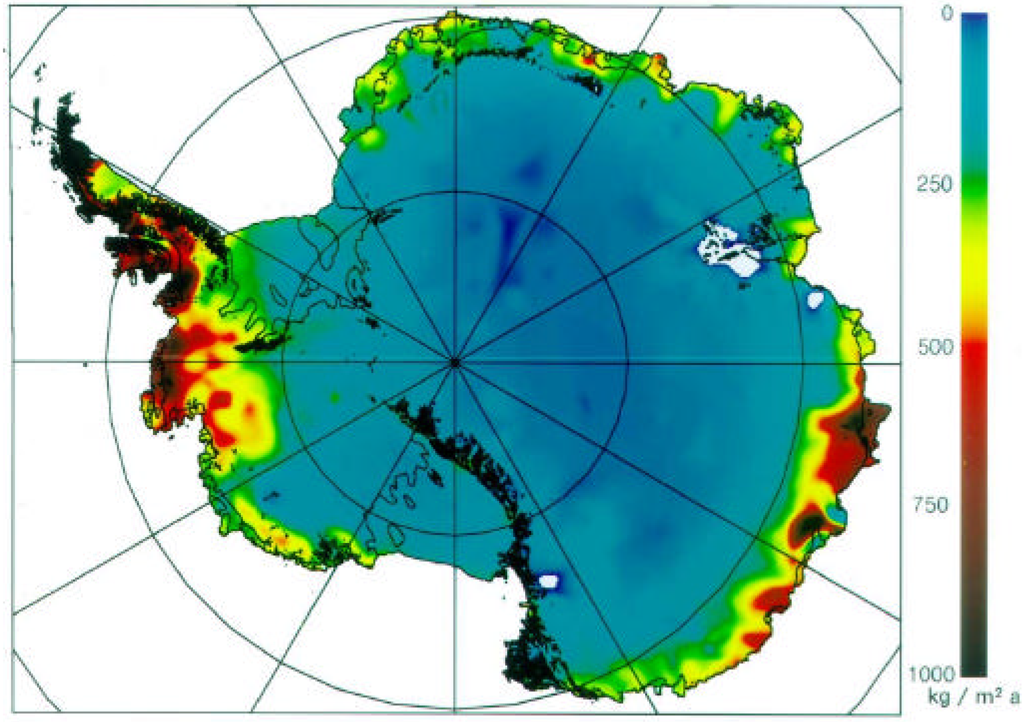

Figure 7 - The distribution of net surface mass balance derived by Vaughan et al., (1999)

Smith et al., (Smith *et al.*, 1998) used sea surface temperatures (SSTs) to force a climate GCM of the Antarctic Ice Sheet over the period 1950-91. The ice-sheet surface was estimated to have warmed by +0.73 EC (+0.18EC per decade), while surface accumulation is estimated to have increased +7.7 mm a^{-1} (+1.9 mm a^{-1} per decade). This equates to an increase of 12.5 mm a^{-1} per degree of warming, -0.4 mm a^{-1} of global sea level.

The surface mass balance of the Greenland and Antarctic Ice Sheet has been simulated using the ECHAM3 GCM (Ohmura *et al.*, 1996) for present and doubled CO$_2$. On Greenland the models indicates a slights decrease in accumulation and substantial increase in melt, while on Antarctica a large increase (+10%) in accumulation without melt is predicted. Ohmura et al., predicted that the contributions to global sea level would be +1.1 mma^{-1} and –0.9 mma^{-1} respectively – a net contribution of near zero (see Appendix 9 – Do Antarctic and Greenland contributions to sea level cancel out?).

5.5 Ocean temperature/circulation

Williams et al. (Williams *et al.*, 1998) suggested that an increase in the temperature of the seas around the Amery Ice Shelf of 1EC, EAIS Antarctica would increase the net melting from the ice shelf by a factor of four. Their proposed warming was less than that likely to result from a trebling of CO$_2$ according to (O'Farrell *et al.*, 1999). Warner and Budd (Warner & Budd, 1998) considered that the greatest impact on the Antarctic Ice Sheet was likely to be through increased basal melting from the oceans. They highlighted the role of enhanced basal melting from ice shelves and increased strain rate of unimpeded thick ice in driving the retreat of marine ice sheets. They suggest that “a 3EC global mean warming, corresponding to a 2EC of warming for the water under the ice shelves and resulting in 5 m yr^{-1} basal melt rates, is enough to cause the demise of the marine ice regions of West Antarctica and a retreat of coast ice towards more firmly grounded regions elsewhere, over a period of about

2000 years." They go on to say, "Once the ice shelves disappear, after the first few hundred years, is likely that the continued retreat would be irreversible until the new grounding line configuration [is reached]."

Many studies of increased ice shelf melting begin with the assumption that the coastal sea temperatures rise as some proportion of atmospheric temperatures. This may be a significant shortcoming, as a change in ocean circulation leading to an incursion of warmer water onto the continental shelves may be more likely. Indeed, such an incursion, by Cold Deep Water (CDW) may have already occurred in the Amundsen Sea and be giving rise to the unusually high melt rates measured beneath Pine Island Glacier (Hellmer *et al.*, 1998; Jenkins *et al.*, 1997).

5.6 Subglacial geology

It is generally accepted that fast-flow in ice streams helps to generate high basal temperatures through the mechanism of strain heating, and that free-water is a requirement to maintain the lubrication required to facilitate fast-flow. Two aspects of sub-glacial geology have been implicated in change in the ice sheet.

5.6.1 Volcanism

Blankenship et al. (Blankenship *et al.*, 1993) conducted airborne geophysical surveys over the upstream portion of Ice Stream B (Siple Coast, Antarctica) and found in topography, magnetic and gravity, the signature of what they believed to be a "recently active volcano". The interpretation that the volcano was recently or, perhaps currently, active came from observations of a surface depression that appeared to be associated with the volcano. They suggested that the presence of the volcano and similar ones that they inferred to be present on Ice Stream E were "an important control on the dynamics of WAIS".

The original paper describing the "volcano" beneath Ice Stream B has been widely cited and is quite influential. It has been taken by some to imply that a volcanic eruption could trigger the collapse of WAIS, although this is not mentioned by Blankenship et al.; what they did suggest was that the volcano indicates a region of thinner crust with higher geothermal heat flux, and that WAIS would become unstable if grounding lines were to retreat to the margin of this thinner crust.

Bentley (Bentley, 1993) discussed Blankenship's conclusions but was unconvinced that the observations had such serious implications. He noted that if the grounding lines were to retreat to position of the volcano, then a major retreat was already underway and that "an instability had already been triggered". More seriously, Bentley doubted that high geothermal flux was an important control on ice dynamics, citing the fact that glaciers and ice streams exist on thick and presumably cold Precambrian shields in East Antarctica and Canada.

More recently, sub-glacial volcanism has clearly been associated with catastrophic surging of a normally slow-moving ice sheet (Gudmundsson *et al.*, 1997), although this was on a much smaller scale.

5.6.2 Sediment and sediment supply

MacAyeal's (MacAyeal, 1992) model of the WAIS included a treatment of the transport of sub-glacial till, it showed that without a forcing the ice sheet eventually attained equilibrium after 50 000 years, but with glacial climate or sea-level forcing the ice sheet occasionally and aperiodically collapsed. This occurred when the region underlain by deformable till managed to breach the frozen-bed zone that ringed the margin of the ice sheet. Once ice streams were activated then the ice sheet rapidly shrank to less than its equilibrium volume.

In MacAyeal's model it is the distribution of the sediments and temperature which are largely responsible for initiating the collapse of WAIS, although this was weakly linked to an external forcing. A simplistic interpretation of MacAyeal's work might lead us to believe that the numerous active ice streams in WAIS, which clearly do breach the frozen-zone, are evidence that the WAIS has already entered a collapse phase and might expect change to be ongoing.

6. INTERNAL DRIVERS OF CHANGE

6.1 Ice stream instability

There is a considerable body of evidence that ice streams may, within a few decades, switch on and off (Retzlaff & Bentley, 1993), change their flow-rate (Stephenson & Bindschadler, 1988), alter the position of their margins (Jacobel *et al.*, 1996; Frolich & Doake, 1998), or the flow relicts that they leave behind (Cassasa *et al.*, 1991). Alley and Whillans (Alley & Whillans, 1991) believed that while such changes in ice streams may have been "set on course by external events, but now, internal processes, that are specific to ice streams must be playing a large role." In other words, the dynamical instabilities, which give rise to ice streams in the first place, the formation of shear margins, basal sliding and the onset of streaming flow itself, may lead to ice stream change (Whillans & van der Veen, 1993).

6.2 Readjustment to the end of the last glacial.

(Hindmarsh, 1990) used analytic ice sheet models to estimate that "The 3 km thick East Antarctica (sic), with accumulation rate as low as 0.03 ma^{-1}, has a time-scale [of dynamic response] of 100 000 years". Thus a periodic change in accumulation or insolation with a time-scale of 20 000 years would never produce a completely equilibrated response. Similarly Hindmarsh indicated that an ice sheet 2 km thick and with an accumulation rate 0.1 ma^{-1}, roughly correct for the WAIS, should have a response time-scale of around 20 000 years, while MacAyeal (MacAyeal, 1992) estimated a 50 000 year response time for WAIS. The exact value is unimportant, except that they suggest it is unlikely that the WAIS, or EAIS, have achieved equilibria after the rapid changes in climate and accumulation at the end of the last glaciation.

Alley and Whillans (Alley & Whillans, 1991) suggested that ongoing changes ice thickness on the Siple Coast ice streams could be explained as a "continuing response to the major global changes at the end of the last glacial. Bindschadler (Bindschadler, 1997b) found the pattern of surface elevation change on ice streams B, D and E showed a pattern of surface elevation change that he interpreted as indicating an ongoing surge condition. From this Bindschadler inferred a headward migration of the onset of ice streaming, 488 ma^{-1} in the case of Ice Stream B. He then inferred that such a rate of headward migration was consistent with a constant rate of grounding line retreat since the end of the last glaciation. From these arguments Bindschadler gave an expected lifetime for the rest of the WAIS of 1200-6000 years – in terms of sea level rise 50-10 cm per century. After this it would require 50 000-100 000 years to regenerate the WAIS.

Many of these concepts have been revisited (Bindschadler, 1998). Using geological evidence of grounding line and ice front positions for Ice Stream B and the Ross Ice Shelf, Bindschadler mapped the history of grounding line and ice front retreat since the last glacial maximum (20 ka bp). Although there are only a few data available, those that exist are compatible with the notion that the grounding line and ice fronts have retreated, perhaps continuously, perhaps through a succession of jumps, since the LGM. Since WAIS has contributed 11 m to eustatic sea level over this period, an average contribution might be 0.8 mm a^{-1}. Continued retreat at the same rate would suggest a 4000-year lifetime for the WAIS. Bindschadler concluded that the WAIS might still be in the process of readjustment to inter-glacial conditions, and that even without an external driver change the WAIS might retreat. Bindschadler could find little evidence for a major mass imbalance in the present-day WAIS, either from *credit & debit* or *balance-of-account* calculations, but noted the considerable evidence of rapid sea level rise resulting from ice sheet retreat; for these reasons he seemed to favour a step-wise retreat. Finally he suggested that in future the WAIS has the ability to retreat dramatically without external forcing.

7. FEEDBACK SYSTEMS

An important element of our analysis concerns the identification of either positive or negative feedback systems within the Antarctic Ice Sheet. It is from these feedback systems that we may discern the greatest impacts.

7.1 Ice Shelf Stability

Many authors have long debated the stability of ice shelves (Mercer, 1978; Mercer, 1978; Robin, 1979) (Hughes, 1983). But recently numerical models of ice shelves, largely based on the work of MacAyeal (Lange & MacAyeal, 1989; Lange & MacAyeal, 1988; Lange & MacAyeal, 1986; MacAyeal *et al.*, 1986; MacAyeal & Thomas, 1982; Rommelaere & MacAyeal, 1900)have become more sophisticated and more realistic. In particular, one application of MacAyeal's model (Doake *et al.*, 1998)has shown that after retreat beyond a critical limit, governed by the ice-shelf thickness and the span between pinning points, the ice shelf will become unstable and rapidly collapse. The result accurately explains the collapse of Larsen Ice Shelf (A) in the austral summer of 1995 (Vaughan & Doake, 1996; Rott *et al.*, 1996). Similarly, Rommelaere and Ritz (Rommelare & Ritz, 1996) showed that even a small island within an ice shelf result in around half the restraint on the ice shelf and be required to maintain its stability. A reasonable conclusion to draw from these studies is that the configuration of ice shelves may not be robust in the face of changing boundary conditions. A change in the rate of iceberg calving or basal melt could result in a modest progressive change in the ice shelf, but this could lead to a dynamically unstable ice shelf which would collapse very rapidly.

In terms of ice sheet mass balance, it is probably safe to assume that only the largest (Ronne-Filchner, Ross and Amery) are really important – it has been argued that the loss of much of the small Wordie Ice Shelf had little effect on the glaciers which feed it (Vaughan, 1993). Certainly, it widely believed that the largest ice shelves are not immediately threatened by atmospheric warming, but it is important to know if changes in any of their boundary conditions could eventually lead to dynamic collapse.

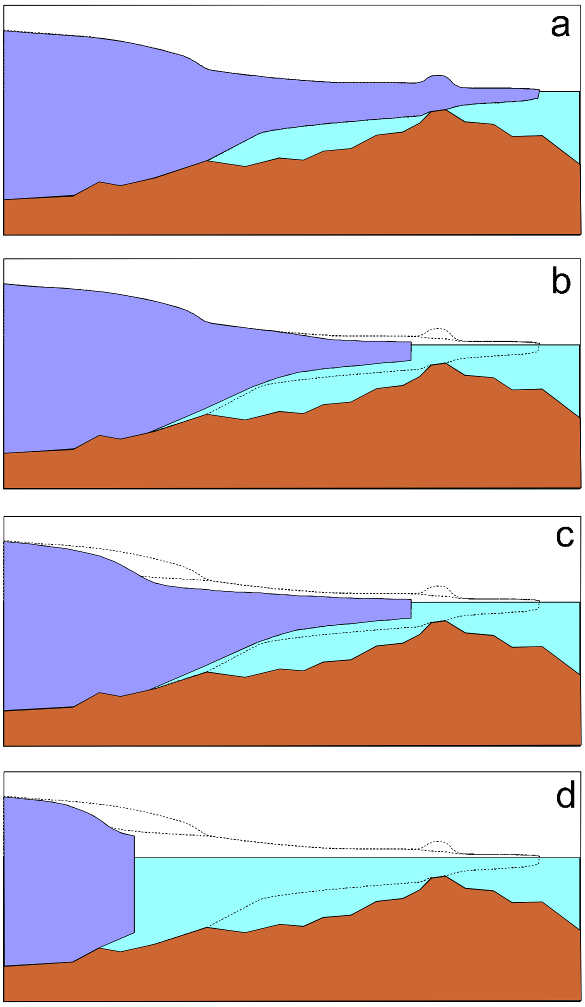

Figure 8 - Cartoon describing the ice shelf / grounding line instability. (a) A pinned ice shelf restrains its inland ice sheet. (b) If forced to retreat by increased melting or calving the ice shelf becomes unpinned providing less buttressing to the inland ice sheet. (c) As a result of decreased buttressing from the ice shelf, the grounded ice sheet thins and the grounding line retreats until, (d) grounding line retreats either until it rests on some bed obstruction or the ice sheet is entirely lost.

7.2 Grounding line retreat

It has long been argued the bed beneath a grounding line dips inland, the grounding is inherently unstable and should either be migrating inland or out towards the shelf-edge (Weertman, 1974). It has also been argued that the stabilising or “buttressing” force on grounding lines in WAIS is the presence of ice shelves, and that loss of these ice shelves could lead to collapse of WAIS (Thomas, 1973; Thomas *et al.*, 1979).

The stability of grounding lines and role of ice shelves in helping to maintain grounded ice sheets is now a much debated topic and there still seems to be no clear consensus and there is some theoretical evidence that there may be no such instability. (See Appendix 10 – Summary of Hindmarsh, 1993).

7.3 Thermohaline melting

Direct measurements from beneath Filchner-Ronne Ice Shelf (Nicholls *et al.*, 1991) showed a strong thermohaline circulation beneath Filchner-Ronne which leads to melting at the ice shelf's base. Nicholls (Nicholls, 1997) went on to show that the thermohaline circulation was strongly seasonal and results from intense wintertime production of sea ice. Nicholls argued that the springtime warming, during which the thermohaline circulation is reduced, could be used as an analogue of climate warming. The resulting cooling of the waters in contact with the ice-shelf base would reduce present melting. Nicholls suggested that an early response to climate warming would be a thickening of the ice shelf (Figure 9). Typical melt-rates beneath the ice shelf are currently around 1 ma^{-1}. The depth of the water column beneath the ice shelf has been mapped (Vaughan *et al.*, 1995) and near the ice shelf front shown to be less than 100 m. Thus a reduction in melt-rate could, within a century, cause grounding of these hitherto floating areas and so an increase in the area of the grounded ice sheet.

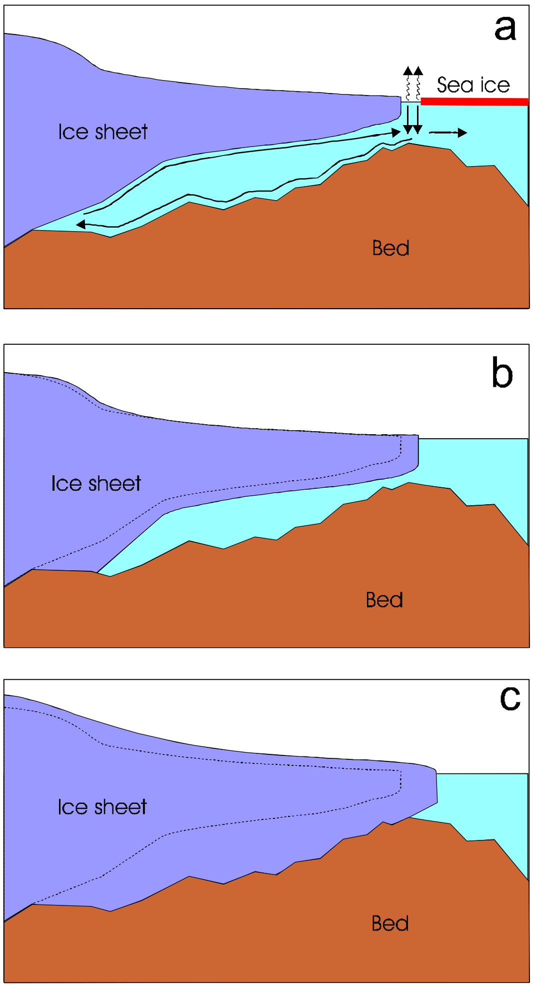

Figure 9 - Cartoon describing the thermohaline feedback scenario. (a) a sub-ice shelf thermohaline circulation is maintained by the production of sea ice and HSSW. (b) Decrease in sea ice production as a result of climate change reduces the thermohaline circulation. (c) With reduced basal melt-rates the ice shelf thickens and grounds, initially near its ice front. The extent of the grounded ice sheet is increased.

Part Three - Ice Sheet modification scenarios

The preceding discussion highlights the point that there is no single theory of ice sheet change, rather a multiplicity of drivers, mechanisms of ice sheet dynamics, and boundary interactions, that could lead to change in the Antarctic Ice Sheet. Figure 10 shows the pathways that emerge from a consideration of the literature.

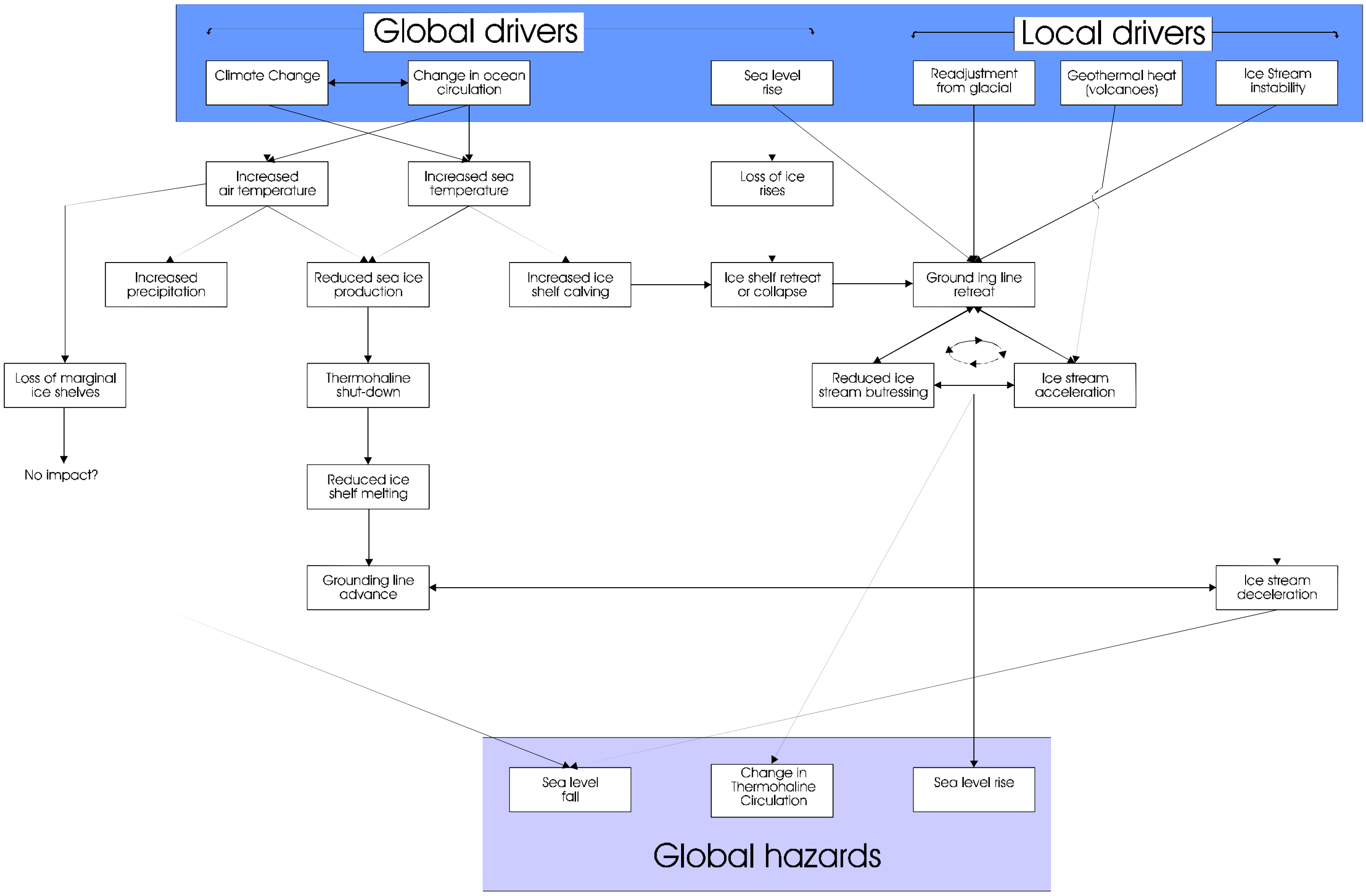

Figure 10 - A flow diagram from globally important change in the Antarctic Ice Sheet

Not all of the paths through the flow diagram are equally plausible or are likely to be significant on human time-scales, but some are worthy of serious consideration. The following sections contain summaries of each of the scenarios that have been proposed may lead to globally important change in the Antarctic Ice Sheet. The summaries are not meant to be exhaustive discussions of the subject but rather to form the basis for discussion by the expert panel.

SCENARIO 1 - "OCEAN EROSION"

Summary

Global forcing	Change in climate, ocean circulation or temperature
Direct forcing	Rise in sea temperatures around ice sheet
Primary change	Increased coastal ice sheet melt
Secondary change	Grounding line retreat & ice stream acceleration
Tertiary change	Ice sheet thinning due to reduced output
Century-scale risk/benefit	Promotes further change in oceans
Ultimate risk/benefit	Sea level rise

Primary sources

(Hellmer *et al.*, 1998; Titus & Narayanan, 1995; Titus & Narayanan, 1996; Jacobs *et al.*, 1996; Jenkins *et al.*, 1997; Rignot, 1998)

Abstract

A change in ocean circulation causes an incursion of warmer waters on the Antarctic continental shelf. Coming into contact with the ice sheet these warmer waters cause a rapid increase in the rate of melting beneath ice shelves especially close to grounding lines. Grounding lines retreat and reduce restraint on ice streams. Increased flux in the ice streams "draws-down" the interior basin.

Comments

- Basically the hypothesis pursued by Titus and Narayanan (1996)
- Melt-rates are important to overall balance of the Antarctic Ice Sheet (Jacobs *et al.*, 1992). Pine Island Glacier may have been suffering from precisely this mechanism in recent years.

SCENARIO 2 - "THERMOHALINE SHUT-DOWN"

Summary

Global forcing	Climate Change - increased atmospheric temp.
Direct forcing	Reduced sea ice production and thermohaline shut-down
Primary change	Reduced ice shelf melting and ice shelf thickening
Secondary change	Grounding of ice shelves and advance of grounding lines
Tertiary change	Thickening ice sheet due to reduced output flux
Century-scale risk/benefit	No effect?
Ultimate risk/benefit	Sea level fall

Primary sources

(Nicholls, 1997; Vaughan *et al.*, 1995; Nicholls, 1997; Nicholls, 1996; Nicholls & Jenkins, 1993)

Abstract

The thermohaline circulation beneath Filchner-Ronne, and perhaps other, ice shelves, is apparently controlled by the rate of sea ice production in the adjacent sea. If atmospheric warming reduces sea ice production then the thermohaline circulation would reduce and thus reduce melt-rates. Grounding of the ice shelf could then occur within a century in some areas.

Supporting evidence

- Seasonality of thermohaline circulation beneath Filchner-Ronne Ice Shelf.
- Recent reductions in sea ice extent in Amundsen and Bellingshausen seas.

Comments

- How many ice shelves might be affected?
- Nicholls suggests only a 10% reduction in basal melt-rates is likely.

SCENARIO 3 - "INCREASED PRECIPITATION"

Summary

Global forcing	Climate Change - increased poleward transport of moisture
Direct forcing	Increased precip. over Antarctica
Initial change	Thickening ice sheet
Ultimate change	Thickening of ice sheet (output flux constant)
Century-scale risk/benefit	Mitigation of other sea level rise components
Ultimate risk/benefit	Sea level fall

Primary sources

(Ohmura *et al.*, 1996; Bromwich, 1995; Bromwich, 1988)

Abstract

An increased poleward transport of moisture, either as a result of increased air temperature at the source of evaporation or due to alterations in storm tracks, causes increased precipitation over the Antarctic Ice Sheet.

Comments

- This mechanism would operate as a mitigator of sea level rise?

SCENARIO 4 - "UNSTABLE ICE STREAMS "

Summary

Global forcing	None
Direct forcing	Change in flow of one or more ice streams
Initial change	Thickening or thinning of ice sheet
Secondary change	Change in output flux
Century-scale risk/benefit	Sea level change
Ultimate risk/benefit	Sea level change

Primary sources

(Stephenson & Bindschadler, 1988; Retzlaff & Bentley, 1993; Anandakrishnan & Alley, 1997)

Abstract

The switch-on or off of ice streams in WAIS (or EAIS) would alter the output flux.

Comments

Could this happen to enough ice streams at the same time to make it important?

SCENARIO 5 - “GLACIAL READJUSTMENT ”

Summary

Global forcing	None
Direct forcing	Continuing (stepwise) change in ice streams
Initial change	Retreat of grounding lines
Secondary change	Increased output flux
Century-scale risk/benefit	Sea level rise
Ultimate risk/benefit	Sea level rise

Primary sources

(MacAyeal, 1992; Bindschadler, 1997a)

Abstract

As a continuing readjustment to the change in environmental conditions at the end of the last glacial period, the Antarctic Ice Sheet is still retreating, possibly in a stepwise fashion.

Comments

- Does this square with a current zero mass balance?
- “The fuse may have been lit 10 000 years ago for a possible ice-sheet H-bomb.”

SCENARIO 6 - “SUB-GLACIAL ERUPTION”

Summary

Global forcing	Sub-glacial eruption beneath the ice sheet
Direct forcing	Increase in basal temp and water pressure
Primary change	Collapse of ice-drainage basins
Century-scale risk/benefit	Sea level rise
Ultimate risk/benefit	Destabilisation of ice sheet

Primary sources

(Blankenship *et al.*, 1993; Jacobs *et al.*, 1996; Jenkins *et al.*, 1997; Rignot, 1998)

Abstract

A major sub-glacial eruption increases basal water pressure beneath the ice sheet and causes local ice-drainage basins to surge and perhaps destabilise neighbouring basins.

Comments

Part Four - Appendices

APPENDIX 1 – SUMMARY OF TITUS AND NARAYANAN, 1995/6

The study completed by Titus and Narayanan (Titus & Narayanan, 1995; Titus & Narayanan, 1996; Titus & Narayanan, 1996, together hereinafter T&N) is perhaps the closest predecessor to the present review, and is still the most comprehensive study completed to date. T&N studied all sources of sea level that are considered to result from climate change, loss of non-polar glaciers, thermal expansion of the oceans and changes in the Greenland and Antarctic ice sheets. While this sounds comprehensive, T&N's treatment of the Antarctic Ice Sheet was perhaps, less than satisfactory in that:

- They dealt only with climate-related change in the ice sheet
- They consider only increased, precipitation and change in ocean temperature causing ice shelf melting, as the drivers of change in the ice sheet.

T&N assume that global warming is proportional to greenhouse forcing, which they argue is roughly the case in many GCMs (Manabe & Stouffer, 1993). Even on the large-scale, this is a gross simplification, but on the continental or regional-scale it makes little sense. The regional warming of the Antarctic Peninsula during the last 50 years, which has been around five times the global mean warming, is a prime example of where such an assumption may turn out to be hopelessly inadequate.

T & N basically disposed of the Antarctic contribution to sea level rise by concentrating on one scenario of change, they reduced the problem of change in the Antarctic Ice Sheet to a linear framework, which allowed for elements of non-linearity but assumed that these would be covered by the extremities of the probability distributions which their panel produced - this was essentially a non-Bayesian approach. In summary; "…we focus on the possibility that warmer circumpolar ocean water will intrude beneath the ice shelves, increase their rates of melting, decrease the backpressure that they exert on the ice streams, and thereby accelerate the rates at which ice streams convey ice from the antarctic interior toward the oceans.". They attack the problem in four steps

- *Polar Temperatures* - T&N calculated Antarctic atmospheric temperatures by applying an simple amplification factor and lag to their global warming rates, which were in turn was proportional to increased radiative forcing.
- *Increase in ocean temperature beneath ice shelves* - The change in Antarctic circumpolar sea-temperatures were assumed to be some fraction of the change in Antarctic atmospheric temperature, with the possibility that should this temperature exceed some threshold the Antarctic continental shelf might be flooded by circum-polar deep water (CDW).
- *Increase in ice shelf melt-rate* - T&N noted that the ice-shelf [melting] model was probably the weakest link in their chain of assumptions (pg. 185). There is some discussion as to whether they should assume that melt-rates ought to be proportional to the ice shelf / ocean temperature difference or perhaps to its square.
- *Increase in discharge from the ice sheet* - Reviewers were asked to assign probabilities to eight alternative "assumptions" about the impact of ice-shelf thinning on the mass of the Antarctic Ice Sheet. Ranging from a "Minor response" for which increased ice shelf melting results in no increased discharge from Antarctica, to unstable responses in which on the model by Thomas (Thomas, 1985) and applied to an decreasing fraction of the ice streams and glaciers.

In addition, I believe that T&N add to the confusion of, *probability* and *risk*, with *uncertainty*. They are aggregating estimates of uncertainty gathered from across the scientific community to give a overall estimate of *uncertainty*, but they describe the value as a *probability* where I would argue it is not. (See Appendix 3 – Probability vs. Uncertainty)

APPENDIX 2 – A SCIENTIFIC APPROACH TO RISK ASSESSMENT

It may be interesting to step back from the detail for a moment and think about the nature of the problem, evaluating the risk assessment of globally important change in the Antarctic Ice Sheet, and how we are approaching it.

Rigorous risk assessments are generally approached in two ways:

- By the analysis of real-world data specifying the number of times some specific initial conditions were met and the number of times a particular hazard was realised. Examples of this approach abound in the insurance industry, for example specifying the risk (probability) that at least one in a group of 1000 houses will burn down in a year.
- By developing a good understanding of the physics of the system, which allows us to construct a mathematical model that adequately describes the processes leading from some specified initial conditions to some particular *hazard*, and assuming that this model provides an entirely adequate description. An example might be, to determine the risk that debris from an explosion at a nearby factory would fall on a particular housing estate – given the mass and energy distribution of the debris, calculating the likelihood of the village being hit would be a relatively simple numerical task.

In some cases, however, neither of these approaches is useful. Such cases usually involve infrequent and complex hazards. Their infrequency means that there is no adequate dataset describing previous occurrences and their complexity means that we cannot hope to model every aspect of the path to the hazard. While not unique in this respect, the present investigation (risk assessment of globally important change in the Antarctic Ice Sheet) certainly falls into this category. After all, we have only an imprecise record of changes in the Antarctic Ice Sheet in the geological record, and the ice sheet is an inhomogeneous, continental-scale system that we cannot hope to model entirely realistically.

The methodology that appears to have become a *de facto* standard scientific approach to problems of this class is to attempt to use field and laboratory observations to identify the physical processes that are most important in controlling the large-scale behaviour; to build *reduced* numerical models that contain approximate descriptions of these processes, and use these models to predict outcomes given specified starting conditions and forcing fields. In our case the starting conditions are derived from present (or past) configurations of the ice sheet and the forcing fields are climatic and environmental parameters from other models of the Earth system. Since such models are generally deterministic we usually attempt to use an *ensemble* of runs of the model, in which the starting conditions and forcing fields are allowed to vary within realistic limits, to establish the level of our uncertainty which we usually can express as a percentage. The better we understand the problem and the initial conditions, the more reliable the answer we get from the exercise.

Understanding the process prompts the question of how we should now discuss the results of such the exercise. I do this in Appendix 3 Probability vs. uncertainty.

APPENDIX 3 – PROBABILITY VS. UNCERTAINTY

While we cannot yet exclude the possibility that there is some chaotic behaviour in the Antarctic Ice Sheet system (MacAyeal, 1992) there is a general assumption that we are dealing with an effectively deterministic system (on human time-scales), which tends to evolve in response to mean climate rather than individual extreme-weather events etc. Given that this is a largely deterministic problem we must consider carefully the terms we use to describe how much reliance we can place on the results of procedures described in Appendix 2.

Probability is the mathematical expression of chance; the chance that a particular event will occur in a period of time. Probability is best applied to chaotic systems or events that occur many times and that can be measured statistically, they are inappropriate for systems that will have only one outcome and whose outcome we believe to be deterministically related to the initial conditions and forcing function. In the case of the Antarctic Ice Sheet, probability are clearly inappropriate terms since there will be only one realised outcome, and at least to first order, we believe that the outcome is likely to be predictable. Research does not help reduce the probability of the hazard unless it leads you to reduce the factors that lead to it. The probability is essentially fixed by the physics of the problem – no matter how much you understand about the physics of a dice-in-flight the *probability* of throwing a six remains 1-in-6 (16.6%).

So in considering how to report the results of this and similar studies (Risk assessment of globally significant change in the Antarctic Ice Sheet) I believe we should use the term, *uncertainty*, rather than any definition of probability. Uncertainty arises from poor understanding of the physics of the problem, inadequate initial conditions and uncertainty over the forcing fields. The main difference between uncertainty and probability is that further research will allow one to reduce the uncertainty.

I have laboured this distinction for good reason; it has a real impact on the risk perception. Titus and Narayanan (1996) suggest that there is a 50% probability that anthropogenic greenhouse warming will give rise to more than 34 cm of sea level rise by 2100 (their Figure 14a). I believe that this expression is unhelpful and in some respect misleading for the following reasons. Firstly, this probability is not realistic, this amount of sea level rise may already be inevitable (100% probability) or it might be a practical impossibility (0% - we might conceivably be on the verge of a new ice age). Secondly, presented as a probability, the future appears very depressing, especially for island states that would be devastated by a 34-cm sea level rise, and for policy-makers who feel that early, and probably Draconian, measures of mitigation, are warranted: whereas the same information presented as an *uncertainty* might simply prompt us to admit the risk, and accept it until the uncertainty is reduced through an aggressive programme of research.

APPENDIX 4 – GLOSSARY

Consequences - Adverse effects or harm which cause the quality of human health or the environment to he impaired in the short or longer term (Department of the Environment, 1995).

DEM – Digital Elevation Model a numeric description of topography in an area. For an ice sheet it might represent either the ice surface or the bed surface.

Deterministic – describes a model or physical system in which, given a specified set of starting conditions and forcings, there is only one possible outcome.

Eustatic sea level change – change in sea level caused by the rise and fall of the sea-level due to a change in mass of water in the oceans and not by subsidence of the land.

GCMs – The Global Circulation Models used to understand present and future climates. They include integrated atmospheric and oceanographic models.

Glacial Ice – The ice which makes up the majority of glaciers and ice sheets, it is distinct from *sea ice*.

Global Warming – a misleading and unhelpful term, which fails to recognise the complexity of future climate response to rising levels of greenhouse gases. Preferred is “Climate Change” which may be natural of anthropogenically-induced.

GPS – Global positioning system, a method of satellite navigation capable of allowing the precise determination of the position of an object with reference to a geographic frame.

Hazard - A property of situation that in particular circumstances could lead to harm (Department of the Environment, 1995).

Mass balance – the difference between the amount of snow, ice entering a particular area of ice sheet and the amount leaving in the same period.

Negative feedback – a mechanism in which the consequence tends to reduce the forcing, such that the response tends to reduce the cause. A negative feedback system thus tends to suppress change to some extent.

NWP-GCM – A general circulation model that is used for the prediction of weather and so during the model run is reinitialised, or forced using meteorological measurements.

Positive feedback – a mechanism in which the consequence tends to compound or intensify the forcing. A positive feedback system thus tends to enhance and promote change, although its effects are not necessarily be catastrophic nor instantaneous.

Probability – “is the mathematical expression of chance (for instance, 0.20, equivalent to a 20 per cent or a one in five change), wherever this usage is possible but in many cases it can be no more than a prospect which can be expressed only qualitatively. The definition applies to the occurrence of a particular event in a given period of time or as one among a number of possible events.” (Department of the Environment, 1995)

Risk estimation - The determination of the outcome or consequences of an intention taking account of the probability of occurrence (Department of the Environment, 1995).

Risk evaluation - the determination of the significance of the estimated rises for this affected including an element of risk perception (Department of the Environment, 1995).

Risk perception - the overall view of risk held by a person or group and includes both feeling and judgement (Department of the Environment, 1995).

Sea Ice – frozen sea water, which forms on the surface of polar seas.

Steric sea level change - changes in sea level due to changes in seawater density (temperature and salinity).

Surface balance – more properly *mean net surface mass balance* (Vaughan *et al.*, 1999) is the mean mass of snow or ice accumulating on the ice sheet each year. The figure accounts for, precipitation, evaporation, melting, wind-driven redistribution, etc.

Sustainable development - “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs” - Brundtland Commission, 1987.

Uncertainty – A expression of doubt in the outcome of a particular event which might, like probability, be expressed in percentage terms.

WAIS - The WAIS Antarctic ice sheet. The portion of the Antarctic Ice Sheet occupying the sector between 75EW and 175EE, much of which rests on rock considerably below sea level and has been suggested to have the potential for rapid collapse.

Ice Divide – The geographic line dividing different ice-drainage basins -- similar to a hydrological watershed.

APPENDIX 5 – NOTES ON NOMENCLATURE

Strictly the terms *glacier*, *ice stream* and *outlet glacier* are often miss-applied even in the glaciological literature. The strict definitions being that; *ice streams*, are areas of fast-moving ice bounded by slower moving ice, *outlet glaciers*, are bounded by nunataks; and *glaciers*, is a generic term that covers any ice in an ice sheet (Bentley, 1987; Swithinbank, 1954). I use the term *ice stream* more loosely to refer to all fast-moving grounded ice, including outlet glaciers.

APPENDIX 6 – WHAT IS THE GLOBAL HAZARD ASSOCIATED WITH SEA LEVEL RISE?

Clearly an assessment of what sea level rise constitutes a hazard is beyond the scope of this review – this will be a matter for government and intergovernmental discussion. There are however a couple of guiding points that I believe should be borne in mind:

- The damaging effect of sea level rise is largely a result of increased frequency and increased intensity of extreme storm and tidal events.
- The primary review of data on the regional impact of sea level rise was given by the IPCC Working Group II (Watson *et al.*, 1998). Their estimates for the number of people that will be affected by a 1-m rise in sea level are shown in Table 4.
- It will be a relatively simple procedure to determine how much extra damage has been done by a particular storm event as a result of increased sea level, and so given reliable climate and sea level predictions the increased hazard can be calculated.
- The question of blame or responsibility is, however, far more uncertain. Two questions need to be addressed, is there an increase in storm frequency and intensity which is attributable to the, increase in greenhouse gases and is sea level rise attributable to the increase in greenhouse gases.
- In calculating the future cost of sea level rise, the only concrete comparison we can make is to the cost of sea level rise in the 20th Century, and this may have been substantial (Zhang *et al.*, 1997).
- Because the effect of sea-level rise is to increase the hazard of infrequent storm surges, the relationship between sea level rise and the cost of the hazard is highly non-linear. For example: The Thames Barrier which is the City of London's primary sea defence system is closed each time the predicted tidal height is within 0.45 m of the top of the Embankment wall. Since being completed in the early 1980s the barrier has been closed for sea defence reasons only 33 times, about twice each year. Given a sea level rise of 0.5 m the barrier would be closed around 300 times per year, severely restricting the use of the Port of London as a port (UK Environment Agency, 1998).

Area	Population effects
Egypt	8 000 000 displaced
Nigeria	3 700 000 displaced
Senegal	110 000 – 180 000 displaced
The Gambia	> 42 000 displaced
Europe	40 Million threatened by 1-in-1000 year storm damage
Belize	70 000 “affected”
Guyana	600 000 “affected”
Uruguay	13 000 displaced
Venezuela	56 000 displaced
Japan	4 100 000 “in flood-prone areas”
Bangladesh	15 000 000 displaced
India	7 000 000 displaced
Indonesia	2 000 000 displaced

Table 4 – Summary of the population effects of a 1-m sea level rise given by IPCC Working Group II (Watson et al., 1998). Most other nations with coastlines will also be affected so some extent but they were not assessed in that report.

APPENDIX 7 – IMPACT OF CLIMATE-RELATED CHANGE ON THE ANTARCTIC PENINSULA

At least 5 meteorological records from the scientific stations on the Antarctic Peninsula have shown decadal warming trends (King, 1994; Harangozo *et al.*, 1997; Skvarca *et al.*, 1998). While the period and seasons of observations have been different between the stations the records show consistent warming trends of (up to 0.07 EC a^{-1}) - considerably higher than the global mean. This atmospheric warming appears to have caused several notable changes in the ice cover of the Antarctic Peninsula, including changes in the snow elevation (Morris & Mulvaney, 1995; Smith *et al.*, 1999)and the extent of surface snow cover (Fox & Cooper, 1998). The most significant of these has been the retreat of ice shelves around ice shelves.

Seven ice shelves on the Antarctic Peninsula have thus far shown significant progressive and continued retreat, Wordie Ice Shelf, Müller Ice Shelf and George VI Ice Shelf and Wilkins Ice Shelf on the west coast (Vaughan & Doake, 1996; Ward, 1995; Luchitta & Rosanova, 1998); the ice shelf that occupied Prince Gustav Channel, that which occupied Larsen Inlet and Larsen Ice Shelf A on the east coast (Vaughan & Doake, 1996; Rott *et al.*, 1996; Skvarca *et al.*, 1998). Thus far around several thousand km^2 of ice shelf have been lost.

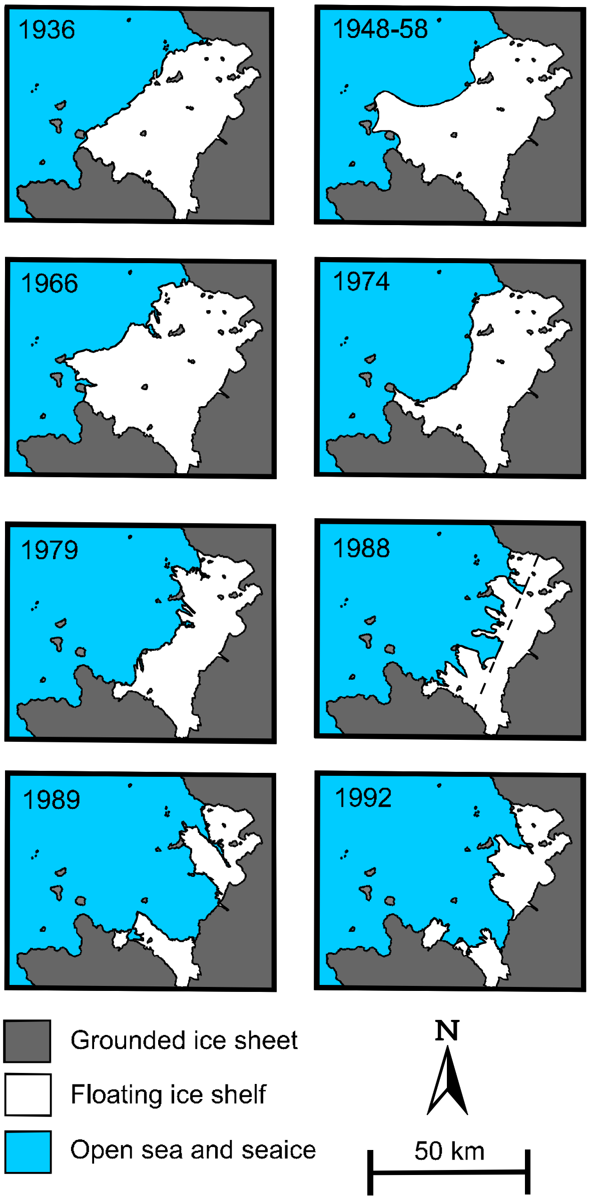

Figure 11 - Cartoon of the retreat of Wordie Ice Shelf since its earliest exploration. Ice shelf extent was derived from oversnow survey, aerial photography and satellite imagery. Reproduced from Vaughan and Doake (1996)

Following Mercer (Mercer, 1978), Vaughan and Doake showed that the pattern of retreat could be explained by a southerly movement of the 0 EC January isotherm which appears to define a limit of viability for ice shelves. However, Vaughan and Doake disagreed with Mercer’s implication that the loss of ice shelves on the Antarctic Peninsula would be a close-precursor for loss of the major ice shelves around the WAIS.

While retreat of the ice shelves on the Antarctic Peninsula has attracted considerable media coverage and non-Governmental environmental campaigns have expressed the view that these events presage a more important collapse in the WAIS Antarctic ice sheet (Rose & Greenpeace, 1997; Greenpeace, 1998), the retreat of Antarctic Peninsula ice shelves should raise few concerns:

- The retreat is due to regional atmospheric warming but, a causal connection between this warming and increase in greenhouse gases cannot be yet be made.
- The ice shelves were floating and so their melting gives only an insignificant steric sea level rise.
- Since the Antarctic Peninsula is steep and rugged there no evidence to believe that the removal of ice shelves will cause the glaciers that fed them to accelerate and add to sea level (Vaughan, 1993).
- Terrestrial ecosystems will be generally unaffected by the ice shelf retreat.
- It is expected that the areas of seabed no longer covered by ice shelf will be newly colonized by marine ecosystems.
- Since the warming seen on the Antarctic Peninsula exceeds that over much of the rest of the continent (Jacka & Budd, 1998) the migration of the limit of viability for ice shelves is unlikely to affect the Ronne-Filchner or Ross ice shelves for perhaps hundreds of years (Vaughan & Doake, 1996).

The real implications of the ice shelf retreats are more that they highlight issues of risk perception and the public understanding of climate change rather than real physical impacts. These include:

- Should we interpret the Antarctic Peninsula warming as resulting from a global effect or simply from natural regional climate variations. Such problems of attribution of climate change will recur, especially if the costs of adaptation are to be spread across nations.
- The inherent non-linearity of natural systems promotes exaggerated local responses to small climate changes.
- The predictions of the present generation of GCMs, for climatically distinct regions such as the Antarctic Peninsula are not regarded as reliable and so local effects on these scales cannot yet be reproduced or predicted (Connolley & O'Farrell, 1998). Since human activities and natural ecological systems are particularly susceptible to changes in local rather than regional climate, it is precisely these effects that will be the most important to predict accurately.

APPENDIX 8 – PREDICTIONS FROM HADLEY CENTRE CLIMATE MODEL

For illustrative purposes there follows some climate predictions produced by the Hadley Centre for Climate Change. The results are from the model *HADCM2* which is described in detail by Mitchell et al. (Mitchell *et al.*, 1995) . Specifically the snapshots presented result from a comparison of a control model-run with no external forcing and a model-run forced using IS92a CO_2 scenario (Houghton *et al.*, 1996), which reaches around twice pre-industrial levels of CO_2 by the year 2100. The model includes the effects of sulphate aerosols.

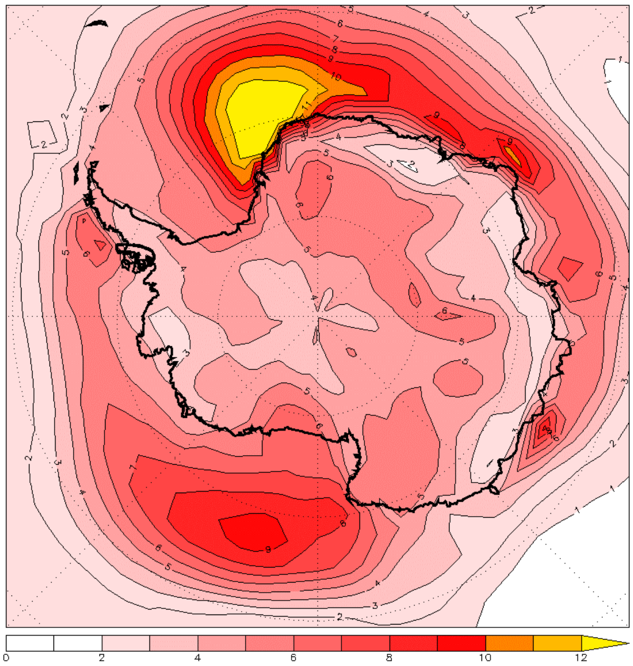

Figure12 – Increases in June/July/August (winter) sea and ice surface temperatures in 2100 due to IS92a CO_2 scenario. The major increase in temperature off the coast between 0EE and 30EW is possibly the result of the return of a feature similar to the Weddell Sea Polynya, which was common in this area until the mid-1970s but has since failed to reappear.

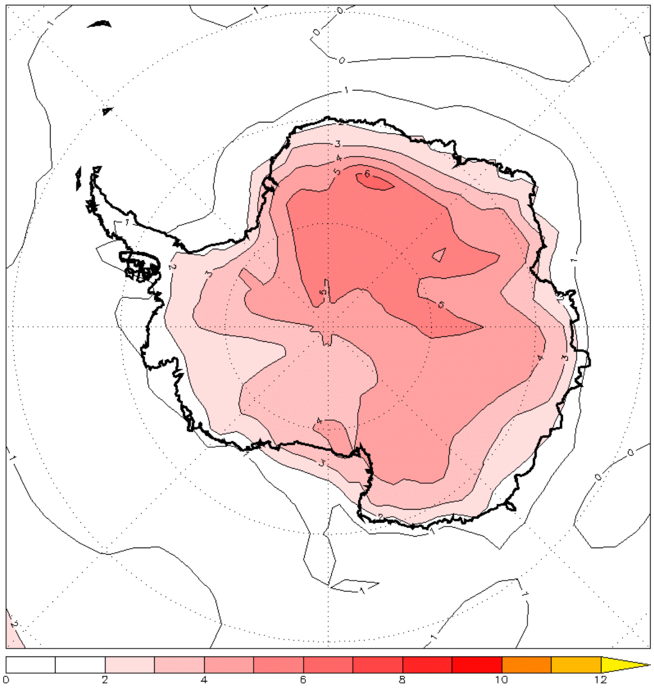

Figure 13 – Increases in December/January/February (summer) sea and ice surface temperatures by 2100 due to IS92a CO_2 scenario.

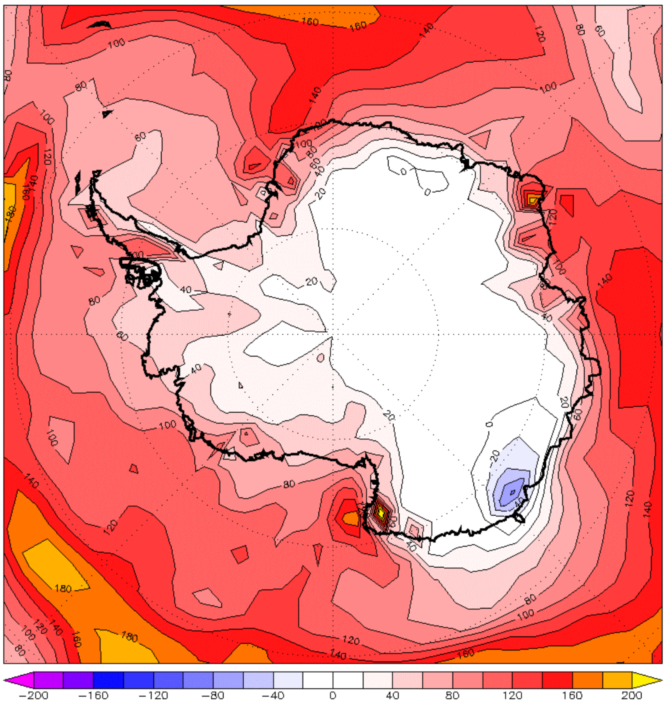

Figure 14 – Increase in mean annual precipitation in 2100 in mm a^{-1}of water. Note that this includes both precipitation from large-scale storm events and small-scale convective processes.

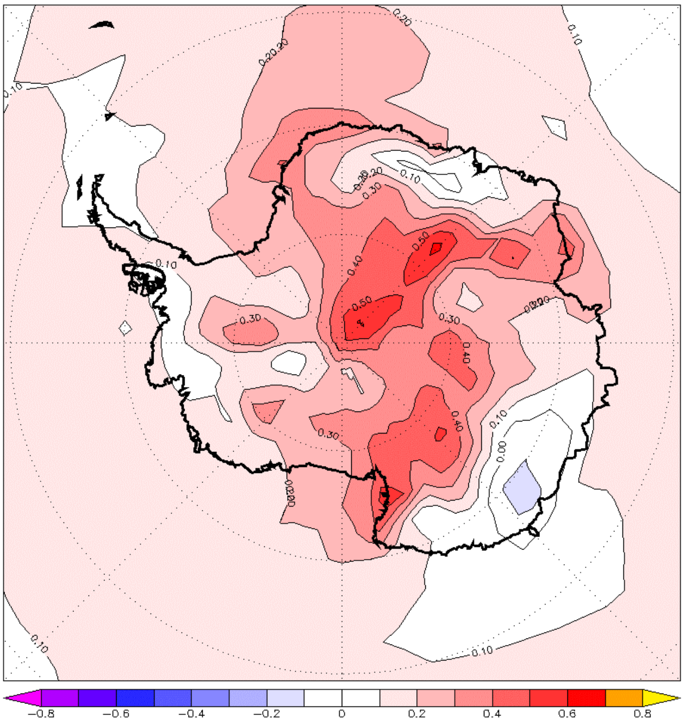

Figure 15 – Ratio of increase in mean annual precipitation in 2100 under IS92a to that from the unforced control run representing pre-industrial conditions. Note that this includes both precipitation from large-scale storm events and small-scale convective processes.

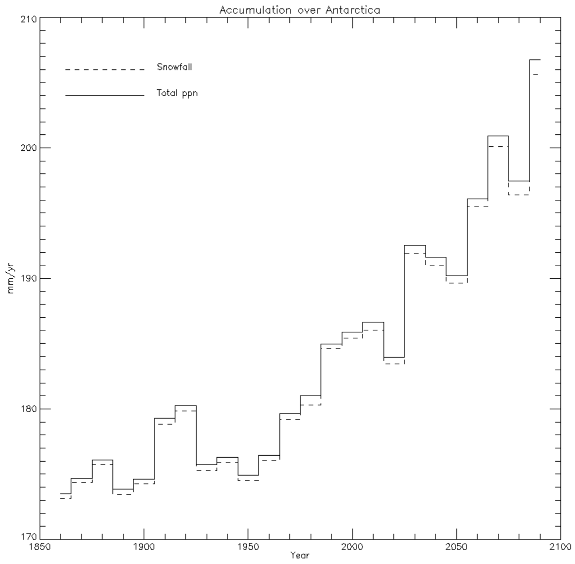

Figure 16 – Mean precipitation from HADcm2 for the area of the Antarctic Ice Sheet, averaged over 10-year periods. Note that this graph implies that towards the end of the next century increased precipitation will force global sea level down by 1 mm a^{-1}.

APPENDIX 9 – DO ANTARCTIC AND GREENLAND CONTRIBUTIONS TO SEA LEVEL CANCEL OUT?

(Ohmura *et al.*, 1996) - "*The change in the combined mass balance of the two continents [Greenland and Antarctica] is almost zero. The sea level change of the next century can be affected more effectively by the thermal expansion of seawater and the mass balance of smaller glaciers outside Greenland and Antarctica*"

An implication that many readers would draw from these and similar ones comments that have appeared in the literature, is that because the predicted contributions to sea level change from the Greenland and Antarctic ice sheets are opposite and roughly equal in magnitude, together they result in no significant change in eustatic sea level and from the point of view of sea level rise ice sheets can be excluded from the assessments of the prediction of future sea level rise. I believe that such a conclusion is both misleading and unhelpful.

Sea level change will be driven by several sources and sinks. The recent estimates of the likely contributions to sea level change during the coming century (Warrick *et al.*, 1996) indicate that there are at least four contributions that must be accurately predicted for us to produce a reliable estimate of sea level rise. They are; the thermal expansion of the oceans, the wastage of mountain glaciers, the Greenland ice sheet and the Antarctic Ice Sheet.

APPENDIX 10 – SUMMARY OF HINDMARSH 1993

One paper above all (Weertman, 1974) has been significant in shaping the interpretation of the stability of polar ice sheets. It has been widely cited to promote the general view that the WAIS must be unstable. However, amongst others, Hindarsh (Hindmarsh, 1993a; Hindmarsh, 1993b; Hindmarsh, 1996) has recently fundamentally questioned Weertman's conclusions. *Hindmarsh's result are born out of a complex mathematical analysis which is inaccessible even to some in the subject of glaciology, and so I believe that it is a useful exercise to amplify his findings in an abbreviated form.*

Weertman developed a simple model of the behaviour of the stability of the junction between ice sheet and ice shelf, the grounding line and concluded that where the bed sloped down inland the grounding line would not be stable, except when it was at the continental shelf edge. This led to the widely cited hypothesis that the current configuration of WAIS Antarctic Ice Sheet (WAIS) was inherently unstable, and might collapse - especially if the restraint exerted by Ross and Filchner-Ronne ice shelves was removed. Some authors have even suggested that climate change might begin the process by removing the ice shelves (Mercer, 1978) although this was never widely supported within the glaciological community.

Although it seemed self-evident, Weertman's assumption that ice thickness must be continuous at the grounding line is now in doubt. Considering ice streams and outlet glaciers as intermediates between grounded ice sheets and ice shelves allowed Hindmarsh to relax this condition - considering ice streams cans effectively as a buffer between the grounded ice sheet and the ice shelf (Hindmarsh, 1993b). Hindmarsh showed that an infinite number of grounding line positions are compatible with equilibrium and the ice sheet itself can achieve a *neutral equilibrium* with an ice stream grounding line at any point. Furthermore, he found that the ice stream - ice shelf transition is largely unimportant in controlling the configuration of the ice sheet. Weertman's original argument is considerably shaken.

ACKNOWLEDGEMENTS

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DISCLAIMER

Reference List

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