THE WEST ANTARCTIC ICE SHEET AND LONG TERM CLIMATE POLICY

An Editorial Comment

1. Introduction

Disintegration of the West Antarctic ice sheet (WAIS) has long served as a benchmark of dangerous climate change (Mercer, 1968, 1978; Revelle, 1983; Smith et al., 2001). Recent findings with implications for the future of the West Antarctic ice sheet in a warming world (Rott et al., 2002; De Angelis and Skvarca, 2003) may be of importance to policy makers and others (Berk et al., 2002) grappling with the meaning of Article 2 of the U.N. Framework Convention on Climate Change and its injunction to avoid 'dangerous anthropogenic interference with the climate system.' These observations show acceleration of glaciers coupled to abrupt ice-shelf disintegration along the Antarctic Peninsula (Doake et al., 1998). The key issue is whether the main body of the ice sheet would behave similarly if its ice shelves were thinned or removed by a warming climate.

The accompanying editorial essay by Dessai et al. (2004) argues 'internal definitions of dangerous climate change –"danger as experienced" – warrants at least as much attention as external definitions – "danger as defined" '. We agree that the interpretation of Article 2 ought to expand beyond traditional approaches grounded in climatology, biology, economics and engineering. The editorial further states 'it is not possible to make progress on defining dangerous climate change, or in developing sustainable responses to this global problem, without recognising the central role played by social or individual perceptions of danger.'

There is a substantial risk in adopting the latter view. Addressing the psychological and much of the social dimension of dangerous climate change is in its infancy in comparison to the decades-old process of physical assessment. An equally prolonged discussion of the social and psychological dimension is in the offing. The continuing increase in greenhouse gas concentrations could make certain dangers unavoidable unless a preliminary interpretation of Article 2, based largely on the 'external' framework, is implemented (O'Neill and Oppenheimer, 2002). In practice, such an approach already may be feasible for a handful of climate changes, such as the 'large-scale discontinuities' (e.g. disintegration of WAIS, shutdown of the thermohaline circulation) noted in the Third Assessment Report of the Intergovernmental Panel on Climate Change (Smith et al., 2001).

The recent glaciological findings provide an opportunity to consider how a long-term objective consistent with Article 2 might be selected, because they shed

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new light on the range of climate change that may trigger disintegration of WAIS. Here we explore the key scientific issues and consider a long-term approach to limiting greenhouse gas concentrations based upon these observations, tied to the viability of the major West Antarctic ice shelves. We believe the consequences of a WAIS collapse would be so large that despite uncertainties, external considerations supplemented by a precautionary interpretation of the recent observations may be sufficient to define dangerous levels of climate change, and the corresponding greenhouse gas (ghg) concentrations.

2. WAIS in a Warming World

Projecting the behaviour of WAIS has proven nearly intractable thus far, yet it remains a high priority from the perspective of forming credible policy on climate change. Disintegration of WAIS would raise global mean sea level by about 5 m, gradually displacing or destroying coastal settlement, infrastructure, and ecosystems worldwide (Revelle, 1983). The combination of a very large potential impact along with great uncertainty over the probability and timing of disintegration (Oppenheimer, 1998) makes this a classic decision-making quandary, one reminiscent of that faced by governments pondering the future of the ozone layer before the discovery of the ozone hole (Benedick, 1998; Parson, 2003; Anderson and Sarma, 2003).

WAIS, which accounts for 10% by volume of the entire Antarctic ice sheet, is maintained by a balance between precipitation and loss of ice to the ocean through melting and iceberg calving (Rignot and Thomas, 2002). Ice streams are fast-moving ($\sim$1 km/yr) rivers of ice that transfer mass from the relatively static interior of the ice sheet to its periphery. There the ice either calves into the sea directly or, more typically, is incorporated into ice shelves by crossing the grounding line where it begins to float. Ice shelves maintain their mass balance by producing icebergs at their seaward edge and by melting, primarily on their undersides (Jacobs et al., 1992).

Thirty-five years ago, John Mercer (1968) speculated that warming due to 'industrial pollution of the atmosphere' could cause the ice shelves of West Antarctica to disintegrate, producing a catastrophic release of ice to the sea, thus causing a sea level rise of about 5 m during the course of a century.

Mercer argued that absent ice shelves, which may be viewed as extensions of the land-based ice, WAIS would float off into the sea because the grounded ice rests on a bed that by and large lies far below sea level. He speculated that under current circumstances, disgorgement of the grounded ice is inhibited because forward motion of the ice shelves (and consequently the grounded ice as well) is blocked by friction with the sides and local high spots on the floors of the rocky embayments in which the ice shelves float.

Mercer's views, first buried in a publication of the International Association of Scientific Hydrology, caught the attention of policy makers when published in 1978 in *Nature* under the title 'West Antarctic ice sheet and CO_2 greenhouse effect: A threat of disaster' (Mercer, 1978), and were extensively reviewed in the 1983 National Research Council study, *Changing Climate*, the first comprehensive assessment of science and policy pertinent to the global warming problem (Revelle, 1983). A physical basis for Mercer's qualitative arguments was provided by early models of the ice sheet–ice shelf junction (Weertman, 1974; Thomas and Bentley, 1978).

Subsequent studies found a lifetime for the ice shelves of hundreds to thousands of years in a warmer climate, and placed a lower limit of 200 years on the ice sheet disintegration time once the ice shelves melted. By the late 1980s the notion that loss of ice shelves could lead to disintegration of the entire ice sheet fell out of favour in some quarters of the glaciological community. Numerical ice sheet models had found stable solutions for the state of the ice sheet even with ice shelves removed (van der Veen, 1985; Herterich, 1987; Hindmarsh, 1993). Factors other than ice shelf buttressing, such as friction between ice streams and neighbouring, static ice, were thought to control ice stream flow (Echelmeyer et al., 1994).

But the peace has been an uneasy one for glaciologists because no ice sheet model has accurately reproduced the existing ice streams, which are the major dynamical features of the ice sheet. Whether projections of a stable future can be trusted under such circumstances is a matter of judgement, and opinions differ widely (Oppenheimer, 1998; Vaughan and Spouge, 2002).

3. Recent Findings

Two recent sets of observations have brought renewed attention to Mercer's speculations. Ice shelves along the Antarctic Peninsula, which projects north from the WAIS into warmer regions, have been disintegrating for about 35 years, beginning with the small Wordie ice shelf on the Peninsula's western side, in response to a long-term warming trend that may be partly tied to the rise in global mean temperature (Vaughan et al., 2003). In the past decade, the Larsen ice shelf on the eastern side has experienced progressive, spectacular collapse of neighbouring sections, starting at its warmest, northernmost end. Such a southward progression was indeed proposed by Mercer (1978) as an early warning sign for the entire ice sheet.

But it is the short time scale of collapse (one 2,500 km^2 section shattered within days) that caught the attention of scientists and the public. One hypothesis is that surface melt water seeping into crevasses wedges them open via the forcing effect of water pressure (Scambos et al., 2000, 2003). Downward heat transport by melt water and expansion of re-frozen water may also contribute to the resulting catastrophic failure (Doake et al., 1998). Confined ice shelves, like George VI, or those not subject to crevassing, apparently sustain melt water ponds without experiencing such failure (Scambos et al., 2003).

Short timescales call into question the earlier supposition that ice shelves can endure for millennia in a warming climate once temperatures sufficient to produce surface melting are reached. Although the large ice shelves bordering the bulk of WAIS' ice farther to the south are much more extensive and thicker than those along the Peninsula, the thickness difference is not so huge that a similar future is implausible. The $\sim$200 m thickness of the Larsen B ice shelf (Scambos et al., 2000) is not very different from the mean ice shelf thickness of the Ross and Filchner-Ronne ice shelves (427 m and 475 m, respectively). One large section of the Ronne ice shelf has a minimum thickness $<$200 m, and both of the large ice shelves have long sections lacking any major obstructions to ice flow (Drewry, 1983).

With regard to early warning signs, the second pertinent observation would be the fate of the ice behind the erstwhile ice shelves along the Peninsula. One assessment of glaciers behind the Wordie ice shelf (Vaughan, 1993), which has been called into question recently (Rignot et al., 2003), found no response.

But two studies of glaciers behind the northern section of the Larsen ice shelf have revealed the opposite: Following the collapse of the ice shelf in 1995, five of the six largest former tributary glaciers experienced flow acceleration and other changes, including a tripling of velocity on one glacier and a doubling on another by 1999, then an additional doubling of velocity on the latter glacier by 2001 (Rott et al., 2002; De Angelis and Skvarca, 2003). The amount of ice on the Peninsula is not large in terms of global sea level but the changes in speed would be very significant if applicable to the bulk of WAIS in the future.

Do these two sets of observations really constitute an early warning sign? Just as there is no fully validated model of the ice streams draining WAIS, there has been little modelling and sparse observation of the glaciers on the Peninsula. We cannot say if the same dynamical processes apply in both places. Furthermore, the cause-and-effect relation between ice shelf collapse and glacier surge may be more apparent than real. Because the timing of onset of surge is not clear, it is conceivable that the surging started first and contributed to the ice shelf collapse, perhaps because the enhanced melting linked to the ice shelf collapse also supplied more water to lubricate the glacier beds (Zwally et al., 2002).

But it is also plausible that outlet glaciers, whose dynamics are thought to be controlled by friction with the sides and bottoms of the valleys in which they flow, may be partly buttressed by an ice shelf. In that case, the acceleration of these glaciers may be pertinent to the ice streams farther south that differ primarily by having less bedrock control and more basal lubrication than outlet glaciers are generally thought to have (Bentley, 1987).

4. Assessing the Risk

Among the several policy frameworks for evaluating the hazards that may arise from global change is the precautionary approach (Gollier, 2001) highlighted in Article 3.3 of the Framework Convention. This view would give considerable weight to the new observations, which reopen the possibility that loss of the large ice shelves in the Ross and Weddell seas would cause acceleration of the ice streams, increased discharge of grounded ice to the sea and a much faster rate of global sea level rise than otherwise projected (Church and Gregory, 2001). Then a key issue for policy makers becomes, *At what temperature are the ice shelves vulnerable to collapse?*

According to the crevasse/melt water hypothesis, ice shelves become vulnerable when surface temperature exceeds the melting point for a significant part of summer, which would require ∼8°C warming in the latitude zone 75–80 S. General circulation models (GCMs) indicate that this outcome becomes plausible near equilibrium at greenhouse gas levels greater than an equivalent doubling of CO_2 concentration (Manabe et al., 1992). The rate of warming is geographically variable at the high latitudes and varies substantially from model to model, and the seasonal rate of warming at particular locations is very uncertain. Nevertheless, climate forcing sufficient to cause disintegration of the ice shelves decades or more later could be set in place *during this century* (Cubasch and Meehl, 2001; Wild et al., 2003).

We conclude that allowing the concentration of greenhouse gases to reach a level equivalent to a doubling of CO_2 poses a significant, although poorly quantified, risk of disintegration of WAIS. GCMs provide limited guidance because the ice shelves are small features compared to the resolution of most global models, and surface trends around Antarctica are projected to be spatially quite variable. Because we do not know precisely when melting would become widespread on the ice shelves, nor precisely how fast the ice streams might respond, we cannot yet estimate how soon collapse could occur. One well-respected ice sheet model that lacks the dynamics of ice streams found that an annual warming of between 9°C and 10°C or perhaps less over the entirety of WAIS was sufficient to remove it, but changes typically require a millennium or longer (Huybrechts, 1994; Huybrechts and De Wolde, 1999).

We have referred to our approach as precautionary because it assumes that enhanced discharge of grounded ice is triggered once ice shelves are lost via surface melting as air temperatures reach the freezing point. However, other mechanisms may cause loss of ice shelves at lower temperature. It is worth taking note of the limited (and controversial) evidence that WAIS disintegrated sometime during the Pleistocene (Scherer et al., 1998), a period when local air temperature inland probably rose to no more than 4°C above current levels (Petit et al., 1999), and the global mean to no more than 2°C warmer than today.

The most likely mechanism for melting at lower temperatures is via warming of the circumpolar deep water (cdw). Where such water intrudes beneath ice shelves (Jacobs et al., 1996), its warming may speed thinning and contribute to ice shelf loss. A compelling picture has emerged of ice shelf melting (Rignot and Jacobs, 2002) and thinning (Rignot, 2002), as well as the acceleration (Rignot et al., 2002) and net loss of grounded ice (Rignot, 1998; Shephard et al., 2001; Rignot and Thomas, 2002) in the Amundsen Sea–Pine Island Bay region. There, relatively warm cdw already comes into contact with small ice shelves that may have provided some buttressing for grounded ice (Schmeltz et al., 2002). Relatively modest warming or re-arrangement of the flow of cdw in the future might bring substantial increases in melt rates under the larger ice shelves (Oppenheimer, 1998).

We hesitate to use this mechanism to derive target temperatures or concentrations because, in contrast to the links that may be made between ghg concentrations and surface temperatures, there is as yet no quantitative link among surface temperatures or ghg concentrations and changes in cdw temperature, location, or flow. Neither is there sufficient information on the previous extent and duration of the Amundsen Sea ice shelves nor on marine temperatures at earlier times to tie recent changes in the ice to even local warming.

Aside from basal melting, ice shelves may become vulnerable to rapid disintegration before mean seasonal surface air temperatures reach the freezing point generally over an ice shelf. For example, melt water ponds in local warm spots have lower albedo than ice (Scambos et al., 2003), enhancing the melt water source to crevasses. Applying the ECHAM4 GCM to Antarctica, one study finds that the –2°C summer isotherm approaches the edge of both large ice shelves around the time of CO_2 doubling (Wild et al., 2003). It has also been suggested that ice shelves may be pre-conditioned to rapid fragmentation as a result of either basal melting (Shephard et al., 2003) or, alternatively, long-term surface warming well below the freezing point accompanied by episodic high temperatures due to local climate variability (MacAyeal, D.R., personal communication). Some may view these factors as making our assessment insufficiently precautionary.

There are several links in our inferential chain. These links may evaporate or strengthen over time, and if an aggressive research program is mounted the target concentrations or temperatures noted above might be refined or dispensed with altogether. Focused research might involve such topics as ongoing and recent changes in the ice sheet, interactions between ice shelves and oceans, mechanisms of ice shelf decay perhaps using iceberg calving as a proxy, obtaining baseline and continuing data on an ice shelf that is possibly prone to future collapse such as the remaining section of Larsen B (Shephard et al., 2003) as well as on adjacent outlet glaciers, and modelling to incorporate new insights and assess their significance.

5. Learning from Experience

It is worth recalling experience with the ozone layer in evaluating the merits of a limit on warming keyed to the future of the ice shelves. Long before any diminution of the stratospheric ozone was observed, Molina and Rowland (1974) proposed that halocarbon emissions would cause ozone depletion. Models were developed based on gas-phase kinetics that projected that measurable depletion was decades away. The effects of heterogeneous reactions occurring on particle surfaces were subsequently dismissed as 'minor' and 'unlikely to change our overall picture of the chemistry of the stratosphere' (W.M.O., 1986). But rates of heterogeneous reactions were difficult to measure, and occasionally, concern was raised that their inclusion could significantly enhance projected depletion. Comforted by model projections and by decreasing chlorofluorocarbon production resulting from a public boycott of CFC-containing aerosol sprays, regulators took limited steps. Between 1978 and 1980, the use of chlorofluorocarbons in aerosol spray cans in the United States, Canada, Sweden, and Norway was banned, and production of CFCs for this use was capped in the European Community. Other uses of CFCs were allowed to grow (Parson, 2003).

But in 1985, the ozone hole was identified and some scientists pointed to signs of ozone depletion at the mid-latitudes as well. Within a few years, the role of CFCs in both polar and mid-latitude depletion, which was occurring much faster than projected earlier, was confirmed. Heterogeneous reactions, downplayed previously, were the key factor (Newman and Pyle, 2003).

Is there an analogy here to the fate of the Mercer hypothesis? Only time will tell. In retrospect, considering the modest cost of substitute chemicals and processes, the aerosol bans were an inadequate response to the Molina–Rowland hypothesis and to the uncertain projections of early models. More aggressive precautionary action would have been justified (Ha-Duong et al., 2003).

Bearing the ozone history in mind and recalling that the disintegration of WAIS is effectively irreversible, a cautious approach would accord the recent findings from the Antarctic Peninsula, along with those in the Amundsen Sea region, considerable weight in determining long-term objectives for greenhouse gases, as outlined in Article 2 of the U.N. Framework Convention on Climate Change. Disintegration of the major ice shelves provides one plausible measure of 'dangerous anthropogenic interference' with global climate. This choice would imply selection of a corresponding concentration or temperature target, and a serious worldwide effort to avoid exceeding it.

Returning to Dessai et al. (2004), their argument on the need for a broad framework for interpreting Article 2 is compelling. Indeed, there are two value-laden choices inherent in our framework for interpreting 'dangerous'. We apply a precautionary approach to evaluating the uncertainty in the response of grounded ice to ice shelf disintegration by assuming that the latter automatically triggers the former. We also assume that human-induced WAIS disintegration should be avoided *per se*, regardless of the time scale over which it might occur. A conversation over the merits of these assumptions, in conjunction with the evolving physical evidence, would lay the groundwork for choosing a long-term goal for climate policy. Progress could occur now, even lacking a comprehensive framework for examining the 'internal' aspects of such a choice.

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References

Anderson, S. O. and Sarma, K. M.: 2003, *Protecting the Ozone Layer*, Earthscan Publ., Ltd., London.

Benedick, R. E.: 1998, *Ozone Diplomacy: New Directions in Safeguarding the Planet*, Harvard University Press, Cambridge, MA.

Bentley, C. R.: 1987, 'Antarctic Ice Streams: A Review', *J. Geophys. Res.* **92**, 8843–8858.

Berk, M. M., van Minnen, J. G., Metz, B., Moomaw, W., den Elzen, M. G. J., van Vuuren, D. P., and Gupta, J.: 2002, 'Climate Options for the Long Term (COOL) Global Dialogue – Synthesis Report', RIVM Report 490200003, Bilthoven, the Netherlands.

Church, J. A. and Gregory, J. S.: 2001, 'Changes in Sea Level', in Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A. (eds.), *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Cambridge, UK, Chapter 11.

Cubasch, U. and Meehl, G. A.: 2001, 'Projections of Future Climate Change', in Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., Johnson, C. A. (eds.), *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Cambridge, UK, Chapter 9.

De Angelis, H. and Skvarca, P.: 2003, 'Glacier Surge after Ice Shelf Collapse', *Science* **299**, 1560–1562.

Dessai, S., Adger, W. N., Hulme, M., Turnpenny, J., Köhler, J., and Warren, R.: 2004, 'Defining and Experiencing Dangerous Climate Change', *Clim. Change* **64**, 11–25.

Doake, C. S. M., Corr, H. F. J., Rott, H., Skvarca, P., and Young, N. W.: 1998, 'Breakup and Conditions for Stability of the Northern Larsen Ice Shelf, Antarctica', *Nature* **391**, 778–780.

Drewry, D. J. (ed.): 1983, 'Antarctic Ice Sheet Thickness and Volume', in *Antarctica: Glaciological and Geophysical Folio*, Scott Polar Research Institute, Cambridge, UK, Sheet 4.

Echelmeyer, K. A., Harrison, W. D., Larsen, C., and Mitchell, J. E.: 1994, 'The Role of the Margins in the Dynamics of an Active Ice Stream', *J. Glaciol.* **40**, 527–538.

Gollier, C.: 2001, 'Precautionary Principle: The Economic Perspective', *Econ. Policy* **16**, 301–327.

Ha-Duong, M., Megie, G., and Hauglustaine, D.: 2003, 'A Pro-active Stratospheric Ozone Protection Scenario', *Global Environ. Change* **13**, 43–49.

Herterich, K.: 1987, 'On the Flow Within the Transition Zone Between Ice Sheet and Ice Shelf', in van der Veen, C. J. and Oerlemanns, J. (eds.), *Dynamics of the West Antarctic Ice Sheet*, Reidel Publ., Dordrecht, the Netherlands, pp. 185–202.

Hindmarsh, R. C. A.: 1993, 'Qualitative Dynamics of Marine Ice Sheets', in Peltier, W. R. (eds.), *Ice in the Climate System*, **I 12**, Springer, Berlin, pp. 67–99.

Huybrechts, P.: 1994, 'Formation and Disintegration of the Antarctic Ice Sheet', *Ann. Glaciol.* **20**, 336–340.

Huybrechts, P. and De Wolde, J.: 1999, 'The Dynamic Response of the Greenland and Antarctic Ice Sheets to Multiple-Century Climatic Warming', *J. Clim.* **12**, 2169–2188.

Jacobs, S. S., Hellmer, H. H., Doake, C. S. M., Jenkins, A., and Frolich, R. M.: 1992, 'Melting of Ice Shelves and the Mass Balance of Antarctica', *J. Glaciol.* **38**, 375–387.

Jacobs, S. S., Hellmer, H. H., and Jenkins, A.: 1996, 'Antarctic Ice Sheet Melting in the Southeast Pacific', *Geophys. Res. Lett.* **23**, 957–960.

Manabe, S., Spelman, M. J., and Stouffer, R. J.: 1992, 'Transient Responses of a Coupled Ocean-Atmosphere Model to Gradual Changes of Atmospheric CO_2. Part II: Seasonal Response', *J. Clim.* **5**, 105–126.

Mercer, J. H.: 1968, 'Antarctic Ice and Sangamon Sea Level', *Int. Assoc. Sci. Hydrol. Symp.* **79**, 217–225.

Mercer, J. H.: 1978, 'West Antarctic Ice Sheet and CO_2 Greenhouse Effect: A Threat of Disaster', *Nature* **271**, 321–325.

Molina, M. J. and Rowland, F. S.: 1974, 'Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom-Catalysed Destruction of Ozone', *Nature* **249**, 810–812.

Newman, P. A. and Pyle, J. A.: 2003, 'Polar Stratospheric Ozone: Past and Future', *Scientific Assessment of Ozone Depletion: 2002,* World Meteorological Organization, Global Ozone Research and Monitoring Project-Report No. 47, Geneva, Chapter 3.

O'Neill, B. C. and Oppenheimer, M.: 2002, 'Dangerous Climate Impacts and the Kyoto Protocol', *Science* **296**, 1971–1972.

Oppenheimer, M.: 1998, 'Global Warming and the Stability of the West Antarctic Ice Sheet', *Nature* **393**, 325–332.

Parson, E. A.: 2003, *Protecting the Ozone Layer: Science and Strategy*, Oxford University Press, Oxford.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Bender, M., Chappallez, J., Davis, M., Delaygue, G., Delmotte, M., Kotylakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M.: 1999, 'Climate and Atmospheric History of the Past 420,000 Years from the Vostok Ice Core, Antarctica', *Nature* **399**, 429–436.

Revelle, R. R.: 1983, 'Probable Future Changes in Sea Level Resulting from Increased Atmospheric Carbon Dioxide ,' in *Changing Climate*, National Academy Press, Washington, D.C., Chapter 8, pp. 441–448.

Rignot, E. J.: 1998, 'Fast Recession of a West Antarctic Glacier', *Science* **281**, 549–551.

Rignot, E.: 2002, 'Ice-shelf Changes in Pine Island Bay, Antarctica, 1947–2000', *J. Glaciol.* **48**, 247–256.

Rignot, E. and Jacobs, S. S.: 2002, 'Rapid Bottom Melting Widespread Near Antarctic Ice Sheet Grounding Lines', *Science* **296**, 2020–2023.

Rignot, E. and Thomas, R. H.: 2002, 'Mass Balance of Polar Ice Sheets', *Science* **297**, 1502–1506.

Rignot, E., Vaughan, D. G., Schmeltz, M., Dupont, T., and MacAyeal, D.: 2002, 'Acceleration of Pine Island and Thwaites Glaciers, West Antarctica', *Ann. Glaciol.* **34**, 189–194.

Rignot, E., Pritchard, H., Vaughan, D., Rivera, A., Kanagaratnam, P., Casassa, G., and Thomas, R.: 2003, 'Velocity Change and Ice Discharge from Antarctic Peninsula Glaciers', *Eos. Trans. AGU* **84**, C41A-07.

Rott, H., Rack, W., Skvarca, P., and De Angelis, H.: 2002, 'Northern Larsen Ice Shelf, Antarctica: Further Retreat After Collapse', *Ann. Glaciol.* **34**, 277–282.

Scambos, T. A., Hulbe, C., Fahnestock, M., and Bohlander, J.: 2000, 'The Link between Climate Warming and Break-up of Ice Shelves in the Antarctic Peninsula', *J. Glaciol.* **46**, 516–530.

Scambos, T. A., Hulbe, C., and Fahnestock, M.: 2003, 'Climate-Induced Ice Shelf Disintegration in the Antarctic Peninsula', *Antarctic Res. Series* **76**, 335–347.

Scherer, R. P., Aldahan, A., Tulaczyk, S., Possnert, G., Engelhardt, H., and Kamb, B.: 1998, 'Pleistocene Collapse of the West Antarctic Ice Sheet', *Science* **281**, 82–85.

Schmeltz, M., Rignot, E., Dupont, T. K., and MacAyeal, D. R.: 2002, 'Sensitivity of Pine Island Glacier, West Antarctica, to Changes in Ice-shelf and Basal Conditions: A Model Study', *J. Glaciol.* **48**, 552–558.

Shephard, A., Wingham, D. J., Mansley, J. A. D., and Corr, H. F. J.: 2001, 'Inland Thinning of Pine Island Glacier, West Antarctica', *Science* **291**, 862–864.

Shephard, A., Wingham, D. J., Payne, T., and Skvarca, P.: 2003, 'Larson Ice Shelf Has Progressively Thinned', *Science* **302**, 856–859.

Smith, J. B., Schellnhuber, H.-J., and Mirza, M. M. Q.: 2001, 'Vulnerability to Climate Change and Reasons for Concern: A Synthesis', in McCarthy, J. J., Canziana, O. F., Leary, N. A., Dokken, D. J. and White, K. S. (eds.), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, Cambridge University Press, Cambridge, Chapter 19.

Thomas, R. H. and Bentley, C. R.: 1978, 'A Model for Holocene Retreat of the West Antarctic Ice Sheet', *Quat. Res.* **10**, 150–170.

van der Veen, C. J.: 1985, 'Response of a Marine Ice Sheet to Changes at the Grounding Line', *Quat. Res.* **24**, 257–267.

Vaughan, D. G.: 1993, 'Implications of the Breakup of Wordie Ice Shelf, Antarctica, for Sea Level', *Antarctic Sci.* **5**, 403–408.

Vaughan, D. G. and Spouge, J. R.: 2002, 'Risk Estimation of Collapse of the West Antarctic Ice Sheet', *Clim. Change* **52**, 65–91.

Vaughan, D. G., Marshall, G. J., Connolley, W. M., Parkinson, C., Mulvaney, R., Hodgson, D. A., King, J. C., Pudsey, C. J., and Turner, J.: 2003, 'Recent Rapid Regional Climate Warming on the Antarctic Peninsula', *Clim. Change* **60**, 243–274.

World Meteorological Organization: 1986, *Atmospheric Ozone 1985*, World Meteorological Organization, Global Ozone Research and Monitoring Project, Report No. 16, Geneva, p. 48.

Weertman, J.: 1974, 'Stability of the Junction of an Ice Sheet and an Ice Shelf', *J. Glaciol.* **13**, 3–11.

Wild, M., Calanca, P., Scherrer, S. C., Ohmura, A.: 2003, 'Effects of Polar Ice Sheets on Global Sea Level in High-Resolution Greenhouse Scenarios', *J. Geophys. Res.* **108** No. D5 10.1029/2002JD002451.

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K.: 2002, 'Surface Melt-Induced Acceleration of Greenland Ice-Sheet Flow', *Science* **297**, 218–222.

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