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The melting of floating ice raises the ocean level

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SUMMARY

It is shown that the melting of ice floating on the ocean will introduce a volume of water about 2.6 per cent greater than that of the originally displaced sea water. The melting of floating ice in a global warming will cause the ocean to rise. If all the extant sea ice and floating shelf ice melted, the global sea level would rise about 4 cm. The sliding of grounded ice into the sea, however, produces a mean water level rise in *two parts*; some of the rise is delayed. The first part, while the ice floats, is equal to the volume of displaced sea water. The second part, equal to 2.6 per cent of the first, is contributed as it melts. These effects result from the difference in volume of equal weights of fresh and salt water. This component of sea rise is apparently unrecognized in the literature to date, although it can be interpreted as a form of halosteric sea level change by regarding the displaced salt water and the meltwater (even before melting) as a unit. Although salinity changes are known to affect sea level, all existing analyses omit our calculated volume change. We present a protocol that can be used to calculate global sea level rise on the basis of the addition of meltwater from grounded and floating ice; of course thermosteric volume change must be added.

Key words: density, laboratory measurement, oceans, present-day ice melting, sea level change.

1 INTRODUCTION

Common lore (Warrick *et al.* 1996; Church *et al.* 2001; Miller & Douglas 2004; Oppenheimer 2004; Spokes 2004; Wadhams & Munk 2004; Williams 2004; Weart 2005; Kolbert 2005) holds that, due to Archimedes' Principle (Archimedes, *ca.* 220BC), the melting of floating ice will not change the global mean sea level. The *melting* of ice was heretofore believed to raise the sea level only when the ice is supported by land ('grounded ice'). This supposition is implicit in analyses of sea level rise that omit floating ice from the fluid budget (Meier & Wahr 2002) and explicit in Munk (2003), as well as Antonov *et al.* (2002), who directly state that the melting of floating ice is to be excluded in calculating sea level rise. Antonov (private communication, 2005) confirms that their term 'sea ice' refers to all floating ice and that zero direct volumetric effect was expected from the melting of floating ice. When grounded ice either slides or calves directly into the sea, it is usually supposed to add at once to the oceans the volume of its eventual meltwater, but we will show that both the foregoing suppositions are inaccurate. Our effect is not related to ice buttressing (Alley *et al.* 2005; Dupont & Alley 2005) or to either eustatic or steric rise as usually defined (Munk 2003; Dupont & Alley 2005), because it involves neither inflow of continental fresh water (eustatic rise) nor thermal expansion. Actually, steric rise can be broken into *thermosteric* rise, due to thermal expansion, and *halosteric* rise due to change of salinity (Antonov *et al.* 2002.) The latter portion of steric sea level change can be interpreted as consistent with our effect. In fact, because the melting of floating ice does not involve a gain or loss of mass, differences in specific volume due to differences in salinity can be found from formulas or graphs usually used for halosteric change, such as those in Pattullo *et al.* (1955), or in Gill (1982). The dependence of density on salinity and temperature is referred to as the 'equation of state,' hereinafter 'EOS.' Nevertheless, all existing discussions of melting and freezing (excepting Grumbine 1997) exclude our calculated volume change, a 2.6 per cent effect, because the analysis specifically excludes the melting of floating ice on the basis of a misapplication of Archimedes' Principle (Section 2). (When ocean water freezes into sea ice, a similar decrease in effective ocean volume, equal to 2.6 per cent of the volume that has frozen, occurs.) Even Grumbine (1997) found, however, only a 4 mm sea rise from the melting of sea ice (frozen sea water), a number that increases tenfold when floating ice sheets in Antarctica are included. Changes in salinity are used variously by different researchers to estimate eustatic sea level change (net addition of fresh water), and, locally, the halosteric rise or fall (which we show to be related to our effect). To highlight the problem areas, we first delineate the sources of sea water freshening.

A decrease of salinity can result in following three basic ways.

(1) An infusion of fresh water from the melting of grounded ice, or from precipitation or river run-off.

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(2) Dilution by streams of sea water with lower salinity.
(3) The melting of floating ice.

Existing studies often have difficulty in sorting out these cases, so that halosteric rise is not always cleanly separated from eustatic rise. In case (1), global sea level rise results. In case (2), the change in global sea level should be very small, but local effects can be substantial. In case (3), previous analyses have been based, explicitly or implicitly, on the assumption that the total meltwater volume matches that of the displaced sea water. If that were so, a salinity change from such melting would lead to no global sea level change at all, violating the EOS; indeed, most authors explicitly make exception for cause (3).

2 ANALYSIS

2.1 Applying Archimedes' principle

Sea ice (frozen sea water) and ice shelves are composed of nearly pure water which has density $\rho_W \approx 1000\ \mathrm{kg\ m^{-3}}$ when melted, and $\rho_1 \approx 917\ \mathrm{kg\ m^{-3}}$, more or less, when frozen (remarkably, the density of the ice makes no difference to the argument so long as the ice floats). Brine inclusions that are sometimes found in the ice have very little effect. The ice shelves have extremely low salt content. Sea ice, formed by the freezing of sea water, has some salt although it is largely purified, through 'brine rejection' (Eicken 1992; Shcherbina *et al.* 2003). Some brine inclusions remain, especially in first year sea ice. Air bubbles can be entrained in either sea ice or shelf ice, but they make no difference in our analysis, because only the density of the meltwater counts. The brine inclusions *do* affect the meltwater density somewhat, though the effect on our results will be small because shelf ice totals about ten times the mass of sea ice. Nevertheless, the effect of the brine inclusions will be considered in Section 6 through reducing the mass of the sea ice by a factor based on its salinity, as if it were made up of pure ice and sea water (the latter having neutral buoyancy). The correction will be negligible. The density of surface ocean water is about $\rho_0 \approx 1026\ \mathrm{kg\ m^{-3}}$. An iceberg or piece of floating sea ice is assumed to have volume V_1 above mean waterline and V_2 below, with

$$V = V_1 + V_2 \tag{1}$$

(Fig. 1). The weight W of the ice is

$$W = \rho_1 g V = \rho_1 g (V_1 + V_2), \tag{2}$$

where g is the acceleration of gravity. By Archimedes' Principle,

$$W = \rho_0 g V_2. \tag{3}$$

After melting, the volume of the meltwater will be

$$V_{\mathrm{melt}} = W/(\rho_W g) \approx W/(1000g). \tag{4}$$

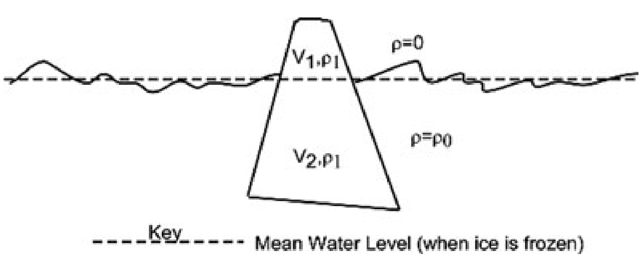

Figure 1. A schematic of floating ice, with geometry appropriate to an iceberg (for ice sheets and sea ice see next figure). The exposed part has volume V_1 and the submerged part V_2. The ice has density ρ_1 (unimportant) while the sea water or brine has density ρ_0.

Combining eqs (3) and (4) we find

$$V_{\mathrm{melt}} = V_2 \rho_0/\rho_W \approx 1.026 V_2. \tag{5}$$

Thus, the volume of meltwater is 2.6 per cent more than that of the displaced sea water, and the water level rises. When pure meltwater combines with the salt water, there is a very small volume contraction, of order 0.01 per cent or less, due to mixing, but it is negligible compared to the increase found here. How is the volume increase just found consistent with Archimedes' Principle? That law refers to *weight*, not to volume. Although the ice displaces its own *weight* of the underlying liquid, it does not displace the same *volume* as the meltwater. Our analysis of sea level rise is good to perhaps 10 per cent, because of the changing physical situation, the combination of data from sources as different as submarines and spacecraft, the errors of measurement in these data, the presence of poorly determined impurities on floating ice, the variability of salinity in the sea water that provides flotation, and our neglect of the contribution of melting ice to thermosteric changes. Rather than providing formal error bars, we simply carry a small number of significant digits in our volumetric calculations.

2.2 Reducing measured quantities to mass and volume

The volumes and weights (reducible to masses) in the previous section were assumed known, but in practice the volumes are estimated in various ways that complicate the analysis. The thickness T can be measured by extracting cores, by radar, or by measuring the draft of the sample, generally using submarines (Rothrock *et al.* 1999; Wadhams & Davis 2000). Fig. 2 shows a stylized version of a slab of floating ice in the context of relating volume to thickness and draft. The thickness is the sum of the draft h_2 and the freeboard h_1,

$$T = h_1 + h_2 = W/(g\rho_1 A) \tag{6}$$

which is easily solved for W. If the thickness is measured it may be necessary to allow for a lower density ($\rho_1 < 917\ \mathrm{kg\ m^{-3}}$) when air inclusions are substantial, as in frazil or grease ice (Smedsrud & Skogseth 2006). However, the draft is, by Archimedes' Principle

$$h_2 = W/(g\rho_0 A). \tag{7}$$

Thus, if the draft is measured, and we assume $\rho_0 \approx 1026$ kg $\mathrm{m^{-3}}$or a like value, the weight per unit area W/A is known. The draft method of mass determination, then, is unaffected by air inclusions. To take into account the effect of air inclusions in sea ice or snowpack on shelf ice, we correct volumes based on thickness rather than draft downward by the factor 0.9. It should be emphasized that this correction does not change our conclusion that when floating ice melts, the meltwater volume exceeds the displaced volume by ∼2.6 per cent; we are only comparing different methods of estimating the ice volume or mass.

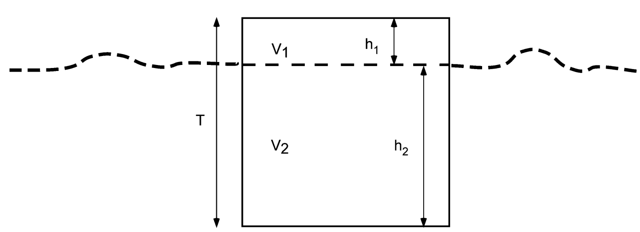

Figure 2. A schematic of sea ice or an ice shelf floating. The exposed part has volume V_1 and the submerged part V_2. The densities are as denoted in Fig. 1 and the dashed line again indicated sea level. The thickness T is the sum of the freeboard h_1 and the draft h_2. The area A is not shown, as the slab is edge-on.

3 FURTHER CONSIDERATIONS; ALIASING TO HALOSTERIC RISE

The sea level rise just derived can be interpreted as a form of halosteric sea level change by regarding the displaced salt water and the meltwater (even before melting) as a unit. Let us explore this. The mass M_i of the ice is

$$M_i = \rho_1 V. \tag{8}$$

The mass of the displaced volume of sea water V_2 is

$$M_0 = \rho_0 V_2, \tag{9}$$

while that of the meltwater is $\rho_{\mathrm{w}} V_{\mathrm{melt}}$; $\rho_{\mathrm{w}} \approx 1000\,\mathrm{kg\ m^{-3}}$. Since mass is conserved,

$$\rho_{\mathrm{w}} V_{\mathrm{melt}} = \rho_0 V_2. \tag{10}$$

However, ρ_0 and ρ_{w} can be found from tables of the equation of state. Thus, on solving for the ratio of volumes, the volume change could be classified as halosteric change. The result is identical to that in eq. (5). The same result now appears by two differing analyses. Nevertheless, in view of its nearly universal neglect, and some resistance in the scientific community to accept it, we conducted an experiment. A description of the experiment, including a composite photograph (pre- and post-melt), as well an estimate of volume change due to mixing are in Section 5.

4 PROTOCOLS: THE EUSTATIC AND HALOSTERIC BUDGETS

In view of the poor coordination of the various methodologies and equations used in relating sea level change to sources and sinks of water and changes in temperature and salinity, it is desirable to define a single accurate protocol. The correct protocol for dealing with the causes of global sea level change is as follows.

(1) Measure mean global salinity change.

(2) Estimate the influx of water from melting of floating ice and grounded ice as well as from rivers.

(3) Deduct from item (2) an allowance for transfer of fresh water as new snow and ice on grounded ice sheets and glaciers (Davis *et al*. 2005).

(4) Use 2.6 per cent of the meltwater from floating ice as halosteric rise (other halosteric level changes are not global).

(5) Take 100 per cent of the other sources (item 2 minus item 3) as eustatic rise.

We contrast Munk's (2003) approach, which, as is typical, uses change in salinity as a measure of fresh water influx. The procedure is first to determine the whole-ocean salinity change (Antonov *et al*. 2002), estimate fresh water arrival from the salinity change via $\delta h_{\mathrm{eustatic}} = (\rho/\Delta\rho)\delta h_{\mathrm{steric}} = 36.7\delta h_{\mathrm{steric}}$ (the unnumbered equation at the end of the legend to Munk's (2003) unnumbered second figure, p. 2042), where $\Delta\rho$ is the difference in density of sea water and fresh water, and δh the change in sea level. Denoting this as eustatic change, the halosteric change has been translated into eustatic change. The next step, typically, is to correct all the values just calculated for the melting of floating ice, which is assumed to freshen sea water with *no* volume increase, rather than allowing 2.6 per cent of the freshwater volume. Thus, the freshening is 'corrected' to remove the contribution from the melting of floating ice, an error. Of course it is understood that one would add thermosteric effect, and one should account for imbalances in evaporation and precipitation (Davis *et al.* 2005). Holland & Jenkins (personal communication, 2007) have pointed out that, assuming adiabatic conditions, the latent heat of the melting ice contributes a negative thermosteric volume change that will mitigate our volume increase. The system of floating ice and sea water is open to other heat losses and gains, and thermosteric effects are commonly evaluated on the basis of a grid of temperature measurements rather than on changes of state. The heat gain due to the reduction in ocean albedo when the ice melts would compensate the thermal loss to latent heat in a few decades.

5 EXPERIMENTAL VALIDATION

Here we present experimental support for our analysis of volumetric changes attendant on sea ice melting.

5.1 Introduction

To provide an effect that is measurable in a moderate precision laboratory, it was decided to use concentrated salt solution rather than sea water concentration. It was verified from tables and experimentally that concentration/dilution effects make negligible changes of volume. The materials used are described in Table 1.

5.2 Experimental procedure

The ice cylinder, approximately 9.75 cm long (in this section, we use CGS units), was inserted in the tall glass cylinder as shown in Fig. 3. Saturated aqueous sodium chloride with blue coloration, 26 per cent salt by weight, was added in sufficient quantity to float the ice cylinder. The initial density of the brine was $1.197\,\mathrm{g\ mL^{-1}}$. The initial height of the meniscus was recorded and photographed (28.3 mm). The bottom of the glass cylinder was warmed to melt the ice and bring the liquid to room temperature. The final position of the meniscus was recorded and photographed (34.0 mm). The final density of the ice-brine mixture was $1.140\,\mathrm{g\ mL^{-1}}$.

5.3 Calculated volume increase

The rise of the meniscus was 0.57 cm corresponding to a volume increase of 21.7 mL. Some melting occurred before the first photo could be taken. The initial volume loss was estimated by taking a second photo after a time interval equal to the initial delay for allowing the system to settle. This photo showed a further increase of 3.4 mL. With this correction the volume increase is 25.1 mL.

Table 1. Materials for the experiment.

Item	Dimensions	Other properties
Tall Glass cylinder	6.0 cm ID	Calibration: $38\,\mathrm{mL\ cm^{-1}}$
Ice cylinder	4.6 cm diameter	149.9 g (9.5–10.0 cm long)
Saturated aqueous NaCl solution	~150 mL	Density $\rho = 1.197\,\mathrm{g\ mL^{-1}}$
Scale calibrated in mm	>10 cm	Attached to glass cylinder

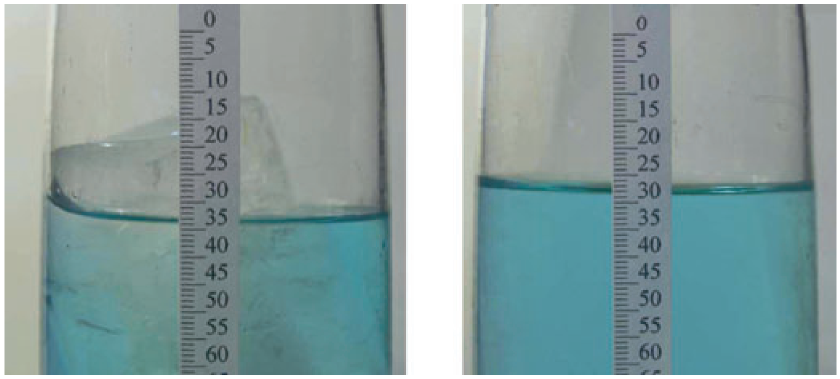

Figure 3. Composite of initial and final state photographs. (left-hand panel) pre-melting and (right-hand panel) melted.

5.4 Theoretical volume increase

The predicted increase of volume is (1.197–1.0) V_2, where V_2 is the initial submerged volume of ice. Thus, $V_2 = 149.9/1.197 = 125.2$ mL, and the predicted increase in volume is $0.197 \times 125.2\,\text{mL} = 24.7$ mL, agreeing within 1.6 per cent with the observation of 25.1 mL.

5.5 Volume change of mixing for brine and water

By the use of density data (CRC Handbook 1985) it can be shown that the change of volume on mixing brine with water should be <0.2 per cent. As a safeguard against error or misunderstanding, we mixed equal 25.0 mL volumes of saturated brine and water and measured a final volume of 50.0 ± 0.4 mL. Fig. 2 shows that the dye is well distributed, yet the volume increase is prominent; this observation should lay to rest any concerns that mixing might have a substantial effect on our results.

6 CONCLUSIONS

Given the substantial melting of sea and shelf ice in progress (Comiso 2002; Dixon 2003; Alley *et al.* 2005; Meehl *et al.* 2005), the volume increase found here could add incrementally to the known sea level rise from the melting of ice. A long-term upper bound to that increment can be derived from the total volume of Antarctic floating ice, which is estimated (Lythe & Vaughan 2001; British Antarctic Survey 2005) at about 700 000 km^3, a value with big standard error because floating ice thicknesses are poorly known (Comiso personal communication, 2005). The approximate nature of such numbers does not appreciably weaken our argument, because it is the *difference* in the volumes of displaced sea water and meltwater that counts. Nevertheless, we adjust the volume estimate downwards for two reasons. First, the number we need is the displacement, or V_2 in Fig. 2, which would be about 0.9 times the volume if the ice were pure, solid water ice and the thickness is measured, rather than the draft (Section 2.2). Secondly, we allow a correction for brine entrained in sea ice. Measurements of the salt content of sea ice vary widely, due to variations in the ice age and thickness, the salinity of the underlying ocean surface layers, and numerous other factors. For sea ice in the Weddell Sea, Eicken (1992) finds about 4–10 ppt by mass salt; we take 7 ppt as typical so the meltwater density would be 1007 kg m^{-3}. We therefore, should adjust the density of $\sim$2.5 per cent of the floating ice by the factor (1000/1007), but we neglect this as below the measurement errors (Fig. 3).

Arctic *shelf* ice in the Eastern sector is of negligible volume (A. Glazovsky, personal communication, 2006), leaving mainly the Ward Hunt shelf at Ellesmere Island (Scott 2004) and seasonal coastal ice. The Ward Hunt shelf has area $\sim$450 km^2 and thickness $\sim$30 m (Braun *et al.* 2004, The Los Angeles Times, 2003 September 23) which leads to negligible volume. *Sea* ice is divided, on the average, about equally between the arctic and Antarctic (Cavalieri *et al.* 2003). Seasonal effects of order $\sim$2–3 per cent are of opposite sign, of course, in the two hemispheres, though a bit larger in the Antarctic. For now we ignore this issue, though at a later date we hope to estimate seasonal effects, which might be measurable since geostrophic effects will tend to slow the propagation of the surface level changes (R. Grumbine, personal communication, 2005). A rough total floating ice volume for the arctic may be obtained by multiplying the areas $\sim 6 \times 10^6$ km^2 (Serreze *et al*. 2003) by the mean drafts from Rothrock *et al.* (1999), or about 2.5 m. The result is $\sim$15 000 km^3. Doubling it to allow for the Antarctic we get $\sim$30 000 km^3, still small compared to the Antarctic ice shelves. Our total estimate for floating ice in terms of displacement is then 660 000 km^3.

The area of the ocean's surface is (National Geographic Society 1996) $A_{\text{ocean}} \sim 3.62 \times 10^8$ km^2. If 660 000 km^3 of ice increases the ocean volume by 2.6 per cent of its displacement on melting, and it all melts, the height increase (ignoring shoreline changes) would be about $\Delta h \sim 0.026 \times 660\,000/(3.62 \times 10^8)$ km ≈ 47 mm, which might be of some interest, by comparison with the $\sim$2.0 mm yr^{-1} rise due to other causes (Munk 2002, 2003; Dixon *et al.* 2003; Cazenave & Nerem 2004; Meehl *et al.* 2005). The last three references describe an unexplained component to the observed sea level rise. We examine whether part of the discrepancy might be due to our effect. For a rough cut at this problem, let's set aside satellite altimetry results as having too short a time base (Cazenave & Nerem 2004), and take the long term sea level rise to be 1.5 ± 0.5 mm yr^{-1}, while the known sources of fresh water are equivalent to $\sim 0.7 \pm 0.5$ mm yr^{-1}. Assuming the errors are independent, and taking them in quadrature, then, we find that the discrepancy is $\sim 0.8 \pm 0.7$ mm yr^{-1}. This number is barely significant, but if we take it at face value and divide our estimate of 47 mm total possible rise by this rate, we get a time interval of $\sim$60 yr over which the total floating ice inventory would have to disappear in order to account for the rate difference. Working backwards, the inventory would have had to be about double its present value 60 yr ago. Estimates of loss of sea ice and shelf ice exist for the stated time period (roughly 1975–2000). Summarizing the results of Johanessen *et al.* (1999), Cavalieri *et al.* (2003), Wadhams & Davis (2000), Rothrock *et al.* (1999), Comiso (2002), Stroeve *et al.* (2005), Shepherd *et al.* (2003), NSIDC 2005, Jenkins *et al.* (2003), Serreze *et al.* (2003) and the United States Office of Naval Research (2001) we get a timescale ~50 yr for mass loss of sea ice, that is, mass divided by mean annual mass loss rate. The loss of the 30 000 km^3 of the sea ice would yield a sea level rise of only 2.2 mm, we get a rate ~0.04 mm yr^{-1}, which is of little interest. The biggest items afloat are the Ross and Filchner – Ronne ice shelves. Their mean thickness is ~450 m (Oppenheimer & Alley 2004; United States Geological Service 2000, 2005). The loss of thickness of large ice shelves is variously estimated in the range 0.22–1.2 m yr^{-1} (Oppenheimer 1998; Jenkins *et al.* 2003). The lifetime of the shelves would then be in the range 375–2000 yr. Taking 1000 yr as a representative value, we find that our 47 mm rise would also yield a negligible annual rate similar to that for shelf ice. Thus we do not explain the apparent discrepancy with either sea ice or shelf ice, but we do suggest that carefully prepared sea volume budgets should include the volume changes found here.

Another effect of the volume change, perhaps more surprising, is a partial delay in the rise of sea level when land ice slides into the sea. The volume of land based ice is estimated at 32 300 000 km^3, almost 50 times that of the floating ice (United States Geological Service 2000). The effect of the sloughing off of grounded ice into the oceans *eventually* raises the mean water level as originally calculated, but 2.5 per cent of the effect is *delayed* until the resulting icebergs melt. (The value 2.6 per cent is based on the original displacement, now understood to be less than the 'classical' value of total meltwater volume. Based on the meltwater volume, the correction is 2.5 per cent.) If part of a large grounded ice sheet were to slide into the ocean, this result suggests additional caution over the delayed 'time-bomb' effect as it melts. (When the melting occurs on land, without sliding, there is no correction to previous calculations, because the volume of run-off water relates to its weight in terms of density ρ_w, not ρ_0, implying that the whole volume is added undelayed.) Let us construct a plausible scenario to examine how big the delayed effect could be. First, note that large ice sheets in Greenland and Antarctica are in faster motion in recent times than heretofore (Bamber *et al.* 2000; Hulbe 2001; Zwally *et al.* 2002; Payne *et al.* 2004; Siegert *et al.* 2004; Bindschadler 2006; Blankenship *et al.* 2006; Rignot & Kanagaratnam 2006) due to penetration of surface melt, undermining ice or water streams, and loss of buttressing or closer contact with warmer ocean water (Rignot *et al.* 2004; Alley *et al.* 2005; DuPont & Alley 2005). The West Antarctic Ice Sheet has volume 26 000 000 km^3. Suppose a 5 per cent chunk slid into the sea in a short time period (say a few years). The sea level rise would be about 4 m. However, 2.5 per cent of that or 10 cm would appear gradually as the ice melted (we ignore a small compensating thermosteric volume decrease). Admittedly, a 4 m sea rise is a disaster, but if one is dealing with it, one should realize that even without more ice release, another 10 cm is coming.

During ice ages, sea ice was more prevalent. Comiso (2002) finds that the volume of arctic sea ice has decreased ~9 per cent per decade from 1978 to 2000. This figure cannot usefully be reduced to sea level change over longer times without an assumption on floating ice shelves (now notable only in Antarctica), but the implication, again, is that the systematic error of omitting sea level changes due to changing inventories of floating ice may deserve attention on long timescales.

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