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Ocean freshening, sea level rising, sea ice melting

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[1] Estimates of 20th Century sea level rise are typically 1.5 to 2 mm/y, with a steric contribution of (0.5 ± 0.2) mm/y. Estimates of the eustatic contribution vary widely between −1.1 and +1.3 mm/y. We attempt an independent estimate of eustatic sea level rise based on the measured freshening of the global ocean, and with attention to the contribution from melting of sea ice (which affects freshening but not sea level). Our estimate is based on a secular decrease in global average salinity estimated by *Antonov et al.* [2002] which, if assumed due entirely to run-off, would produce a eustatic rise of (1.8 ± 0.7) mm/y, and would correspond to a run-off volume of 650 cu km/y. Measurements with upward looking sonars mounted on submarines have suggested a historical thinning of the arctic ice sheet equivalent to 525 ± 105 cu km/y. Allowing for some growth in Antarctic sea ice, a reduced figure of (430 ± 130) cu km/y is obtained, allowing about 220 cu km/y of run-off from land sources such as glaciers. This would produce a eustatic rise of only 0.6 mm/y, for a total of 1.1 mm/y, somewhat less than IPCC estimates. This also has implications for our understanding of glacial retreat for a total of 1.1 mm/y. *INDEX TERMS:* 1635 Global Change: Oceans (4203); 4207 Oceanography: General: Arctic and Antarctic oceanography; 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 4556 Oceanography: Physical: Sea level variations. **Citation:** Wadhams, P., and W. Munk (2004), Ocean freshening, sea level rising, sea ice melting, *Geophys. Res. Lett.*, *31*, L11311, doi:10.1029/2004GL020039.

1. Introduction

[2] Sea level rise during the 20th century has been estimated at 1.5 to 2 mm/y, with a *steric* contribution (mostly thermal expansion) of (0.5 ± 0.2) mm/y. Estimates of the *eustatic* contribution vary between −1.1 and +1.3 mm/y; the wide limits can be attributed to near-cancellation between large and uncertain terms, such as the melting of ice sheets, incremental storage in reservoirs, etc. We attempt an independent estimate of eustatic sea level rise based on the measured freshening of the global ocean. Here the difficulty is associated with the uncertain contribution from melting of sea ice (which does not affect sea level). We find that a net eustatic rise of 0.6 mm/y is not inconsistent with the evidence.

[3] The problem is to account for the recorded sea level rise in terms of changes in ocean volume (mostly thermal expansion) and in ocean mass (melting and other continental storage): sea level = steric + eustatic components. IPCC estimates in 1995 and again in 2001 lie in the range of 1 to 2 mm/y for 20th century sea level rise; we will refer to 1.5 to 2.0 mm/y from a recent summary by *Douglas et al.* [2001]. All these estimates are based on tide records which are poorly distributed and subject to a large and uncertain correction for post-glacial uplift. *Levitus et al.* [2000, 2001] have compiled five million temperature profiles and report an increase in oceanic heat storage by 2×10^{23} J since the mid-fifties, equivalent to a steric rise of (0.5 ± 0.2) mm/y.

[4] The eustatic component has been the most difficult to estimate, being a small relative difference of several large and uncertain terms. *IPCC*'s [2001] central estimate of 0.2 mm/y falls far short of closing the budget, although the generous error bars of ± 1.0 mm/y do not preclude an agreement. The eustatic component is severely restrained by measurements of Earth rotation [*Munk*, 2002]; there is no evidence for a movement of water mass from high-latitude melting ice-sheets towards the equator.

[5] Recent estimates of global ocean freshening [*Antonov et al.*, 2002] offer an alternate approach for estimating the eustatic component. Here we have to separate the freshening from melting sea ice (which does not affect sea level) from the melting of continental ice. The uncertainties are still unsatisfactory, but perhaps somewhat less so than in the approach based on continental measurements alone.

2. Ocean Freshening

[6] Using the same *World Ocean Database* underlying the Levitus et al. estimates of ocean warming, *Antonov et al.* [2002] have computed 5-year running means for 1955 to 1995 in the upper 3000 m of the oceans between 50°S and 65°N. They find a secular decrease in salinity which they present in terms of the equivalent steric sea level:

$$\delta h_{STERIC} = -\int dz\, \delta\rho/\rho = \delta h_T + \delta h_S = (0.50 + 0.05)\,\mathrm{mm/y}, \tag{1}$$

where

$$\delta\rho/\rho = -\alpha\,\delta T + \beta\,\delta S. \tag{2}$$

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is the fractional increase in density associated with an increase in temperature T and salinity S.

[7] δh_S has been widely interpreted as a minor perturbation on thermal expansion. In fact, the interpretation depends critically on the source of the melted water. For continental melting the inferred sea level rise is much larger than δh_S (as will be shown), while, by Archimedes' principle, melting of floating ice does not change the water level.

3. Sea Level Rising

[8] Consider a global mixed ocean of depth h and density

$$\rho = \rho_{FRESH} + \Delta\rho = 1000 + 28 = 1028\,\mathrm{kg/m^3} \quad (3)$$

where $\Delta\rho$ is the incremental density associated with salinity. Continental melting adds a layer δh of fresh water (to include melting sea ice we would need to take into account the expansion of the fluid ocean domain into the volume previously occupied by the ice). The salinity of the mixed ocean is then slightly reduced in the ratio

$$\delta\rho/\Delta\rho = -\delta h/h. \quad (4)$$

[9] In terms of the traditional representation by the steric sea level we have

$$\delta h/h = -\delta\rho/\Delta\rho = -(\rho/\Delta\rho)(\delta\rho/\rho) = 36.7\,\delta h_S/h. \quad (5)$$

[10] The large multiplying factor 36.7 is perhaps surprising, but we note that it takes a lot of fresh water (large δh) to freshen a brackish lake ($\Delta\rho \rightarrow 0$); we refer to *Munk* [2003] for a detailed discussion. Antonov's estimate of δh_S = (0.05 ± 0.02) mm/y then yields a eustatic rise of (1.8 ± 0.7) mm/y for a total of 0.5 + 1.8 = 2.3 mm/y, in excess of the estimated total of 1.5 to 2.0 mm/y. A eustatic rise of 1.8 mm/y over an ocean area of 3.6 x 10^8 km^2 would require a melt volume of 650 km^3/y (*Antonov et al.* [2002] obtained 471 km^3/y). But first we need to allow for the melting of the floating sea ice cover.

4. Sea Ice Melting

4.1. Arctic Sea Ice

[11] There has been a dramatic decrease in arctic sea ice in the last few decades, as indicated by (i) a shrinking of the boundaries, and (ii) a thinning of the interior ice cover.

[12] The annual mean extent is 12.5 × 10^6 km^2, which is diminishing at a rate of 0.3 to 0.4% per annum according to *Cavalieri et al.* [1997] and *Bjørgo et al.* [1997], or (34,300 ± 3700) km^2 per annum according to *Parkinson et al.* [1999]. The extent of Arctic sea ice varies from 15.7 × 10^6 km^2 in winter to 9.3 × 10^6 km^2 in summer, according to passive microwave data [*Gloersen et al.*, 1992]. It is better to use extent, the area north of the ice edge, than actual ice area, since mean thickness values obtained from submarines include the effect of open water along the track and therefore relate to ice extent. The mean thickness of sea ice over the Arctic as a whole is about 3 m (±10%), while the ice around the margins, where the shrinkage is occurring, is mainly first-year ice with a lesser mean thickness of about 2 m. This gives a loss of ice volume from shrinkage alone of (68 ± 8) km^3 of ice per year using *Parkinson et al.* [1999]. To convert into volume of fresh water we reduce by 10% to take account of the density difference (910 versus 1025 kg m^{-3}) and by 10% to allow for the mean salinity of the ice which has melted, typically about 3 psu for first-year ice. This leaves (55 ± 6) km^3 as the annual contribution of water from shrinkage.

[13] Measurements by *Rothrock et al.* [1999] and by *Wadhams and Davis* [2000] indicated a loss of mean thickness of some 1.3 m between sets of submarine cruises spaced about 20 years apart in the 1970s and 1990s. More recently *Rothrock et al.* [2003] have refined these rates by including winter data, and obtain a slightly reduced mean loss of some 1 m over 20 years, with the most rapid decay occurring in the late 1980s and early 1990s. The contribution of ice volume from thinning is assumed to result from 0.05 m per annum of melt basinwide, from the results of *Rothrock et al.* [2003], with a likely error of ±20% given the various sources of uncertainty in converting rates in areas sampled by submarines into basinwide rates. This yields (625 ± 125) km^3 of melted ice per annum, which with reductions of 10% for density and 7% for the lower salinity (2 psu) of Arctic ice as a whole, gives (523 ± 105) km^3 per annum as the volume of fresh water.

[14] It should be noted that a much lower thinning rate of some 8% in 20 years has been inferred by *Johannessen et al.* [2004] from the results of tiltmeter measurements at Russian Arctic stations. Tiltmeters measure the spectrum of flexural-gravity waves at the ice surface, which, according to theory by *Nagurny et al.* [1999, 2004], has a peak at a frequency which is dependent on ice thickness. An examination of the theory, and the results of experiments carried out in 2003 by one of the authors (PW) and colleagues, suggest that the peak frequency is actually related to the mean thickness of undeformed multi-year ice along a path from the ice edge to the sensor. This is a thermodynamic thickness parameter, a measure of global warming, but is not the true mean thickness (volume per unit area of water surface) measured by a submarine, which also takes account of changes in ice concentration, composition and deformation. Submarine transects therefore remain the most relevant basinwide data source for ice thinning, In future much can be expected from satellite altimetry.

4.2. Antarctic Sea Ice

[15] There are few data concerning a contribution from Antarctic sea ice melt. Thickness measurements to date are inadequate to indicate either a thinning or a thickening. Passive microwave evidence points to a small increase in Antarctic sea ice area, of (11,180 ± 4,190) km^2 per annum [*Zwally et al.*, 2002], while previous evidence of a radical decline in sea ice area in the 1960s, based on whaling records [*de la Mare*, 1997], has recently been shown to be mistaken [*Ackley et al.*, 2003]. We can estimate an extraction of fresh water from the ocean, based on area expansion alone, given that the mean thickness of marginal zone ice is 1 m [*Wadhams et al.*, 1987] and the mean salinity is 4 psu. This yields 9 km^3

per annum. If the ice cover is expanding it is reasonable to believe that it is also thickening, since the wider ice limits, if controlled by thermodynamics, suggest colder air temperatures, while if they are controlled by dynamics they suggest a greater rate of opening of new polynyas within the pack, permitting rapid growth rates. In the Arctic the thinning rate appears to be about 10 times the shrinkage rate (expressed as volume contributions). If the same ratio were applied as a rule of thumb to the Antarctic this would yield a contribution from thickening of about 90 km^3 per annum, with guessed error bars of ±30%.

4.3. Global Sea Ice Melt

[16] To be very conservative, we estimate the global sea ice melt rate as being the difference between Arctic thinning and Antarctic thickening. We ignore the contributions from area shrinkage or expansion, since a sea ice cover which is thinner near its edges than in its centre and which is thinning at some constant overall rate will shrink naturally, so we must avoid counting the contribution twice. Thus our estimate of the overall global contribution to the ocean of fresh water from melt of sea ice is (430 ± 130) km^3 per annum.

[17] Improved data on regional melt rates will probably lead to an increase in this conservative figure, since shrinkage may be a function of changing water mass boundaries and lateral heat fluxes as well as of the changing vertical heat fluxes which are the presumed main cause of thinning.

5. Interpretation

[18] We have estimated 650 km^3 per annum of fresh water input to the ocean to account for the measured freshening. This leaves $650 - 430 = 220$ km^3 per annum as an estimate of continental run-off. For an area $A = 3.6 \times 10^8$ km^2 the inferred eustatic rise equals 220/A = 0.6 mm per annum, giving a total rise of 0.5 + 0.6 = 1.1 mm per annum. The estimated rise is below the Douglas 1.5 to 2.0 mm/y estimates, but within the range of the IPCC 1.0 to 2.0 mm/y estimates.

[19] It may be significant that the *Antonov et al.* [2002] salinity census extends only up to 65°N. Fresh water from Arctic sea ice melt does end up pervading the world ocean, but takes its time about doing so. Initially it forms part of the Arctic Surface Water mass and may make a number of circuits of the Arctic Basin. Then it exits in the East Greenland Current from which some of it recirculates into the Greenland Sea at latitudes north of 65°N. The rest passes around Cape Farewell and eventually ends up in the mid-latitude Atlantic, but much of the water from sea ice melt must remain north of 65°N for a considerable time The case could be made that the Antonov census underestimates global freshening because it does not include the contribution from recent melting to the freshening of the Arctic seas.

[20] Uncertainties in our estimates are large and do not exclude a negative eustatic rise, that is, a net movement of water mass onto the continents. Nevertheless we do obtain a total rise which is at the lower end of the range estimated by IPCC. One interesting consequence is that the continental run-off which is "allowed" after subtracting the effect of sea ice melt is considerably lower than current estimates of sub-polar glacier retreat, suggesting a negative contribution from polar ice sheets (Antarctica plus Greenland) or from other non-glacial processes.

[21] In this context it is noteworthy that there are severe constraints on the rate of high-latitude melting imposed by the measured changes in Earth rotation. A eustatic 1 mm/y rise from Antarctic or Greenland melting with subsequent flow of water towards equatorial latitudes would INCREASE the length of day (lod) by 1 millisecond per century, as compared to the observed DECREASE by 0.6 ms per century of the non-tidal change in lod. Evidently the movement of earth mass INTO the regions of post-glacial uplift dominates over any possible movement of water mass AWAY from regions of high-latitude melting. The evidence, as it is, favors mid-latitude sources of melting. It is unfortunate that we have excellent observational data which demonstrate the melt-back of subpolar glaciers, while we do not have good estimates of the mass balance of the Antarctic ice sheet, which could make a much larger positive or negative contribution.

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