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On the rate and causes of twentieth century sea-level rise

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Both the rate and causes of twentieth century global sea-level rise (GSLR) have been controversial. Estimates from tide-gauges range from less than one, to more than two millimetre yr^{-1}. In contrast, values based on the processes mostly responsible for GSLR—mass increase (from mountain glaciers and the great high latitude ice masses) and volume increase (expansion due to ocean warming)—fall below this range. Either the gauge estimates are too high, or one (or both) of the component estimates is too low. Gauge estimates of GSLR have been in dispute for several decades because of vertical land movements, especially due to glacial isostatic adjustment (GIA). More recently, the possibility has been raised that coastal tide-gauges measure exaggerated rates of sea-level rise because of localized ocean warming. Presented here are two approaches to a resolution of these problems. The first is morphological, based on the limiting values of observed trends of twentieth century relative sea-level rise as a function of distance from the centres of the ice loads at last glacial maximum. This observational approach, which does not depend on a geophysical model of GIA, supports values of GSLR near 2 mm yr^{-1}. The second approach involves an analysis of long records of tide-gauge and hydrographic (*in situ* temperature and salinity) observations in the Pacific and Atlantic Oceans. It was found that sea-level trends from tide-gauges, which reflect both mass and volume change, are 2–3 times higher than rates based on hydrographic data which reveal only volume change. These results support those studies that put the twentieth century rate near 2 mm yr^{-1}, thereby indicating that mass increase plays a much larger role than ocean warming in twentieth century GSLR.

Keywords: sea-level rise; ocean thermal expansion; glacial isostatic adjustment; climate change

1. Introduction

Global sea-level rise (GSLR) is an important and often-noted aspect of global climate change. From a purely scientific point of view, GSLR is a measure of the integrated effect of steric and water mass contributions to the total ocean volume, thereby providing an important constraint on climate models. GSLR

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One contribution of 20 to a Theme Issue 'Sea level science'.

may also provide an early warning of future events of great practical importance. For example, sandy beach erosion can be two orders of magnitude greater than the vertical rise of sea-level (Zhang *et al.* 2004), and disappearance of the beach means that fixed coastal structures are increasingly exposed to damaging impacts of storms. This is particularly a problem for developing countries lacking the resources needed to protect their coastal populations (Nicholls & Leatherman 1995; Small & Nicholls 2003).

The modern era of GSLR measurement began in 1992 with the launch of the joint US/France altimeter satellite TOPEX/Poseidon (T/P). Altimeter satellites of this class are uniquely suited to determining GSLR because they provide global coverage of the oceans. Tide-gauges are in contrast at a relative disadvantage because their coverage of the oceans is sparse (although sufficient to provide an essential means for calibrating satellite altimeters!) For the last 14 years, T/P and some of its successors have shown themselves capable of measuring GSLR with a precision of about 1/2 mm yr^{-1} (Cazenave & Nerem 2002). The T/P estimate of GSLR since its launch in 1992 is nearly 3 mm yr^{-1}. In contrast, estimates of twentieth century GSLR based on tide-gauge data range from about 1 mm yr^{-1} (Nakiboglu & Lambeck 1991; Shennan & Woodworth 1992; Lambeck *et al.* 1998; Woodworth *et al.* 1998; Cabanes *et al.* 2001) to about 2 mm yr^{-1} (Trupin & Wahr 1990; Douglas 1991, 1997; Peltier 1996, 2001; Church *et al.* 2004; Holgate & Woodworth 2004; Miller & Douglas 2004; White *et al.* 2005). If the lower estimate is correct, then the T/P result implies that there has been a radical increase of GSLR in the late twentieth century. If the higher tide-gauge estimates are correct, then at the 95% confidence level, there has been little or no significant change in recent decades. Resolution of this issue is a matter of some importance to both global climate change and geophysics (Meier & Wahr 2002; Munk 2002).

Several authors (Woodworth 1990; Douglas 1992) have considered the question of an acceleration of twentieth century global sea-level (GSL) from tide-gauge data. Determining an acceleration of GSL from long tide-gauge records is inherently easier than determining the rate of rise of GSL. This is so because on the maximum time scale of recording tide-gauges (approximately 150 years), vertical movements due to glacial isostatic adjustment (GIA) and tectonic effects at locations with long earthquake recurrence times are essentially linear, and so do not affect an acceleration estimate. The analyses of tide-gauge data by Woodworth (1990, 2003) and Douglas (1991, 1992, 1997, 2001) did not find a statistically significant acceleration of GSL. However, about 20 years more data are available now for computation of accelerations, and a new computation is warranted. The results (kindly provided by P. Woodworth) are illustrated in figure 1, below. What this figure shows is the apparent acceleration of relative sea-level (RSL) in millimetre yr^{-2} taken from a linear regression to t^2 in time on each record greater than 20 years length in the Permanent Service for Mean Sea-Level Revised Local Reference (PSMSL RLR; www.pol.ac.uk/psmsl) database. The enormous and inconclusive scatter of the acceleration terms for records less than 60–80 years in length is due to aliasing of low-frequency undulations of sea-level into the acceleration terms. These undulations arise from sources such as ENSO effects on the eastern boundary of the Pacific Ocean (Chelton & Davis 1982), westward propagating Rossby waves (Hong *et al.* 2000; Sturges & Hong 2001), and various other meteorological forcings. Note that many of the longest

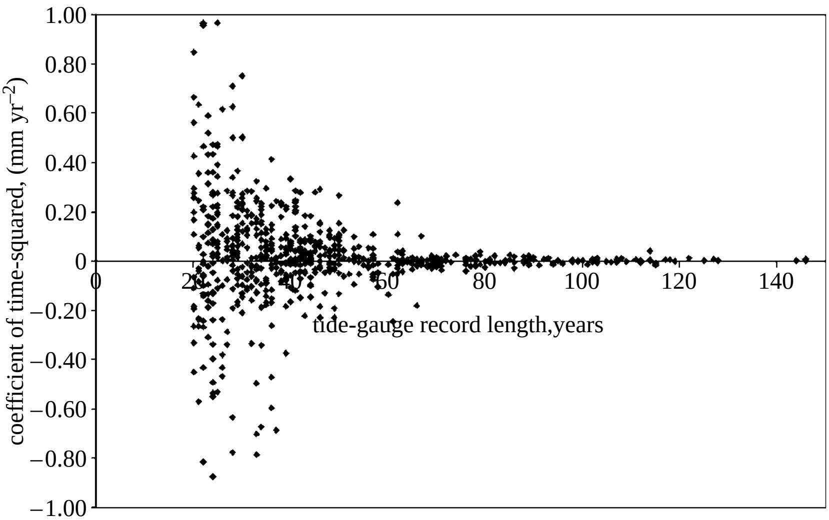

Figure 1. Apparent accelerations of RSL for the PSMSL RLR stations as a function of record length. Note that overall, the accelerations are as likely to be positive as negative except for the very longest ones which reach back into the nineteenth century (see text).

records that reach into the nineteenth century show a small positive acceleration of about 0.01 mm yr^{-2}. Concerning this, Woodworth (1990), Kearney & Stephenson (1991) and Donnelly *et al.* (2004) have given a variety of evidence for an increase of the rate of sea-level rise during the mid-to-late nineteenth century. This historically recent increase contrasts with the very small average over the previous few millennia. For example, Flemming (1978, 1982) concluded from archaeological data that for the last two millennia the rate of GSLR was only a few tenths of a millimetre yr^{-1}. The reason for the change in trend of sea-level rise that began in the mid-to-late nineteenth century has not been explained, but as far as the twentieth century is concerned, figure 1 shows that there is no reason to change the conclusions of Woodworth (1990) and Douglas (1992) that there is no statistically significant evidence for an acceleration of GSL during the twentieth century.

What figure 1 especially shows is that one cannot look to a few decades of tide-gauge data to detect an acceleration of GSL. However, it also appears that sea-level undulations are not large at periods longer than about a century; if they were, they would be absorbed into the acceleration term in the regression and yield large values, as did the higher frequency undulations. This figure then makes plausible the case that as far as the global tide-gauge record is concerned, values of twentieth-century relative sea-level rise (RSLR) from very long tide-gauge records will have similar values if corrections for vertical crustal movements can be found for each tide-gauge site. Until recently, these corrections required models of the GIA process. The new approach is to measure vertical movements directly. There are many ongoing efforts to measure vertical crustal movements at tide-gauge sites using the Global Positioning System (GPS) (see Milne *et al.* 2001, for a successful campaign in Fennoscandia where GIA rates are high) and other satellite technologies, eliminating the need for GIA models. In this paper, we take a different approach by examining the geographic

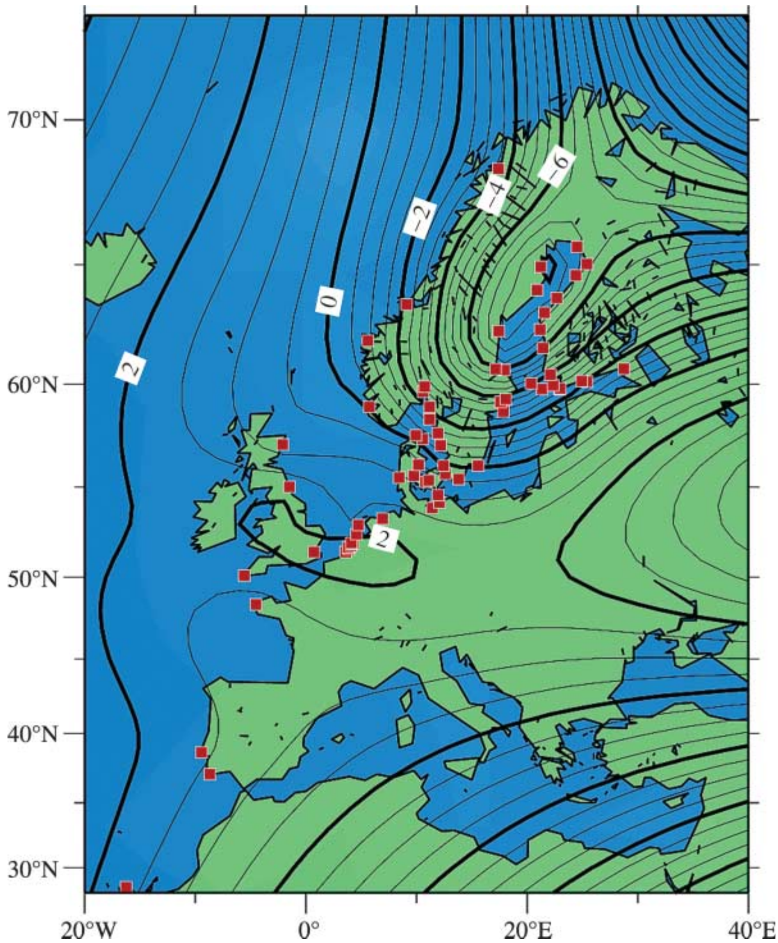

Figure 2. Contours of observed RSLR in Europe from long tide-gauge records. Mediterranean sites not included (see text). Units are mm yr^{-1}.

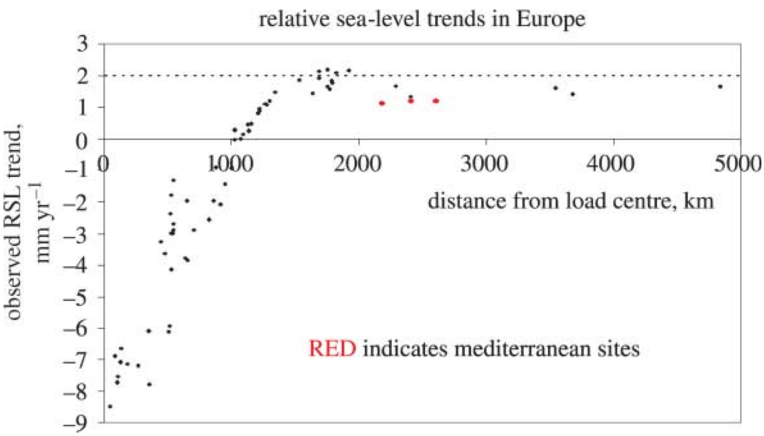

Figure 3. Observed rates of relative sea-level rise as a function of distance from the apparent position of maximum uplift, which occurs in the northwest Gulf of Bothnia.

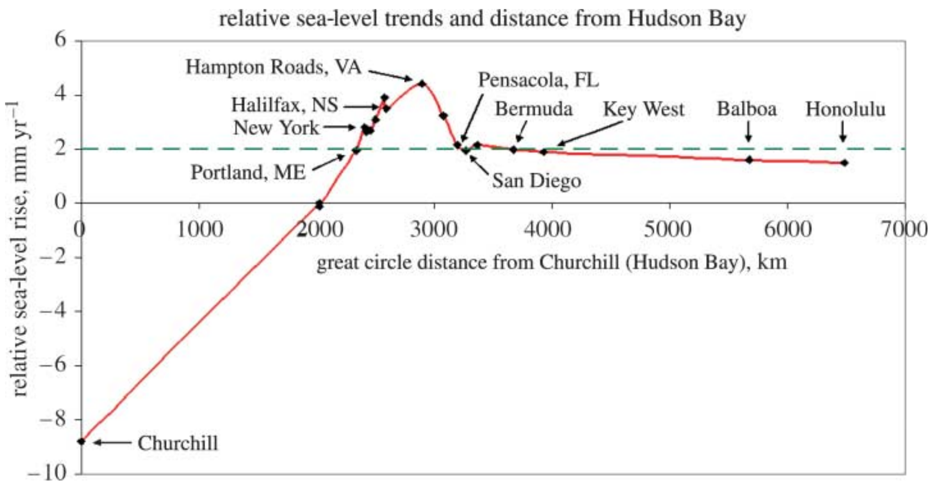

Figure 4. Observed rates of relative sea-level rise (RSLR) as a function of distance from Churchill, Hudson Bay. The forebulge collapse is very obvious, and is about four times as large as the same phenomenon seen in figure 3 for Europe.

patterns of RSLR and arrive at plausible conclusions about GSLR that are independent of GIA models or geodetic measurements.

An important issue remains for the use of long tide-gauge records for determining GSLR. It is that even if corrections for vertical crustal movements can be measured or inferred, do the small number of long tide-gauge records, nearly all from coastal sites, represent the long-term secular behaviour of the broad oceans? This last point was raised by Cabanes *et al.* (2001) in a provocative paper which concluded that sea-level rise in the aggregate is exaggerated at tide-gauge sites by a factor of about 3 due to anomalous warming at coastal sites. If true, it would imply that twentieth century GSLR was ≤ 1 mm yr^{-1} and could easily be explained by a thermal expansion of about 0.5 mm yr^{-1} plus a similar amount from melting of small glaciers. In this paper, we undertake an investigation of both crustal movements due to GIA, and the issue of a possible systematic steric effect on coastal tide-gauge estimates of RSLR.

2. A morphological examination of glacial isostatic adjustment using tide-gauge records

GIA is the subject of an extensive literature (see Peltier 2001 for an overview and many references). The Earth deformed viscoelastically under the immense weight of the kilometres-thick ice sheets that covered Canada and the northern US, and Europe and the northern United Kingdom at last glacial maximum (LGM) 21 000 years BP. Mantle material flowed from under the massive ice sheets to beyond their periphery, producing a subsidence of the land under the ice and a forebulge (uplift) adjacent. By 10 000 years BP the glacial melting that was to occur was essentially complete and sea-levels were not far from present values. But Earth continues to adjust to the removal of the loads. Even today at the locations of the greatest loads the surface is rebounding by nearly 10 mm yr^{-1}, and subsiding in the forebulge region peripheral to the ice masses by as much as 2 mm yr^{-1} as mantle material flows back to the formerly ice-covered areas. Long tide-gauge records clearly show this ongoing GIA. Figure 2 was created by contouring the observed rates of RSLR for 59 European and UK tide-gauge sites (average record length = 84 years). The long Mediterranean records from Marseille, Genoa, and Trieste were not included because of their anomalous behaviour from 1960 onward (Douglas 1997; Tsimplis & Baker 2000), but are considered further below. This familiar elliptical 'bulls eye' plot has appeared many times in the literature (e.g. Lambeck *et al.* 1998; Douglas 2001), but is still worthy of an extended examination. The contours do not close to the northeast, an artefact of the contouring algorithm that occurs because of the lack of values there, but the coverage is good over three-fourth of the compass. The overwhelming impact of GIA on modern Fennoscandia is seen to be centred on the high northwest of the Gulf of Bothnia, the region of maximum ice load at LGM. The rate of rise of RSL there is about −8 mm yr^{-1}, i.e. sea-level is falling because of an uplift that far more than offsets any plausible estimate of GSLR. Note that the rate of RSL rise increases rapidly with distance from the point of maximum decline, reaching a value of zero at southern Norway and Sweden. Let us now examine how RSL rise varies as a function of the great circle distance from the point of maximum uplift. Figure 3, a plot of the actual values of RSL rise as a function of this distance, has a very regular form that contains much information about GIA in Europe.

Up to 1000 km from the load centre, there is some scatter of values, of course because the contours are not circles. But at greater distances a much more regular pattern exists. The peak value of RSLR occurs at about 1800 km distance at a value near 2 mm yr^{-1} (the dotted line in figure 3) with a subsequent falloff from this value by a few tenths of a millimetre yr^{-1}. The Mediterranean sites at Genoa, Marseille, and Trieste are systematically lower because sea-level stopped rising at these sites about 1960 (Douglas 1997; Tsimplis & Baker 2000). The group average rate up to 1960 of the three Mediterranean records is about 1.5 mm yr^{-1}, in line with the other values beyond 2000 km. Figure 3 suggests that the peak of the residual forebulge from the LGM is a little less than 2000 km from the NW Gulf of Bothnia, and that the magnitude of the 'forebulge collapse' is only about 0.5 mm yr^{-1} even taking the Mediterranean trends at face value. In addition, the Mediterranean sites are in the 'far field' of the Fennoscandian GIA and are not submerging, a possibility discussed in a review of long sea-level records (Woodworth 2003). Much farther away, Cascais, Lagos, and Tenerife are all above 1.5 mm yr^{-1}. Far field emergence of a few tenths of a millimetre yr^{-1} at low and mid-latitudes is evident from some geologic data (Peltier 2001), and if the effect has even the same sign for the tide-gauges more than 3500 km from the Gulf of Bothnia, it is seen that the values of RSLR well beyond the forebulge asymptotically approach near 2 mm yr^{-1}.

Unfortunately, a contour figure similar to figure 2 cannot be made for the area of the Laurentide ice mass, since there are no tide-gauges closely surrounding it. However, the greatest ice load was at Hudson Bay (Peltier 2001), and there is a tide-gauge there at Churchill with a 60 year record available from the PSMSL. The trend of SLR at Churchill is −9.7 mm yr^{-1}, indicating uplift as the surface continues to rebound long after the disappearance of the ice load. The abundance

Table 1. Trends of RSLR in order of great circle distance from Churchill, Hudson Bay from a representative sample of long tide-gauge records.

station	distance from Churchill (km)	trend (mm yr^{-1})
Churchill	0	−9.7
Quebec	2020	0
Pointe-Au-Paire	2023	−0.1
Portland, ME	2341	1.95
Saint John, N.B.	2410	2.82
Boston	2425	2.64
New York	2456	2.71
Baltimore	2502	3.1
Atlantic City	2574	3.9
Halifax	2590	3.5
Hampton Roads	2894	4.41
Charleston	3079	3.24
Pensacola	3198	2.15
Fernandina	3268	1.97
San Diego	3364	2.16
Bermuda	3666	1.98
Key West	3927	1.9
Balboa	5675	1.6
Honolulu	6486	1.5

of tide-gauges with long records along North American coastlines enables presentation of a figure similar to figure 3, this time showing the observed trend of RSL plotted as a function of the great circle distance from Churchill. Table 1 gives the trends of RSLR as a function of the great circle distance from Churchill for a representative sample of long Western Hemisphere tide-gauges. Note the general rise in sea-level trend as a function of distance from Churchill as far as Hampton Roads, Virginia, *regardless of the azimuth* of the great circle from Churchill to a station. In particular, we observe that Atlantic City, New Jersey, and Halifax, Nova Scotia are at practically the same distance from Churchill, and have a very similar rate of RSLR. Figure 4 shows that the forebulge collapse is very well defined, reaching its peak at Hampton Roads, Virginia. Other vertical crustal movements could be contributing to the values of RSLR seen in table 1, but are probably small considering the consistency of the pattern shown in figure 4. An example of a tide-gauge site that experiences a large elevation change unrelated to GIA is Wilmington, NC. It is located on the Cape Fear Arch, is uplifted by about 1 mm yr^{-1}, and so is not included in the table.

As in figure 3, addition of a few tenths of a millimetre yr^{-1} for far field emergence strongly points to a rate of GSLR much nearer to 2 mm yr^{-1} than 1 mm yr^{-1}. Note that the forebulge collapse itself reaches about 2 mm yr^{-1}, about four times the value seen in Europe. This is not unexpected, given the much larger ice loads that covered the Laurentide.

This indication of a value for twentieth century GSLR of about 2 mm yr^{-1} based on figures 3 and 4 is admittedly only morphological and subject to issues of geographic sampling. However, it is surely difficult to reconcile figures 3 and 4

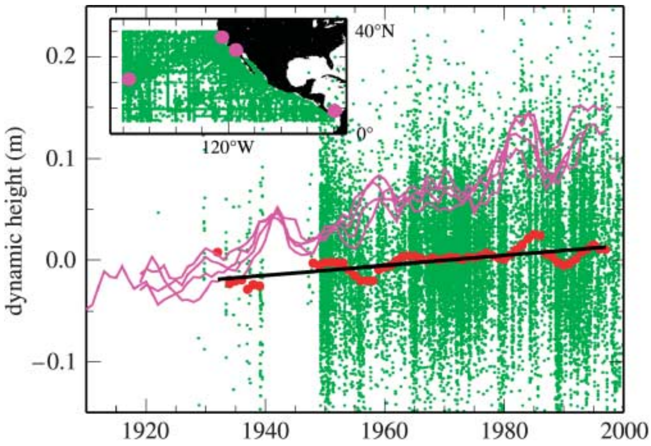

Figure 5. Comparison of GIA-corrected tide-gauge data (purple), and dynamic heights (green) computed from hydrographic data to 1000 m. The red dots are dynamic heights smoothed with a 5 year running mean filter. The tide-gauges give about 2 mm yr^{-1}, and the dynamic heights only about 0.5 mm yr^{-1} (black line).

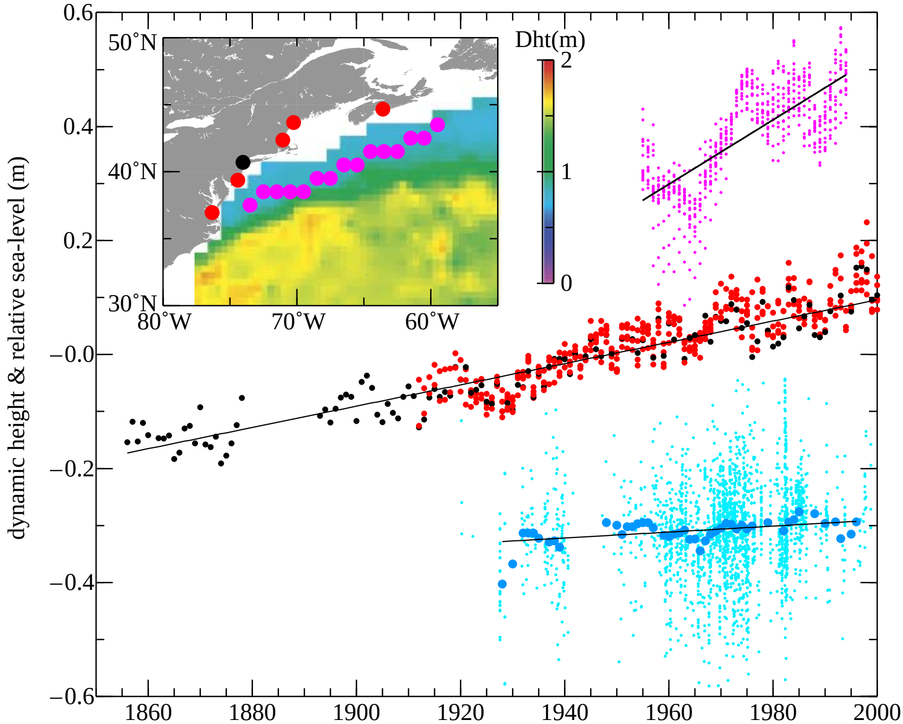

Figure 6. Comparison of sea-level trends from tide-gauge and hydrographic data in the western North Atlantic. Top: surface dynamic height anomalies computed from WOA98v2 interpolated data at grid points closest to the coast (purple dots, map inset). Middle: tide-gauge measurements of relative sea-level at Hampton Roads, Atlantic City, New York, Boston, Halifax (red dots, except black for New York, map inset). Bottom: surface dynamic height anomalies computed from actual observations in Slope Water region. Map shows mean dynamic topography (0–1000 m) with the Gulf Stream evident as approximately 1 m difference between the Slope Water (blue) and Sargasso (yellow).

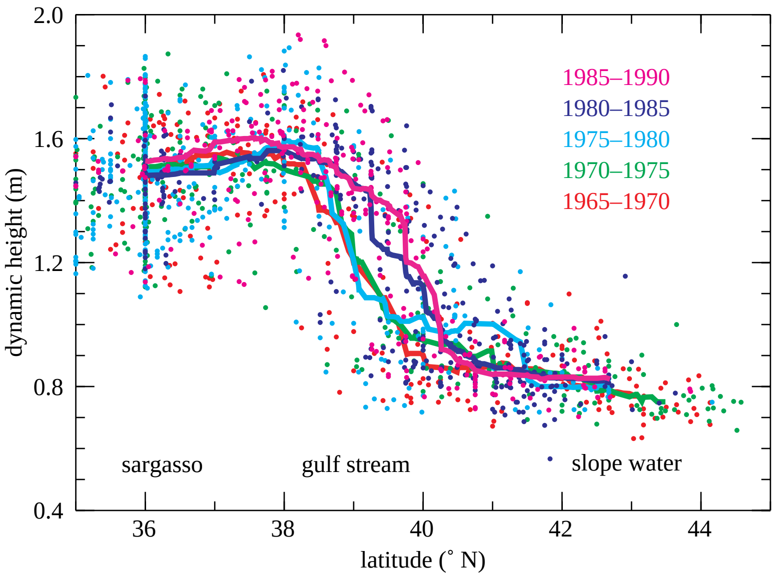

Figure 7. Surface dynamic height (0–1000 m) observations between 60 and 70 W plotted as a function of latitude, crossing the Gulf Stream just north of Bermuda (36N). Coloured dots and lines show actual measurements and the mean profile for each 5 year interval between 1965 and 1990.

with a GSLR value $\leq 1\ \mathrm{mm\ yr^{-1}}$; such a low value is inconsistent with the observed pattern of sea-level trends. But an issue remains; nearly all of the tide-gauge sites in figures 3 and 4 are coastal ones. Is it possible that their trends are systematically in error as suggested by Cabanes *et al.* (2001)? The analysis of hydrographic data that follows indicates that this is not the case.

3. Analysis of sea-level trends from tide-gauges and hydrographic data

In Miller & Douglas (2004), we investigated regions of the Pacific and Atlantic Oceans that were defined and bounded by coastal and island tide-gauges. These gauges were selected on the basis of the similarity of their interannual variations and trends, and included both western and eastern ocean boundaries. Figure 5 shows the method applied in the eastern Pacific. The GIA-corrected (Peltier 2001) tide-gauge data at San Francisco, San Diego, Honolulu, and Balboa (purple curves) show similar trends and interdecadal variations, suggesting that at low frequencies, the region varies in a coherent manner. Surface dynamic heights (0–1000 m) computed directly from all available hydrographic stations with both temperature and salinity data in the region (see map inset for locations) are indicated by green dots. The red dots show the 5 year running means and the black line the linear regression. The trend of the observed dynamic height is about $0.5\ \mathrm{mm\ yr^{-1}}$, roughly one-fourth the trend of sea-level from the tide-gauge series. We obtained similar results for smaller regions close to the gauge sites, leading us to conclude that the gauge trends are not biased and that both locally and regionally, the rate of sea-level rise is considerably larger than the rate of dynamic height rise. Since the gauges measure both the steric and non-steric components of sea-level rise, but the hydrographic observations only measure the steric component, it follows that the non-steric component must be substantially larger than the steric component.

To help explain why our results are so different from those of Cabanes *et al.* (2001), figure 6 presents a new analysis of the Slope Water region (north of the Gulf Stream and east of the tide-gauge sites) in the western North Atlantic from Hampton Roads, Virginia, to Halifax. In the main body of the figure, two types of surface dynamic height anomalies are shown along with tide-gauge measurements. The purple curves at the top are dynamic height anomaly time series computed from the World Ocean Atlas 1998v2 (WOA98v2) at the WOA98v2 grid points nearest the coast (purple dots, map inset). This is the same interpolated dataset used by Cabanes *et al.* (2001) to compare dynamic heights with East Coast tide-gauge measurements of sea-level. The curves all show a dramatic 20 cm increase in the 1970s that causes the linear regression for the 1955–1995 interval to be 6.7 mm yr^{-1}. The middle dataset shows the GIA-corrected tide-gauge measurements of sea-level at Hampton Roads, Atlantic City, New York, Boston, and Halifax. All exhibit similar low frequency variations and trends of about 2 mm yr^{-1}, but no evidence of a 20 cm increase in the 1970s. The bottom dataset shows the dynamic height anomalies computed from actual (uninterpolated) hydrographic observations in the Slope Water region. The trend computed from these data is negligible and, as with the gauges, there is no evidence of an abrupt change in the 1970s.

The fact that WOA98v2-derived dynamic heights in the Slope Water region show a dramatic rise but the surrounding observed values do not is likely an artefact of the large (444–888 km) variable radius of influence used in the WOA98v2 objective analysis. Between the 1960s and 1970s the mean position of the Gulf Stream shifted northward about 100 km in response to large-scale changes in the surface wind field (Joyce *et al.* 2000). Figure 7 illustrates this shift in a set of 5 year mean dynamic profiles computed from hydrographic observations along a meridional band intersecting the Gulf Stream north of Bermuda. The axis of the Stream moved northward about 100 km in 1980–1990 relative to 1965–1980, with no significant change in dynamic height near the coast.

In Miller & Douglas (2004), we assessed the impact of the Gulf Stream smoothing error on the results of Cabanes *et al.* (2001) and concluded that the effect on the western Atlantic trends alone was large enough to account for their conclusion that tide-gauges *on average* exaggerate the rate of GSLR by more than a factor of two.

4. Gyre considerations

Even though we can be confident that the much larger rates of SLR given by GIA-corrected tide-gauge data compared to hydrographic observations are real and not an artefact of some unspecified *steric* sampling problem, we cannot immediately exclude the possibility that the gauges are subject to a *mass* related sampling problem. For example, since most of the gauges used by Douglas (1991, 1997) and others are located along continental margins, and therefore, along the peripheries of the major ocean gyres, it is conceivable that the gauges are recording gyre-scale mass redistributions, rather than a mass increase due to addition of fresh water to the global ocean. In this scenario, part of the nearly 2 mm yr^{-1} rise observed along the US east coast and the west coast of Europe might be caused by a century-long spin-down of the sub-tropical gyre, allowing water to spread to the margins of the basin. However, for this to be true, large areas of the gyre interior would have a falling or at least far more slowly rising sea-level for the twentieth century, and such has not been reported.

In fact, there is some evidence suggesting that sea-level rose in the gyre interior at approximately the same rate as along the gyre boundary. Figure 8 shows a collection of GIA-corrected coastal gauge records from the eastern and western sides of the North Atlantic basin (Brest, Cascais, and New York, Charleston, respectively), as well as Bermuda, which is located near the gyre centre in terms of maximum dynamic height (see map inset of mean dynamic topography). The North American records show sea-level rising at a rate of about 2.0 mm yr^{-1}, while the European records indicate a slightly smaller average rate of about 1.5 mm yr^{-1}. The Bermuda record is marked by large (10 cm), decadal fluctuations associated with wind forced Rossby waves (Sturges & Hong 2001; Hong *et al.* 2000), but also plainly shows an upward trend of 1.5 mm yr^{-1}, as determined from a least squares fit to nearly 70 years of data, i.e. roughly the same rate as recorded by the coastal gauges.

Although Bermuda may not be representative of the entire gyre interior (there may be regional differences and area weighting could play a role), the fact it is centrally located and has a long-term trend similar to that found along the margins of the basin suggests that the rise along the margins is not principally the result of a gyre-scale redistribution. But, what about the issue of mass versus volume change inside the gyre? To be consistent with the gauge and hydrographic observations near the coasts (here figure 6; Miller & Douglas 2004, fig. 3), one would also expect to find a larger (2–3 times) mass change signal than volume change signal inside the gyre. To test this proposition, figure 9 shows a comparison of gauge measured sea-level and dynamic height anomalies for a $6\times6°$ region centred on Bermuda. Bermuda is unusual in having both a long tide-gauge record and a long and continuous record of monthly deep hydrocasts, the Panulirus series initiated by Henry Stommel and carried out by the Bermuda Biological Station since 1954, and useful hydrographic data before 1940. Roemmich (1990) previously studied dynamic heights and tide-gauge data at Bermuda, but only between 1954 and 1981. He showed that the decadal variations of the steric heights closely resembled those seen in the gauge data, but did not regard as statistically significant the differences in their trends. Joyce & Robbins (1996) used a small, select set of observations made prior to 1954 to extend the Panulirus record over 73 years (1922–1995). They found a 0.005 °C yr^{-1} warming trend in the mid-depth (1500–2500 m) range of the water column, which is equivalent to a 0.7 mm yr^{-1} contribution to dynamic height. However, they stated that variability in the upper thermocline would make it difficult to detect this signal in surface dynamic height, and did not estimate the trend of it. We have computed the trend of surface dynamic height and obtained results very different from those indicated by the temperature change at intermediate levels.

The green dots in figure 9 show the surface dynamic height anomalies (0–2000 m), the red dots their 5 year running means, and the blue dots the 5 year

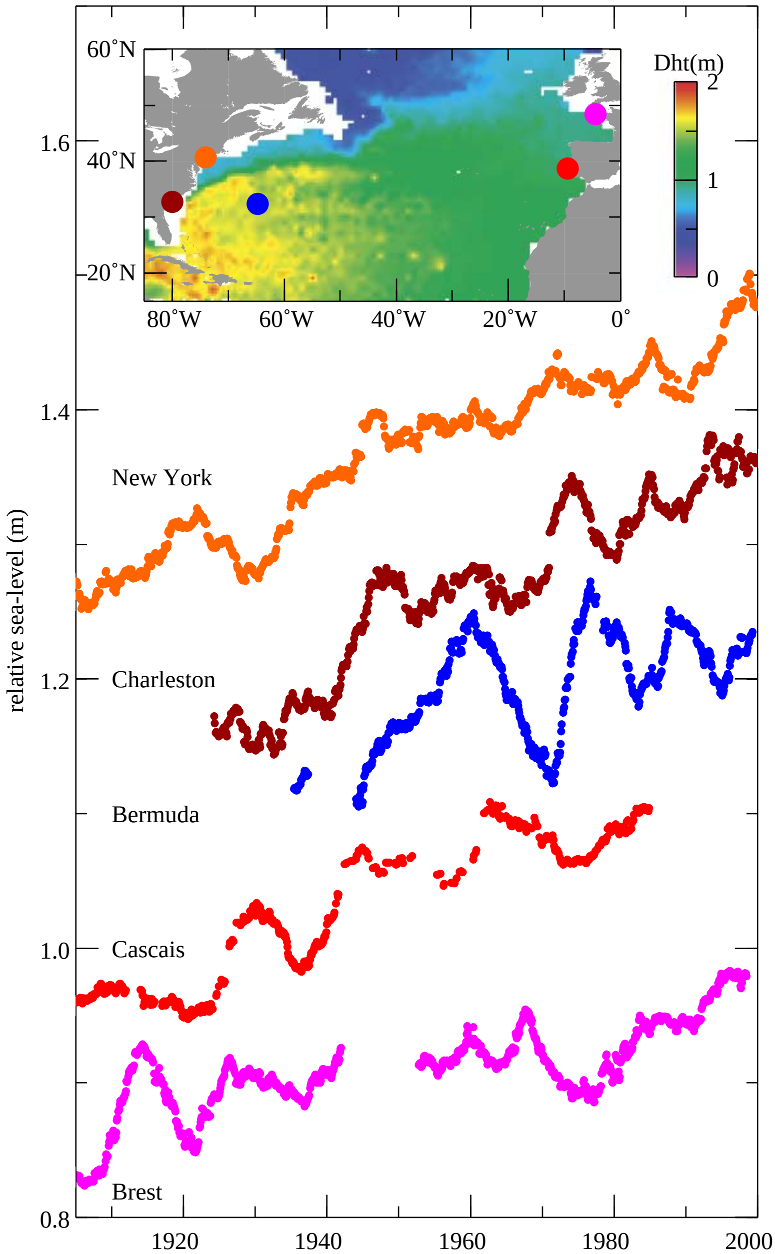

Figure 8. GIA-corrected twentieth century sea-level time series from tide-gauge sites on the eastern and western margins of the North Atlantic subtropical gyre (Brest, Cascais and New York, Charleston, respectively) and near the gyre centre at Bermuda. Map inset shows the mean surface dynamic topography (0–1000 m) and gauge locations.

running means of the tide-gauge sea-level trend. As we have found elsewhere in the North Atlantic and Eastern Pacific, the GIA-corrected tide-gauge trend is much larger than the trend of dynamic heights, in this case about 1.5 mm yr^{-1}, whereas the dynamic height trend is considerably smaller at about 0.2 mm yr^{-1}.

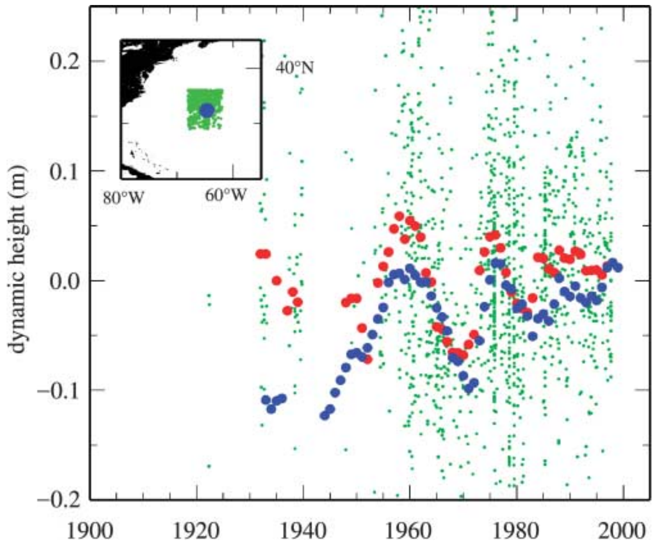

Figure 9. Comparison of GIA-corrected Bermuda tide-gauge time series (blue) and surface dynamic heights (green) computed from hydrographic data in 6×6° box centred on Bermuda. The red dots are dynamic heights smoothed with a 5 year running mean filter, as was the tide-gauge data.

The difference between them using our longer records is significant. Thus, at least in the region surrounding Bermuda, the rate of mass increase is greater than the rate of volume increase. Whether the rest of the gyre interior is currently undergoing such changes remains to be determined, possibly from a joint analysis of Jason satellite altimeter data and Argo float observations.

5. Conclusions

Church *et al.* (2001) in the IPCC Third Assessment Report concluded only that the range of GSLR in the twentieth century was between 1 and 2 mm yr^{-1}. This reflected the range of estimates from investigations using tide-gauge data at the time of the report's preparation. Authors had used different methods and models for GIA corrections, and also differing tide-gauge datasets, and regions for their analyses. We now believe that the morphological analysis of tide-gauge trends presented in this paper makes untenable values of GSLR much below about 2 mm yr^{-1}, as does our analysis of hydrographic data.

At the time of preparation of the IPCC TAR, it was not possible to determine independently a reliable budget for GSLR based on mass and volume contributions because some of the constituents, including especially the mass increase due to meltwater from Greenland and Antarctica, were very uncertain. The uncertainty of these is so great that a value near zero for the combined contribution of these great high latitude ice sheets is within the range of observations. The analyses of Miller & Douglas (2004) and this paper reach a different conclusion concerning the role of grounded ice from the great high latitude ice sheets. Our results indicate that there is a surplus of near 1 mm yr^{-1} of twentieth century GSLR over and beyond that attributable to thermal expansion and melting of small glaciers. Previously, Antonov *et al.* (2002)

calculated that the observed freshening of the global oceans since 1950 requires a fresh water sea-level equivalent of about 1.4 mm yr^{-1}. However, they could not conclude whether the source of this fresh water was from Arctic (floating) ice, or grounded ice. Wadhams & Munk (2004) and in this volume offer evidence that a secular thinning of the Arctic ice pack can account for the freshening, and of course would not affect sea-level. They estimate that only 0.6 mm yr^{-1} of grounded ice is likely to be coming into the oceans. However, this conclusion depends critically on the accuracy of the Antonov *et al.* (2002) result, which is subject to large uncertainties. The historical salinity dataset is notoriously sparse both in time and space, so much so that the objectively analysed and interpolated set of grid point values used by Antonov *et al.* (2002) may not represent the actual global ocean salinity *trend* with the requisite accuracy.

We conclude from our investigation that the excess of SLR that we observe in comparing tide-gauges with steric heights is likely from water coming from grounded ice, and Greenland and/or Antarctica are the dominant contributors beyond the relatively low amount coming from small glaciers. In addition, our morphological analysis of the trends of RSL in relation to their distances from the positions of maximum ice load at LGM supports our conclusions based on hydrographic data analyses.

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