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Relative importance of mass and volume changes to global sea level rise

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[1] We examine the relationship between 50-year-long records of global sea level (GSL) calculated from 1023 tide gauge stations and global ocean heat content (GOHC), glacier and ice sheet melting. The lack of consistent correlation between changes in GOHC and GSL during the period 1955–2003 argues against GOHC being the dominant factor in GSL as is often thought. We provide clear evidence of the substantial and increasing role in GSL from the eustatic component (47%) compared with the contribution from increasing heat content (25%), suggesting that the primary role is being played by the melting glaciers and ice sheets. There remains about 1/4 of GSL rise unaccounted for by the best estimates of both eustatic and thermosteric effects. This fraction also exhibits large variability that is not readily associated with known causes of sea level variability. The most likely explanation of this unknown fraction is underestimated melting, climate-driven changes in terrestrial storage components, and decadal timescale variability in global water cycle. This argues for a concerted effort to quantify changes in these reservoirs.

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1. Introduction

[2] The global sea level (GSL) rise over the 20th century is 1.7 ± 0.5 mm a^{-1} [*IPCC*, 2007], which is a combination of ocean volume change associated with thermal expansion (thermosteric) and change in the mass of the ocean due to melting of continental ice and filling of continental reservoirs (eustatic). It is debated, however, which of the two causes: expansion of ocean waters due to warming, or freshwater input from the continents, dominated the GSL rise. In 2001, the IPCC (TAR) concluded that the main cause of this rise is the thermal expansion of the ocean. However, the new *IPCC* [2007] report, states that it is likely that the sum of all known contributions for this period is smaller than the observed sea level rise, and therefore it is not possible to satisfactorily account for the processes causing sea level rise.

[3] According to *Antonov et al.* [2005], over the period 1955–2003, the thermal expansion of the top 700 m of the World Ocean contributed approximately 0.33 mm a^{-1} to GSL rise, with a 1.23 mm a^{-1} rise during the period 1993–2003. *Cabanes et al.* [2001] claim that over 6 years (1993–1998) thermostric sea level rise amounted to 3.1 ± 0.4 mm a^{-1} and that the GSL rise calculated using the Topex/Poseidon altimeter measurements was 3.2 ± 0.2 mm a^{-1}, from which they conclude that sea level rise can be fully explained by the thermal expansion during the past decade. However, later *Willis et al.* [2004] deduced a thermosteric trend over 1990s of about 1.6 ± 0.3 mm a^{-1} compared with about 3 mm a^{-1} from altimetry. *Lombard et al.* [2005] readdressed the *Cabanes et al.* [2001] study specifically and found that the 1993–1998 trend calculated from global ocean temperature data set [*Ishii et al.*, 2003] is only 1.7 ± 0.4 mm a^{-1} and accounts for only about half of the rate of sea level rise observed from satellite altimetry.

[4] On the other hand, *Munk* [2003] argues that a recent decrease in global ocean salinity may point to a dominant contribution from freshwater input. Furthermore, *Miller and Douglas* [2004] found a large difference between the tide gauge-determined sea level rise and the regionally average steric sea level rise, suggesting a large mass contribution. The importance of nonthermal factors in GSL has been demonstrated by *Grinsted et al.* [2007], who show that the impact of large volcanic eruptions on observed GSL is a rise of 9 mm due to disturbance of the global water cycle during the first year following an eruption whereas model simulations [*Hansen et al.*, 2002; *Church et al.*, 2005] predict a decrease of ocean heat content (and hence GSL).

[5] Here we challenge the hypothesis that GOHC is the principal driving force for sea level rise since the 1950s by showing how the relationship between GSL calculated from 1023 tide gauge records [*Jevrejeva et al.*, 2006] and GOHC [*Levitus et al.*, 2005] is very variable over time. In contrast with previous studies [e.g., *Lombard et al.*, 2005], where only slopes of trends in individual sea level time series were compared with slopes of trends in regional ocean heat content, in this paper for the first time we investigate

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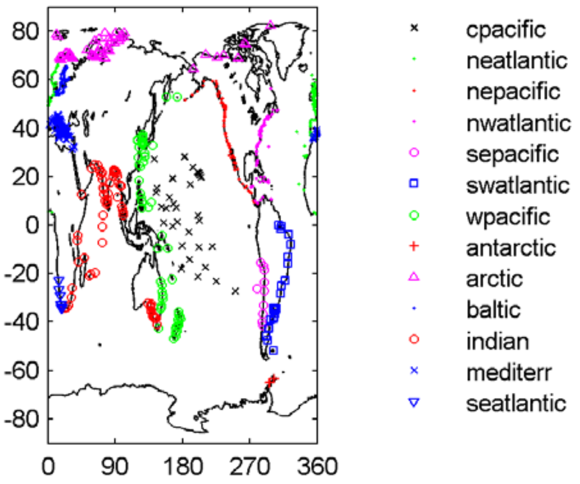

Figure 1. Location of the tide gauges included in this study (13 regions: cpacific- Central Pacific, neatlantic- Northeast Atlantic, nepacific- Northeast Pacific, nwatlantic- Northwest Atlantic, sepacific- Southeast Pacific, swatlantic- Southwest Atlantic, wpacific- Western Pacific, Antarctic- Antarctica, arctic- Arctic, baltic- Baltic, indian- Indian, mediterr- Mediterranean, seatlantic- Southeast Atlantic).

temporal correlations between global sea level and GOHC. We then estimate the contributions to GSL rise from two separate components: thermosteric sea level (TSL) rise [*Antonov et al.*, 2005], associated with changes in GOHC, and eustatic sea level (ISL) rise, related to the melting of continental glaciers and ice sheets in Greenland and Antarctica [*Dyurgerov and Meier*, 2005; *Krabill et al.*, 2004; *Thomas et al.*, 2004].

2. Data

[6] We utilize 1023 time series of monthly mean relative sea level (RSL) from the Permanent Service for Mean Sea Level (PSMSL) database [*Woodworth and Player*, 2003]. Detailed descriptions of these time series are available from www.pol.ac.uk/psmsl; locations of the tide gauges included in this study are presented in Figure 1. RSL data sets were corrected for local datum changes and glacial isostatic adjustment (GIA) of the solid Earth [*Peltier*, 2001]. We have developed a new "virtual station" method to overcome geographical bias and which can quantify the uncertainties due to representativity issues of the stations employed [*Jevrejeva et al.*, 2006]. Our global sea level trend estimate of 2.4 ± 1.0 mm a^{-1} for the period from 1993 to 2000 is comparable with the 2.6 ± 0.7 mm a^{-1} sea level rise calculated from TOPEX/Poseidon altimeter measurements, which shows the ability of our "virtual station" method to resolve the temporal evolution of the spatial sea level field and confirms good quality of the global sea level reconstruction. The GSL quantities (together with calculated errors) are available from http://www.pol.ac.uk/psmsl/author_archive/jevrejeva_etal_gsl/.

[7] We use the heat content data for the period 1955–2003 from *Levitus et al.* [2005], available from www.nodc.noaa.gov/oc5/data_analysis/heat_intro.html, and the derived thermosteric sea level (TSL) during 1955–2003 from *Antonov et al.* [2005]. For the period 1961–2003 data on glacier volume change and their contribution to sea level rise are taken from *Dyurgerov and Meier* [2005]. This data is corrected for spatial bias by area-weighting of regional averages. We extended this backward to 1955 using the simple estimates of sea level contributions from a few small glaciers and ice caps [*Cogley*, 2005]. Estimates of the contributions from Greenland and Antarctica ice sheets are taken from *IPCC* [2007]; 0.2 mm a^{-1} for 1955–1993 and 0.4 mm a^{-1} since 1993 [*Krabill et al.*, 2004; *Thomas et al.*, 2004]. From the sum of the glaciers, ice caps, Greenland and Antarctica ice sheets contributions we calculate the total contributions from ice masses (ISL).

3. Results

3.1. Relationship Between GSL and GOHC

[8] Results of correlation analysis between heat content and sea level for the global, Atlantic, Indian, and Pacific oceans are presented in Table 1. The highest regional correlation coefficients (0.84 and 0.83) are for the North and South Atlantic, respectively. A weak relationship, with correlation coefficient of 0.3, exists for the Indian Ocean. Central Pacific sea level is more strongly correlated (r = 0.64) with heat content than the Pacific as a whole (calculated as the average from the northwest, northeast, Central, South Pacific). Figure 2 demonstrate the difference in patterns of sea level and thermosteric sea level for the Atlantic and Pacific oceans.

[9] The overall correlation between the GSL and GOHC (0–1500 m layer) is 0.78. However, Figure 3a reveals, with the use of a running correlation coefficient (10-year window), that the relationship changes with time, with a minimum (−0.6) in 1982 and maximum (0.8) for the last 10 years (1993–2003). A rapid increase in heat content in 1976 followed by a fall in the 1980s is not present in GSL. The increase in measured heat content during 1972–1976 reported by *Levitus et al.* [2005] has been challenged by *Gregory et al.* [2004] based on modelled ocean heat content. However, *Levitus et al.* [2005] argue that feature is real since data coverage is excellent. Recently, a concern about the effects of instrumental bias on the estimates of ocean heat content has been raised by *Gouretski and Koltermann* [2007]. The authors have suggested that a positive bias

Table 1. Correlation Coefficients Between Sea Level (Global and Regional) and Ocean Heat Content During 1955–2003

	Heat Content	
Sea Level From Tide Gauges	0–300 (m)	0–700 (m)
Global	0.72	0.74
	Atlantic Ocean	
North Atlantic	0.82	0.84
South Atlantic	0.79	0.83
	Indian Ocean	
Indian Ocean	0.31	0.29
	Pacific Ocean	
Central Pacific	0.61	0.64
Pacific Ocean	0.32	0.36

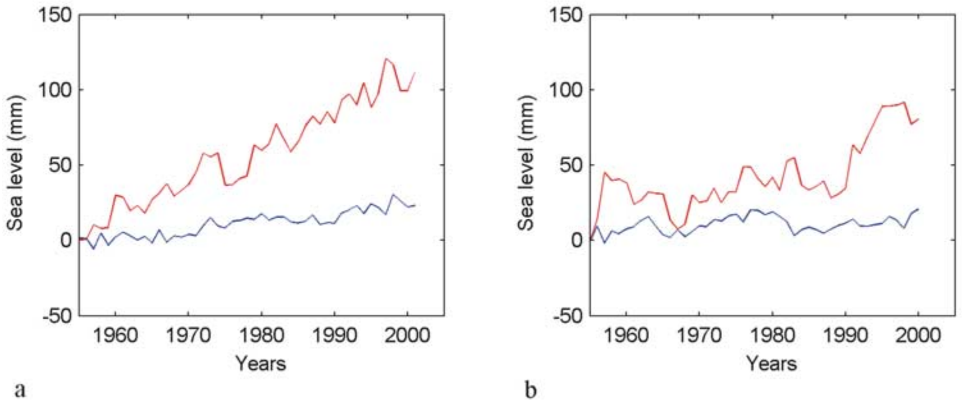

Figure 2. Time series of sea level (blue) calculated from tide gauges and thermosteric sea level (red) calculated from hydrographic data [*Antonov et al.*, 2005] for (a) Atlantic and (b) Pacific oceans.

associated with expendable bathythermographs (XBT) measurements might be responsible for an exaggerated temperature signal during this period. However, global ocean heat content anomalies calculated from all types of hydrographical instrumentation [*Gouretski and Koltermann*, 2007] demonstrate an obvious thermal maximum (with some differences in magnitude) around 1975. This increase of ocean heat content during 1972–1976 and the subsequent drop is reflected in the poor correlation coefficients presented in Figure 3.

[10] Figure 3b demonstrates that the relationship between the GOHC and the GSL changes dramatically from positive to negative for any moving correlation window between 3 and 25 years, suggesting that the relationship conclusion drawn from Figure 3a is robust.

[11] The increase in correlation coefficient between GOHC and GSL during 1993–2003 is also accompanied by close similarity in the slopes of the linear trends in GSL (from both tide gauges [*Jevrejeva et al.*, 2006] and satellites [*White et al.*, 2005]), and in TSL calculated from Simple Ocean Data Assimilation (SODA) ocean reanalysis [*Carton et al.*, 2005]. This similarity in slopes for short time period has lead some authors to the conclusion that sea level rise can be totally explained by the changes in heat content [*Cabanes et al.*, 2001] or that the change in the long-term trend in sea level in the 90 s was thermosteric [*Carton et al.*, 2001]. However, reasonable correlation and similarity of trends do not prove a causal link between time series. Figure 3 also suggests that the robustness of fitting slopes to short GSL time series is questionable due to large uncertainties in the slope estimations caused by the arbitrary selection of start and end years. Naturally, one would expect some amount of interannual to decadal variability to be present which would appear trend-like when using only 6 [*Cabanes et al.*, 2001] or 9 [*Carton et al.*, 2005] years of data. Indeed, several studies [e.g., *Lombard et al.*, 2005; *Willis et al.*, 2004] confirm that thermal expansion patterns are not stationary in time and thus trends derived from intervals shorter than the longest oscillatory timescale cannot be used for extrapolating backward or forward.

3.2. Nonthermal Contribution to GSL Rise

[12] The lack of consistent correlations over the 50 year period of GSL and GOHC leads us to investigate the various contributing factors in sea level rise. For the period 1955–2003 only 25% of the 1.6 mm a^{-1} linear trend in GSL can be explained by the contribution from TSL in the upper 1500 m global ocean layer (linear trend of 0.41 mm a^{-1}). We define the nonthermal component (Δ) as the difference between GSL and TSL (Figure 4). Since 1955 the cumula-

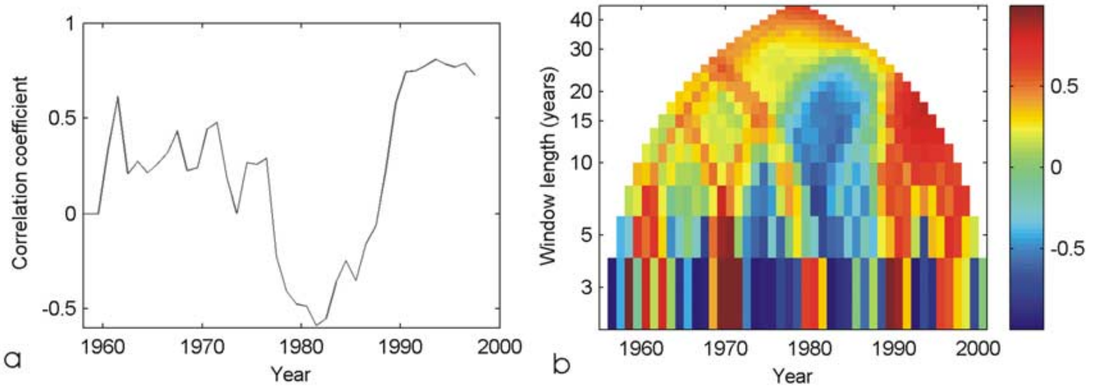

Figure 3. (a) Running correlation coefficient (10-year window) between the GSL and GOHC during 1955–2003; (b) running correlation coefficients with varying window length between the GSL and GOHC during 1955–2003.

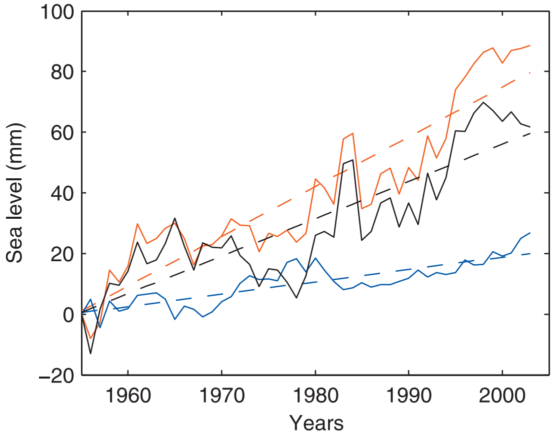

Figure 4. Time series of sea level with linear trends: GSL calculated from tide gauges (red), 1.6 mm a^{-1}; thermosteric sea level (TSL) (blue), 0.41 mm a^{-1} and the residuals, assumed to be estimated nonthermal component (black), 1.2 mm a^{-1}.

tive Δ resulted in a 6 cm rise. The contribution from the Δ component noticeably changed during 49 years. For the first 25 years Δ varies with no evident trend and with a mean value of 0.52 mm a^{-1} (cumulative contribution to GSL rise of 14 mm for the period 1955–1979). From 1979 to 2003, Δ contributed 2.25 mm a^{-1} (a cumulative contribution of 44 mm).

[13] We examine more closely the nonthermal component Δ and compare it with estimates from contributions to sea level rise calculated using direct measurements of glacier volume changes [*Dyurgerov and Meier*, 2005] and ice sheet melting in Greenland [*Krabill et al.*, 2004] and Antarctica [*Thomas et al.*, 2004], named here as ISL. Figure 5 shows that the contribution from melting progressively increased over the last 49 years. The linear trend in ISL is 0.75 mm a^{-1}, which amounts to 47% of GSL rise during the 1955–2003 period.

[14] Figure 5 confirms a suggestion from *Miller and Douglas* [2004] and *Antonov et al.* [2002] that large contribution to GSL must come from increases in the ocean mass component. Furthermore, according to *Dyurgerov and Meier* [2005], the rate of ice loss in ice caps and glaciers since 1988 has doubled and over the last decade has risen to 0.8 mm a^{-1}. They associated the acceleration with changes in climate in Northern Hemisphere glacier areas, being warmer and more humid during the last decades, especially since a climatic shift around 1977, which is about the same time as GSL and TSL diverged dramatically. Winter accumulation and summer melting have both increased with time [*Dyurgerov and Meier*, 2005] and are correlated positively with Northern Hemisphere air temperature [*Greene*, 2005]. *Dyurgerov and Meier* [2005] emphasize that this increase in the intensity of glacier regime (meaning greater mass exchange) leads to a continuing addition to sea level rise and reduction in the rate of wastage. Estimates made from glaciological data are in good agreement with recent estimates of global ocean freshening, based on the decrease in global average salinity estimated by *Antonov et al.* [2002] which, if assumed to be due entirely to changes in mass of the ocean, produce a mean sea level rise of 1.35 ± 0.50 mm a^{-1}.

[15] Unexplained residuals (Δ'), where Δ' = GSL-TSL-ISL, are characterized by a trend of 0.44 mm a^{-1} and a temporal pattern of decadal variability (Figure 5, bottom), suggesting that the unexplained residuals are not systematic errors but are more likely to be climate change related, and we discuss this point now in section 4.

4. Discussion

[16] The lack of consistent correlations over the 50 year period between GSL and GOHC, and the distinct response of the large ocean basins to the changes in heat content emphasize the importance of understanding the mechanism of ocean adjustment to the regional and global changes in ocean heat content. Significantly, higher correlation coefficients exist between the heat content and sea level in Atlantic compared with results for the Indian/Pacific regions and can be explained with reference to several effects. First, over the entire 50-year period, the heat content in the Atlantic Ocean was steadily increasing [*Antonov et al.*, 2005], which is in quite good agreement with rising sea level in the Atlantic (Figure 2a). In contrast, the patterns of changes in heat content in the Pacific (Figure 2b) and Indian (not shown here) oceans demonstrate significant variability, which is not reflected in regional sea level rise and can be explained by the difference in response of individual ocean basin to heat content changes. Second, model results [*Landerer et al.*, 2007] and observations [*Barnett et al.*, 2005; *Levitus et al.*, 2005] provide evidence that the vertical distribution of thermosteric anomalies, which contributes to sea level change, is very different between ocean basins. In the North Atlantic, the thermosteric anoma-

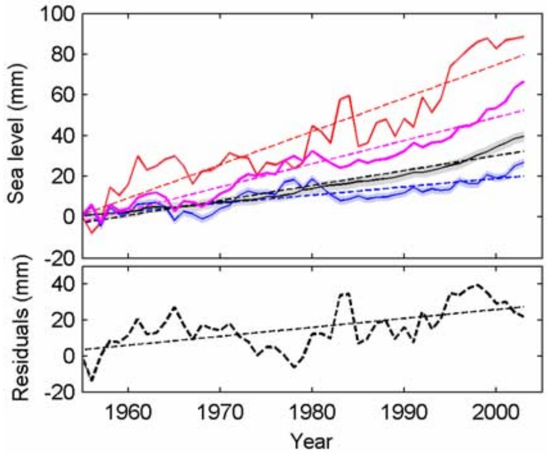

Figure 5. (top) Time series of sea level with linear trends: GSL calculated from tide gauges (red), 1.6 mm a^{-1}; thermosteric sea level (TSL) (blue), 0.41 mm a^{-1}; ISL as a contribution to sea level rise calculated form continental glacier volume changes and ice sheets melting in Greenland and Antarctica (grey), 0.75 mm a^{-1}; reconstructed GSL (TSL+ISL) in purple, 1.1 mm a^{-1}. Shadows paralleling the GSL, TSL, and ISL are errors. (bottom) Unexplained residuals (GSL-reconstructed GSL), with linear trend of 0.44 mm a^{-1}.

lies reach to the depths of the North Atlantic Deep Water (2000 m), whereas thermosteric anomalies in the entire Pacific Ocean occur mainly in the upper 500 m. Thermosteric sea level change in the Atlantic is more significant than in Pacific, due to the effect of deep water formation and enhanced ventilation, by which the warming signal can penetrate to the deeper layers in those regions and then be advected horizontally. Finally, ocean basins will adjust to changes in large-scale circulation, which may redistribute water masses and thus lead to different sea level changes regionally. It hardly affects the global mean sea level, which is consistent with a correlation coefficient of 0.78 between the GOHC and GSL, but it can lead to regional sea level changes.

[17] Since 1980 the nonthermal contribution to the sea level rise appears to be increasing and to be the dominant factor of the sea level rise, compared with contribution from ocean thermal expansion. The shortness of the times series (only 50 years) prompts the question of whether this is just a manifestation of multidecadal variability or is it a long-term trend? This also concerns the unexplained residuals (Δ'), which account of about 25% to the sea level rise and may plausibly be a climate-driven contribution with the trend of 0.44 mm a^{-1} and superimposed on a temporal pattern of decadal variability.

[18] Unexplained residuals (Δ') could, to some extent, be accounted for by contributions from changes in continental water storage as snowpack, soil water, and ground water, all of which according to *Milly et al.* [2003] can contribute 0.1 mm a^{-1} to sea level rise for the period 1981–1998; however, for the 1993–1998, the contribution is modelled to be 0.25 mm a^{-1}.

[19] Recently, the dynamical behavior of the large ice sheets of Greenland and Antarctica has been recognized as potentially able to change on very short timescales [*Zwally et al.*, 2005; *Dowdeswell*, 2006; *Stearns and Hamilton*, 2007]. The processes involved enable the outlet glaciers to react quickly to warming of the atmosphere or ocean contribution via increases of melt-water on the glacier bed, lubrication, increase bottom sliding, and ice discharge through the grounding line of outlets of ice sheets and subpolar ice caps. This allows both ice sheets and subpolar ice caps with floating outlets to respond rapidly to external climate forcing. Support for fast dynamical response of ice sheets comes from repeated series of GRACE observations. These observations generally confirm the results of fast changes in surface elevation of glacier-basins in Greenland, West Antarctic, Canadian Archipelago [*Abdalati et al.*, 2004; *Burgess and Sharp*, 2004] and increase in ice discharge by outlets [*Rignot and Kanagaratnam*, 2006]. Similar considerations show that the unexplained residuals cannot be accounted for by contributions from changes in water storage of the snowpack, from changes in accumulation rate or surface melting [*Krabill et al.*, 2004; *Thomas et al.*, 2004; *Monaghan et al.*, 2006, *Velicogna and Wahr*, 2006].

[20] We suggest that decadal variability pattern is likely to be associated with variability in global water cycle. Changes of 5% in global river discharge [*Fekete et al.*, 1999] correspond to 5 mm a^{-1} in GSL, similar to changes in GSL associated with El Niño or a large volcanic eruption [*Grinsted et al.*, 2007]. In addition, changes in GOHC influence the hydrological cycle, leading to changes in continental water storage, which partly compensates for thermosteric volume changes [*Grinsted et al.*, 2007; *Ngo-Duc et al.*, 2005]. Thus the year to year variability in Δ' is comparable to known variability in the hydrological system; however, the trend cannot be accounted for from these sources. Most probably Δ' is a combination of underestimating the contribution from melting of ice masses, the linear trend component, and decadal variability associated with the hydrological cycle or a water storage contribution. Finally, despite recent advances in the state of the global ocean observing system, estimating ocean variability on basin-wide to global scales remains difficult. Errors in such estimates can be large and unreported in literature. It has been suggested recently [*Gouretski and Koltermann*, 2007] that due to instrument related biases the global ocean heat content might be overestimated by *Levitus et al.* [2005]. That would lead to the reduction of 25% in the sea level rise contribution from ocean heat content, increasing unexplained residuals.

5. Conclusion

[21] For the period 1955–2003 the correlation coefficient between the GSL and GOHC is 0.78. However, increasing GSL does not reflect the significant increase and drop in GOHC in 1976–1985, suggesting that there are substantial contributions associated with nonthermal components in sea level rise. This must be explained by a change in ocean mass caused by an increase of fresh water input into the ocean. This is also associated with a compensating role played by land water storage, which is significantly anticorrelated with variability in thermal expansion of the ocean [*Ngo-Duc et al.*, 2005]. Correlations between the regional sea level and regional heat content vary from 0.3 to 0.8, with largest correlation between the heat content and sea level in the Atlantic Ocean.

[22] The sea level contributions calculated from continental glacier volume changes and ice sheet melting in Greenland and Antarctica make up the leading component (47% contribution to sea level trend) compared with 25% contribution from thermal expansion.

[23] We find a large unexplained sea level rise (about 1/4 of GSL) with substantial variability that is likely caused by combination of underestimating the contribution from melting ice masses, the linear trend component, and decadal variability associated with the hydrological cycle and climate-driven changes in continental water storage contribution.

[24] Global warming naturally impacts melting rates of ice, as well as ocean warming. However, our study reveals the dominant role of ocean mass increase over simple volumetric increase in sea level rise. The large unaccounted for trend most likely reflects uncertainty in the mass balance of the large ice sheets, and in terrestrial storage. Large decadal-scale variability also underscores the lack of understanding in the physical mechanism governing the long-term variability in hydrological cycle and in the hydrological contribution to global sea level.

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