# The historical global sea level budget

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## Abstract

We analyze the global sea level budget since 1955. Good estimates of sea level contributions form glaciers and small ice caps, the Greenland ice sheet and thermosteric sea level are available over this period, though considerable scope for controversy remains in all. Attempting to close the sea level budget by adding the components results in a residual displaying a likely significant trend of about 0.37 mm/yr. This residual also exhibits large variability that is probably associated with variability in the global water cycle, ENSO and long-term volcanic impacts. The most likely explanation of the residual trend is underestimated glacier melting representing an additional continuous ice sheet contribution over the last 50 years; Greenland seems a reasonable candidate.

## Introduction

The relative importance of mass and volume change to sea level rise is of great practical as well as pure scientific interest since their relative response to climate forcing may be very different. We may expect that a change in volume associated with rising temperatures would be relatively smooth, while potential ice sheet instabilities may produce very rapid and large changes in sea level.

There are two main methods of estimating sea level rise 1. the contribution from each component of the system can be estimated – glaciers and small ice caps (GSIC), Greenland ice sheet (GIS), Antarctic ice sheet, thermal expansion (TS), changes in terrestrial storage (T); and 2. the total observed by tide gauges, complimented since

1993 with satellite altimeter measurements.  If these two estimates agree then we call the sea level budget closed. Some authors claim that the se level budget is closed (Domingues and others, 2008), despite, or perhaps utilzing the large errors involved in the contributors, but others claim that the best estimates of the relative contributions leaves a significant discrepancy with observed sea level (Jevrejeva and others, 2008).

In this paper we provide estimates of the various contributions and discuss how close the sum of the parts is to the observed total sea level rise. We show that the best estimates of the sea level components do not result in a satisfactory agreement with observed sea level since 1955, and examine several reasons for that – underestimated impact of volcanic impacts, underestimated influence of ENSO, errors in ocean heat content, errors in terrestrial water balance, and mass balance of glaciers and ice sheets.

## Data

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). RSL data sets were corrected for local datum changes and glacial isostatic adjustment (GIA) of the solid Earth (Peltier, 2001). We use a global sea level (GSL) curve based on the ‘virtual station’ method (Jevrejeva and others, 2006) which overcomes geographical bias and quantifies the uncertainties due to representativity issues of the stations employed. Our global sea level trend estimate of 2.4 ± 1.0 mm·yr-1 for the period from 1993 to 2000 is comparable with the 2.6 ± 0.7  mm·yr-1 sea level rise calculated from TOPEX/Poseidon altimeter measurements, the GSL curve also produces good estimates of the volcanic impacts on sea level (Grinsted and others, 2007), and has been used to reconstruct sea level over the past 2000 year (Grinsted and others, 2009; Jevrejeva and others, 2009). The GSL (together with calculated errors) are available from http://www.psmsl.org/products/reconstructions/jevrejevaetal2006.php

We use the Global Ocean Heat Content (GOHC) data for the period 1955-2008 from Levitus and others, (2009), which includes discussion of systematic errors in the heat measurements from the Argo profiling float data that were included in earlier heat content estimates (e.g. Levitus and others, 2005). We use several estimates of steric sea level derived from the ocean heat content data, but mainly rely on the values from Domingues and others (2008), where we have added 20% to the 0-700 m steric sea level values, as those authors suggest, to account for the deeper ocean contribution.

Data on Greenland mass balance (GIS) history comes from Rignot and others (2008), and past variations in GSIC from Cogley (2009). The GIS extends to direct observations carried out in 1958, while the GSIC has been consolidated into penta-year global averages of mass balance of glaciers from outside Greenland and Antarctica based on both direct glaciological surveys, and geodetic surveys that together are quite reliable back to about 1955. The dataset is extended to include the smaller polar glaciers by methods outlined in Kaser and others (2006), and we use that to derive a sea level equivalent contribution.

To make the data more comparable between the different sources, we compute GIS, GSL and TS in penta-year blocks as does Cogley (2009). This has the impact of removing much seasonal variability, hemispheric differences and noise due to annual snow accumulation variations. Post 1955 penta-year 95% confidence intervals are less than 20% of the mass balance estimates in GSIC (Cogley, 2009). We compute the error in GSL as the yearly standard error/$\sqrt{}/(N-1)$ since autocorrelation within $N=5$ yearly blocks can be neglected and the data assumed to be independent.

## Results

In fig 1 we show the major components of the sea level budget, and their sum compared with the tide gauge observations and its error. Several things are clear from the plot:

1. GSL is not particularly well correlated with TS – this has also been discussed by Jevrejeva and others (2008). Despite corrections to the GOHC dataset (e.g. Levitus, 2009), this remains the case.

2. The TS component is a smaller component of GSL than GIS and GSIC. Hence it is not reasonable to assume (as is often the case e.g. IPCC 2007) that since 1955 TS has been responsible for about 50% of GSL.

3. Despite a considerable acceleration in mass loss from both GIS and GSIC since 2000, the sea level budget is still significantly not closed by the three components alone shown in Fig. 1.

4. The rate of GSL rise between 1930 and 1950 was about as fast as the post 2000 period. The only contributing information available is GSIC (though much less reliably than since 1955 (Cogley, 2009)). Fig. 1 shows that GSIC was not likely to be the main factor in the rapid rise of GSL at that time. The fundamental cause is likely the absence of significant volcanism during that interval (Jevrejeva and others, 2006), the proximate cause however is uncertain. The rather slow changes in TS since 1955 suggest that rapid thermosteric response could only be responsible for the GSL changes if there were dramatic changes in ocean circulation. This implies that other sources of mass were most likely the cause of rising GSL – either from Greenland as has been postulated during the warm 1920s and 30s by Rignot and others, (2009), or from Antarctica.

5. The sum of the components plotted do not appear to close the sea level budget completely at any time since 1955.

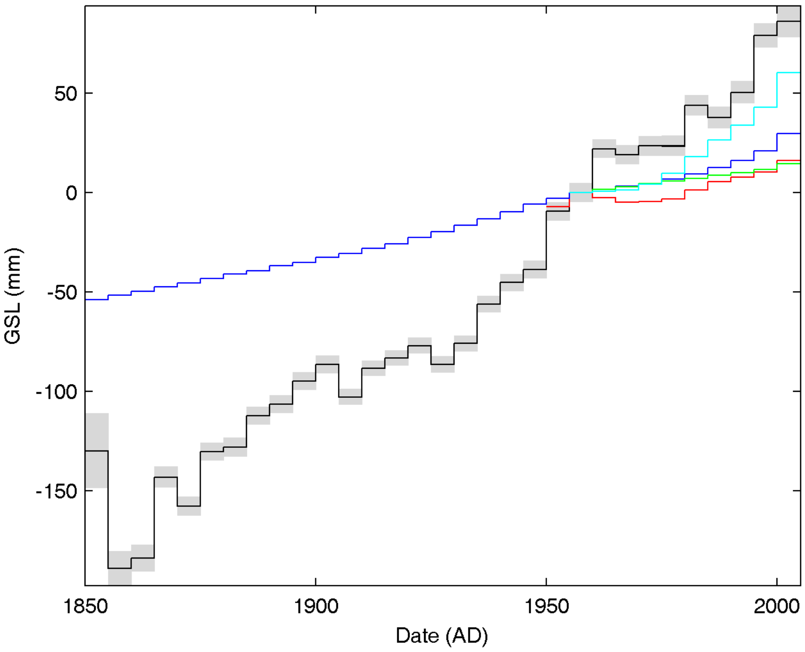

*Fig 1 shows the time series of anomalies in GSL, GSIC, TS and GIS over the duration of the datasets available in penta-year blocks. Black: GSL with standard error as grey shaded region, red: thermosteric (TS), blue: glaciers and small ice caps (GSIC), green: Greenland ice sheet (GIS), cyan: TS+GSIC+GIS. The 1950-1955 period is the baseline for all datasets.*

In Fig. 2 we examine the residuals more closely to determine how the remainder of the sea level budget varies over time. The trend line in Fig 2 is marginally significant (93% significance level). However this was created using the most generous rates of TS in the literature (Domingues and others, 2008) with an additional 20% for deep sea steric sea level rise, using other estimates of TS produces larger trends which are significant at 95% and above. The slope of the trend is 0.36 mm/yr with a standard error of 0.18 mm/yr, and accounts for 36% of the variance of the residual GSL.

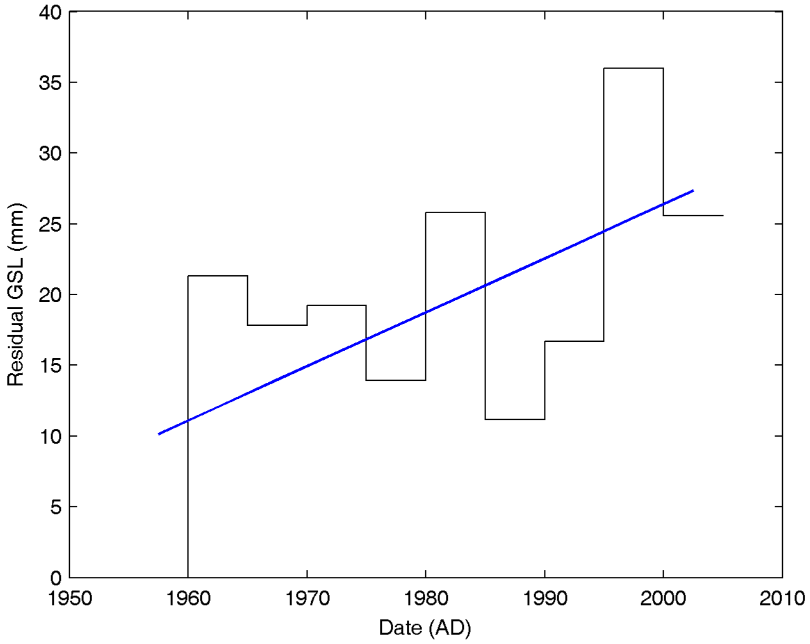

*Fig. 2 Penta-year estimates of residual sea level (GSL-TS-GSIC-GIS) and the linear regression line of the data relative to the 1950-1955 interval.*

## Why is the budget not closed?

Although the errors for the individual components of the sea level budget are large, we explore how well they can predict the observed penta-year GSL with multiple linear regression. When we do this with TS, GSIC and GIS as forcing variables we find that TS (from Domingues and others, 2008) has an unphysical, negative coefficient of -1.2 ± 1.1 whereas we would expect a coefficient of 1. This is a marginally significant result. If we drop TS from the GSL forcing factors then the coefficient for GIS dominates (3.7±1.8) that from GSIC (1.1±1). This could be interpreted as suggesting that it is the Greenland ice sheet – or factors that correlate with it, that may be responsible for the missing sea level component.

To help interpret and attribute the causes of sea level rise further, we use a semi-empirical model (Jevrejeva and others, 2010) that realistically matches observed sea level over a range of timescales from multi-year to centennial scales.

## Volcanic and ENSO variability

Observed sea level is complicated by many other forcing factors such as ENSO, ocean dynamics and global water cycle and so the detailed observed response to individual eruptions contains very high noise. To overcome this signal/noise ratio problem, Grinsted and others (2007) used the five most prominent eruptions in the last century to show the volcanic impact on the observational sea level. ENSO impacts may be removed by making a linear regression of the Niño3 index onto GSL and analysing the residuals following the statistical methods described by Grinsted and others (2007). We use the Niño3 index from Kaplan and others (1998) for the period 1856-1949 and one calculated from the SST fields from Reynolds and others (2002) for the period 1950-present. The results shown in Fig. 3 can be interpreted as follows. Large volcanic eruptions inject aerosols into the stratosphere, and these aerosols reflect sunlight causing global dimming and thus lower temperatures at the earth surface. The cooling of the ocean surface causes less evaporation. As water flux from terrestrial reservoirs and river discharge continue, the combination of less evaporation and water flux results in global sea level rise of 6-12 millimeters during the first year following the eruption. After approximately one year, stratospheric aerosols have been removed and evaporation reaches normal values. However, now the river discharge is reduced due to the low precipitation in the preceding year and sea level therefore drops by 4-10 millimeters 2-3 years after the eruption.

The timing of volcanic eruptions are unaffected by the phase of the ENSO. Some eruptions will by chance occur in El Niño years. In contrast, it is plausible that an eruption would have some impact on the ENSO system, perhaps the cooling weakens the trade winds (a weakening being a precursor to El Niño events). We do not argue that volcanic eruptions trigger El Niño events, rather we argue that it is important to not exclude the possibility of a volcanic influence on the ENSO system.

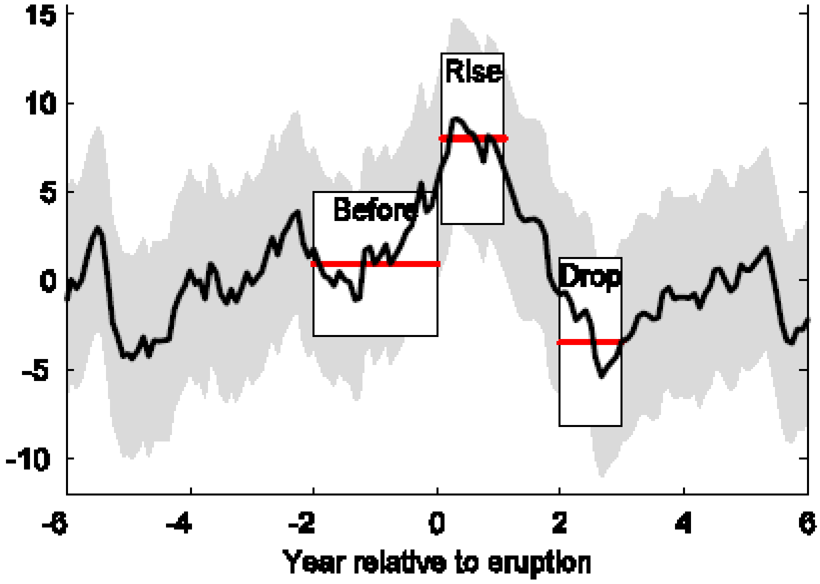

*Fig. 3. The average volcanic impact of 5 volcanic eruptions (Pinatubo, 1991; El Chichón 1982; Agung, 1963; Santa Maria, 1902; Colima, 1890) on detrended GSL (mm) after removing the effects of ENSO. Shaded area shows 95% confidence interval.*

Grinsted and others (2007) Supplementary Methods 6 noted the Church and White (2006) GSL reconstruction does not display statistically significant drops in sea level following the large eruptions. However, in Church and White (2006) the qualitative evidence of a deceleration in GMSL following eruptions is summarized: “The post1960 major volcanic eruptions of Mt. Agung (1963), El Chichon (1982) and Mt Pinatubo (1991) offset about 0.005 mm/yr$^2$ of the acceleration that is otherwise present, perhaps explaining why little acceleration has been detected over the second half of the 20th century.”

Interdecadal and multi-year variability in sea level has been attributed to ENSO and volcanic forcing. While the immediate atmospheric impacts of a large volcanic eruption tend to decay within a few years as stratospheric aerosol is removed (Robock, 2000), it has been realized that the impact on the oceans may be much more pervasive, and could last a decade or more.  Stenchikov, (2009) uses the CM2.1 climate system model to estimate the sea level response of the large Tambora 1815 and Pinatubo 1991 eruptions. The sea level response is essentially determined in the Stenchikov model by the global ocean heat content change. Fig. 4 shows the

Stenchikov modeled response compared with the model of sea level fitted to the GSL data here. Notice that both models predict about the same maximum response, the timing of the maximum drop, and have similar recovery curves. The Tambora response is about 3 times the Pinatubo response in both models. It is also clear that the volcanic response is primarily determined by heat content change rather than mass of ocean water on multi-year timescales, though it also seem the case that our model produces deeper drop than does Stenchikov – perhaps because our model incorporates other effects than simple ocean heat content.

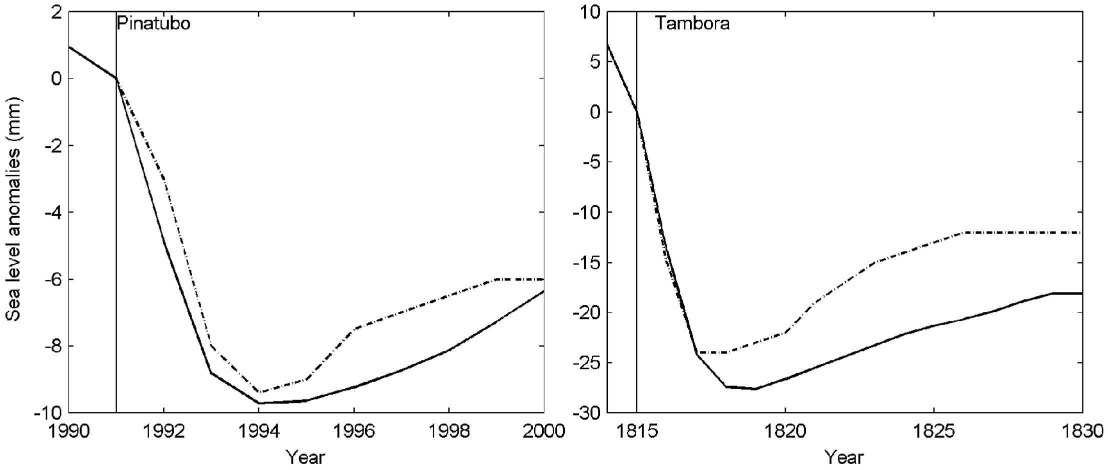

*Fig. 4 , (left) Stenchikov (2009) (dashed), and our model (solid) sea level anomaly responses to the Pinatubo 1991 eruption; (right) modeled response to the Tambora 1815 eruption. Anomalies calculated relative to the sea level at the year of eruption.*

The reduction in radiative forcing due to eruptions for the period 1880-2000 was estimated by Jevrejeva and others (2009) to amount to a reduction of 7 cm in GSL relative to the level it would have reached had no eruptions occurred. The effect of the three large eruptions of the post 1955 period (Agung 1963, El Chichon 1982 and Pinatubo 1991) was a depression in sea level for 5-10 years of about 5 mm (Fig. 4) each. Fig. 2 shows that the 1965-1970 and the 1985-1990 residuals were local minima, while 1990-1995 and 1995-2000 were strongly increasing periods of sea level. This suggests that if observed GSL was reacting to the eruptions, it was not doing so to a degree that dominates total GSL. This again points to something other than thermosteric sea level as the missing component of the GSL budget.

## Thermosteric sea level issues

The main source of ocean heat measurements are the set discussed and updated by Levitus (2009), though Ishii and Kimoto, (2009) supplement these with other data. Widely varying estimates of the rate of increase of GOHC have been derived. For example, linear trends for the 1969-2003 period where measurements were made mainly by one type of instrument range from (with 95% confidence intervals) 0.24 ± 0.04 (Ishii and Kimoto, 2009) to 0.41 ± 0.06 $10^{22}$ J $yr^{-1}$(Domingues and others, 2008). These differences depend on the method used to produce global rates from the spatially inhomegenous dataset.

A key element of the steric sea level rise component is the contribution from the deep ocean below 700 m depth. To date little is known about this component. Antonov and others (2005) suggest that steric sea level rise is about 0.4 mm/yr, with the deeper ocean contributing only about 0.1 mm/yr. Domingues and others (2008) used the approximate ratio of steric sea level rise for the deeper ocean relative to the upper 700 m to correct their steric sea level derived from the upper 700 m alone. But, since their steric sea level rise was already about 50% larger than earlier estimates (Ishii and others, 2006; Levitus and others, 2005: Antonov and others, 2005), Domingues and others (2008) added about a further 0.2 mm/yr for the deeper ocean, resulting in almost a doubling relative to other estimates.

Domingues and others, (2008) reconstructed GOHC and Church and White (2006) global mean sea level using a variant of the optimal interpolation scheme by Kaplan and others (2000). The leading Empirical Orthogonal Functions (EOFs) were determined from 12 years (1993-2004) of detrended TOPEX/Poseidon and Jason-1 satellite altimeter data. The Principal Components of the leading EOFs were then determined in a least squares manner to fit the tide gauge observations.

We note that the last 15 years have been exceptionally warm compared with the historical records (IPCC 2007) and that the EOF patterns may not be representative of the patterns that prevailed earlier in the century. Kaplan and others (2000) caution against using too short a time period for calculating the EOFs: “To obtain faithful field reconstructions, we have to use a relatively long time period for the covariance estimation, and there should be enough data in it for estimating all necessary cross covariances."

As noted above the result of using the thermosteric sea level component from Domingues and others (2008) including the 20% deep ocean addition results in a lower significance level for a linear fitted trend for the residual sea level (Fig. 2).

## Terrestrial water budget

Vermeer and Rahmstorf (2009) used the results from Chao and others, (2008) to estimate potential contribution from water impoundment in the world artificial reservoirs. However, Chao and others, (2008) focused on estimation of contributions that decrease sea level rise (storage in reservoirs) only, and amounts to about -0.44 mm/yr. There are, however, several processes which were not considered by Chao and others, (2008), and they all lead to higher sea levels. The processes that increase sea level, include  ground water mining, estimated as contributing 0.55-0.64 mm/yr between 1990-95 by Shiklomanov, (1997) and urbanization with a contribution of 0.3mm/yr (Gornitz, 2001). The IPCC AR4 makes this statement: "It is very difficult to provide accurate estimates of the net anthropogenic contribution, given the lack of worldwide information on each factor, although the effect caused by dams is possibly better known than other effects. According to Sahagian (2000), the sum of the above effects could be of the order of 0.05 mm yr–1 sea level rise over the past 50 years, with an uncertainty several times as large".

In addition, the recently published paper by Lettenmaier and Milly, (2009) provides a state-of-the-art estimation of the contributions from continental mass loses/gains: "We would find it difficult to refute convincingly, on the basis of observations, the proposition that land, overall, contributes essentially nothing to sea-level rise today".

However, we suggest that decadal variability in sea level is likely to be associated with variability in global water cycle. Changes of 5% in global river discharge (Fekete and others, 1999) correspond to 5 mm/yr in GSL, similar to changes in GSL associated with El-Niño or a large volcanic eruption (Grinsted and others, 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 and others, 2007; Ngo-Duc and others, 2005).

## Underestimated ice sheet response – how long as ice sheet been responding?

Wingham et al (2006) discuss Antarctic mass balance using satellite radar altimetry over the period 1993-2003. They find virtually no significant trend over this time. Estimates based on outflow velocity changes in glaciers using InSAR (Rignot and others, 2008) suggest an increase in mass loss, but with very large error bars, from 112 ± 92 Gt/yr in 1996 to 196 ± 92 Gt/yr in 2006. Since 2003 GRACE estimates indicate significant mass loss (Velicogna, 2009), which taken together with the altimetry and InSAR data suggest accelerating loss of ice. Indeed given a mass loss of 104 Gt/yr in 2002, 247 Gt/yr in 2009 and an acceleration of -26 Gt/yr, mass loss would have been zero in 2000, in reasonable agreement with the altimeter and InSAR results. Hence there is no observational reason to propose that Antarctic mass balance was negative prior to the 1990s.

## Conclusion

Recent (post 2003) components of the sea level budget appear in plausible agreement with observations: steric sea level is rising at about 0.6 mm/yr (ranging from around 0.05 mm/yr (Levitus and others, 2009), to 1.1 mm/yr (von Schuckmann and others, 2009). Mass contributions from GRACE estimates of ice loss from Greenland and Antarctic ice sheets are about 1.1 mm/yr (though with uncertainties of about 50% due to the short time period of the GRACE data). Small glaciers and ice caps contribute about 1.3±0.2 mm/yr. This compares with an observed sea level rise rate of about 3.3 mm/yr. Hence the budget is relatively in agreement with the observations.

The 20th century sea level budget, though measured over longer time intervals, is more open to question, since overall rise rates were lower, the relative magnitude of the errors associated with each component were more significant. The observed sea level rise rate from tide gauges was about 1.7 mm/yr (1955-2000). Glaciological estimates for the mass balance of the ice sheets were based on limited survey methods, and only gained from satellite altimetry from about 1993. The steric component derived from GOHC and models of heat dissipation throughout the ocean is often assumed to be well known, however as we noted above the steric component even post-2000 has produced widely different estimates.

To summarize our findings: we find a likely significant missing component of the sea level trend since 1955 that contributes about 0.36 mm/yr with a standard error of 0.18 mm/yr, and with significant penta-year variability. Some of the variability may be explained by ENSO and volcanic impacts on ocean heat content, global water cycle, and reductions in ice melt. The trend in residual sea level is close to the estimated mass loss from Antarctica in 2009, but evidence is reasonably strong that this cannot be source of extra sea level rise prior to the 1990s. The relatively poor correlation between streric sea level and observed sea level implies that mass components have dominated the total sea level budget since 1955. Given the sensitivity of Greenland to warming, this must be a strong candidate for the missing component. Alternatively the budget may be closed if the steric trend component has been generally underestimated, especially that of the deep ocean.

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