A heuristic evaluation of long-term global sea-level acceleration

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In view of the scientific and social implications, the global mean sea-level rise (GMSLR), its possible causes and future trend have been a challenge for long. For the 20th century, reconstructions generally indicate a rate of GMSLR in the range of 1.5 to 2.0 mm yr^{-1}. However, the existence of non-linear trends is still debated, and current estimates of the secular acceleration are subject to ample uncertainties. Here we use various GMSLR estimates published on scholarly journals since the 40's for a heuristic assessment of global sea-level acceleration. The approach, alternative to sea-level reconstructions, is based on simple statistical methods and exploits the principles of meta-analysis. Our results point to a global sea-level acceleration of 0.54 ± 0.27 mm/year/century (1σ) between 1898 and 1975. This supports independent estimates and suggests that a sea-level acceleration since the early 1900's is more likely than currently believed.

1. Introduction

The changing height of sea-level has been observed and recorded since the early days of the modern era, when measurements of tide oscillations in the harbors became important for navigation. The geophysical significance of sea-level data became clear after the seminal work of *Gutenberg* [1941], who first estimated the global long-term sea-level rise and its uncertainty from instrumental records. Rates of global mean sea-level rise (GMSLR), published on scholarly journals after *Gutenberg* [1941], are chronologically displayed in Fig. 1, which updates the systematic review of *Spada and Galassi* [2012] (numerical values are given in Tables S1 and S2). Although the importance of regional variations of sea-level has been long recognized [*Woodward*, 1888; *Farrell and Clark*, 1976], the 62 studies considered in Fig. 1 were mostly concerned with the estimate of the globally averaged rate of GMSLR (hereinafter r), a proxy of the volume variations of land ice and of the response of the oceans to the rising global temperature [*Levitus et al.*, 2000; *Alley et al.*, 2005; *Rahmstorf*, 2007; *Gregory et al.*, 2013]. Fig. 1 is indicating a rate of GMSLR in the range of 1 to 2 mm yr^{-1}. The value of the mean rate is 1.61 mm yr^{-1} and the weighted average of r values for which an uncertainty (σ_r) is available, is 1.63 ± 0.06 mm yr^{-1}, where the error is twice the standard deviation of the mean. From Fig. 1b it is apparent that after the 80's, with the increased awareness of global climate change [*Fletcher*, 2013] and the improved amount and quality of the sea-level observations, estimates of GMSLR appeared more and more frequently in the literature [*Spada and Galassi*, 2012].

The problem of a possible regional or global sea-level acceleration was only addressed since the 90's [*Woodworth*, 1990; *Douglas*, 1992], i.e. roughly half a century after the

GMSLR was first estimated *Gutenberg* [1941]. In the global context, the simplest approach has consisted in the evaluation of the so-called apparent sea-level acceleration, defined as twice the quadratic term of the parabola that best fits the sea-level time-series [*Douglas*, 1992]. Subsequent investigations (see Table 1 and Fig. S1), based on robust sea-level reconstructions and employing a large set of sea-level observations, have confirmed a long-term sea-level acceleration with values spread between 1 and 2 myc (here and in the following 1 myc = 1 mm/year/century). Such values are, however, quite sensitive to the choice of the analysis time span and to the selection of the tide gauge records, and are characterized by large uncertainties. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) has recently concluded that it is *likely* (probability $> 66\%$) that a positive acceleration occurred between the 19th and 20th century while it is *very likely* ($> 90\%$) that a higher rate of GMSLR has been observed during the "age of altimetry" (1993-2010), thus implying a further acceleration [*Church et al.*, 2013]. Contrary to GMSLR, however, the AR5 did not provide an assessed range for the long-term sea-level acceleration. The reason is probably the limited number of results published before the completion of the report, the spread of the sea-level acceleration values (see Table 1), and the uncertain role of a possible 60-years oscillation [*Chambers et al.*, 2012].

Our aim here is to exploit values of the rate of GMSLR published on scholarly journals to provide new estimates of global sea-level acceleration during the 20th century. This approach, corroborated by a meta-analytical study, is used for the first time in this context; it is computationally inexpensive and it is independent from traditional sea-level reconstructions based on historical data [*Church and White*, 2006; *Jevrejeva et al.*, 2006, 2008; *Church and White*, 2011; *Ray and Douglas*, 2011; *Jevrejeva et al.*, 2014] (see also the PSMSL global sea-level reconstruction page at *http://www.psmsl.org/products/reconstructions/*). In the following we describe the observations published in the literature (Section 2.), we present (3.) and discuss (4.) our results and we draw the conclusions (5.).

2. Observations

Visually, the shape of the scatterplot in Fig. 1 suggests that published r estimates have progressively increased over the years, from values just above ≈ 1 mm yr^{-1} in papers published between 1940 and 1980 to $\approx 1.5-2$ mm yr^{-1} in more recent studies. This is something that so far has not received attention and which could be an indication of a long-term sea-level acceleration. Assuming that the rate of GMSLR was estimated correctly by all the authors within sufficiently long and non-coincident time windows, that the studies are not biased, nor affected by substantial errors, and that significant variations of r have indeed occurred since the early 1900's, one can argue that information about a possible sea-level acceleration could be extracted, at least in principle, from a complete collection of previously published trends. This approach, which has never been proposed so far within the context of sea-level change, constitutes a simple form of meta-analysis [*O'Rourke*, 2007]. It represents an alternative to traditional sea-level reconstructions [*Church and White*, 2006; *Jevrejeva et al.*, 2006, 2008; *Church and White*, 2011; *Ray and Douglas*, 2011; *Jevrejeva et al.*, 2014], directly based on tide gauge and altimetric observations. Meta-analysis can increase the statistical power by shrinking the confidence interval around the estimated quantities [*Cohn and Becker*, 2003] and help to identify, within a collection of scientific reports, previously unnoticed relationships between quantities of interest [*Walker et al.*, 2008]. Using such an approach could be particularly suited here, since the detection of a possible sea-level acceleration was not the target of the individual studies, which were mainly aimed at the determination of the rate of GMSLR.

The r estimates in Fig. 1 are essentially all based on observations from specific sets of tide gauge records during a particular time window. In most cases, r values are obtained from individual sea-level time series by standard linear regression and spatially averaged to obtain a globally representative value (details about the various methods adopted are given in Table 1 in *Spada and Galassi* [2012]). A few studies are based on more complex reconstructions also involving recent altimetric observations (e.g. *Church and White* [2011]). Some have adopted non-traditional methods like neural networks [*Wenzel and Schröter*, 2010], or have accommodated the sparse sampling of global sea-level fields by applying probabilistic methods [*Hay et al.*, 2015]. In some others, the published rates represent expert assessments of previous results (e.g. *Bindoff et al.* 2007). The criteria adopted to select the suitable set of tide gauges varied considerably and have been seldom rigorously quantified [*Douglas*, 1997; *Spada and Galassi*, 2012]. The number and geographical distribution of the tide gauges considered also varied, in the attempt to establish a sufficient geographical coverage and, consequently, accurate global values of r. In some studies, the uncertainty on the rate of GMSLR (referred to as σ_r in the following) has not been determined. In a few of them the determination of r has been deemed to be impossible because of the large spread of the rates of sea-level change recorded at individual tide gauges (see discussion in *Spada and Galassi* [2012]). In GMSLR studies, the important regional effects of glacial isostatic adjustment (GIA) have not been taken into account until the 80's [*Gornitz et al.*, 1982]. Later on, the application of the isostatic correction was facilitated by the availability of accurate global GIA models, first introduced by *Peltier and Tushingham* [1989] in this context.

To mitigate possible effects from methodological diversity and statistical heterogeneity, henceforth we will exclusively consider r values for which an estimate of the uncertainty σ_r has been published and those that have been corrected for the effects of GIA (or for which the GIA correction is inessential, like in *Wenzel and Schröter*, 2010). Indeed, it is apparent from Fig. 1 that the rates which are not corrected for GIA (shown by green symbols) are biased towards relatively low values, most likely because of the large negative rates of relative sea-level change associated with post-glacial rebound in the numerous northern Europe tide gauges. In addition, to prevent contamination from large-amplitude decadal sea-level oscillations [*Sturges and Hong*, 2001], studies where the amplitude of the evaluation time-window is < 50 years will not be considered [*Douglas*, 1992]. Hereinafter, the set of 36 studies obeying these criteria will be referred to as set T36 (see Table S2). Because of the variety of approaches to the GMSLR problem, the different GIA models employed to correct the tide gauge trends and of the different statistical meaning of σ_r in different studies [*Spada and Galassi*, 2012], we are aware that the above criteria could not suffice to ensure a full methodological uniformity. This provides a heuristic rather than a fully rigorous character to our reasoning.

3. Results

In Fig. 2a, the r values for the T36 studies (circles) are shown with their error bars σ_r (green) as a function of $t_c = (t_1+t_2)/2$, the midpoint of the time window over which r has been estimated in each individual study. The t_c values range between 1898 and 1975, the longest time interval P over which the sea-level acceleration can be estimated from this dataset. Keeping a conservative approach, we did not attempt to extrapolate our results outside this range. The weighted linear correlation between r and t_c (with weights σ_r^{-2}), is positive and moderate (the Pearsons's correlation coefficient is $\rho = 0.43$), suggesting the existence of a linear relationship between the two variables. Indeed, it is straightforward to see that if the observed rates were obtained by a least squares linear regression of an hypothetical global sea-level curve

$$s(t) = c_0 + c_1\, t + c_2\, t^2, \tag{1}$$

where t is time and c_0, c_1 and c_2 are constants, a perfect correlation ($\rho = 1$) would be obtained, with

$$r = c_1 + a\, t_c, \tag{2}$$

where $a = 2\, c_2$ is the so-called "apparent" sea-level acceleration [*Douglas*, 1992] (details of the derivation are given in Text S1).

If model (1) is assumed, the spread of the r values in Fig. 2a can be interpreted as the effect of non-linear sea-level variations associated with decadal oscillations [*Sturges and Hong*, 2001], long-term cyclic variations [*Chambers et al.*, 2012], or intermittent (i.e. localized in time and space) variations of the rate of GMSLR rise [*Olivieri and Spada*, 2013]. Of course, the dispersion of the r values could also result from noise or systematic errors propagated through the (different) procedures employed in each of the studies considered, or from sampling effects in early studies that considered a limited number of tide gauges. However, owing to the large uncertainties involved in this analysis, adding more time-dependent terms to Eq. (1) to account for possible fluctuations of r does not appear to be justified.

The problem of the determination of a from set T36 can be reduced to the solution (in the least squares sense) of the overdetermined system $\mathbf{x} = (\mathbf{F}^t\mathbf{F})^{-1}\,\mathbf{F}^t\mathbf{h}$, where $\mathbf{x} = (c_1, a)^t$, $\mathbf{h} = (r_1, r_2, \ldots, r_N)^t$, r_k is the value of the rate of sea-level change obtained in the k-th study ($k = 1, \ldots, N$), $N = 36$ and the array $\mathbf{F}$ has a simple closed form (see Text S2 for details). We find a best fitting sea-level acceleration

$$a_0^{LS} = 0.54 \pm 0.27 \quad \text{myc}, \tag{3}$$

where LS stands for Least Squares and the uncertainty, determined by a Monte Carlo simulation, corresponds to 1σ. Result (3) holds during the period $P_0 =$ (1898-1975), defined by the range of t_c values in Fig. 2a. The line that best fits the r values for the studies of set T36, with slope a_0^{LS}, is shown in Fig. 2b. We have verified that the application of the generalized least squares (GLS) method to avoid possible effects of heteroscedasticity arising from r values within set T36 having different standard deviations, would provide $a_0^{GLS} = 0.52 \pm 0.28$ myc, fully consistent with (3). Assuming that the rate of GMSLR has kept increasing at an acceleration a_0^{LS} also after 1975, Fig. 2b would suggest a rate of ~ 2 mm yr^{-1} for year 2010. This value is significantly smaller than the rate of ~ 3 mm yr^{-1} observed by the satellite altimetry (1993-2010) and by tide gauge data over the same period, which could indicate either an important recent increase of the sea-level acceleration or the effect of decadal variations of mean sea-level [*Church et al.*, 2013].

To corroborate result (3), we have performed a meta-analysis aimed to identify possible linear time variations of the published rates of GMSLR. The meta-analysis method is widely employed in the medical sciences (see *Walker et al.* [2008]), and has proven to be useful for "conducting research about previous research" (*http://en.wikipedia.org/wiki/Meta-analysis*). Meta-analysis extends the capability of standard inferential methods to those cases in which datasets are limited and heterogeneous [*Guolo*, 2012]. Here, the meta-analysis has been performed by using package `metaLik` [*Guolo and Varin*, 2012] in the framework of `R` (`R` Core Team, 2012). The core of the package (function `metaLik`) is used to assess the likelihood of a linear relationship between the rate r of sea-level change and t_c, which is suggested by the heuristic model (2). The results of the analysis give a p-value $= 0.0289$ and Skovgaard p-value $= 0.0355$, which confirms the hypothesized linear relationship [*Guolo and Varin*, 2012]. During period P_0, the corresponding best estimate for the sea-level acceleration is

$$a_0^{MA} = 0.63 \pm 0.28 \quad \text{myc}, \tag{4}$$

where the uncertainty corresponds to 1σ and MA stands for meta-analysis. This value is consistent with the estimate obtained by the traditional LS approach (3).

4. Discussion

In the convergence plot of Fig. 3, a is evaluated considering r values from an increasing number (n) of chronologically ordered studies from set T36. The sea-level acceleration is positive regardless the value of n and the (1σ) confidence interval (cyan-shaded regions) only marginally contains negative values. This indicates that the evidence for a *positive* sea-level acceleration is clear and it is supported with high confidence even by a relatively small number of studies, during relatively short time periods P. The shrinking of the 1σ confidence interval with increasing n indicates that evidence for a sea-level acceleration is emerging coherently from values of the rate of GMSLR progressively published in the T36 studies. This confirms the effectiveness of meta-analysis in evidencing interesting relationships in the context of multiple studies [*O'Rourke*, 2007].

Values of a in the range of 0 to 1 myc (dotted lines in Fig. 3), in broad agreement with estimates obtained in dedicated reconstructions listed in Table 1, are found already for $n = 10$ (i.e., since 1995) although characterized by a large uncertainty. Starting from $n \sim 21$ (year 2005) the relative uncertainty on a (i.e. $|\sigma_a|/|a|$) remains close or below 50% (solid blue lines). By the Monte Carlo simulation described in Text S3, we have verified that the existence of a sea-level acceleration during period 1898-1975, with values consistent with a_0^{MA}, would be equally suggested by subsets of 20 papers randomly extracted from T36 (90% confidence).

In his paper, *Douglas* [1992] found no evidence for a sea-level acceleration during the 20th century (see Table 1). This negative result was explained by the limited number of instrumental records employed and the strong decadal sea-level variability affecting the sea-level observations [*Church and White*, 2006]. According to our results in Fig. 3, a hypothetical meta-analysis performed in the early 90's would have not provided a significant result, since until 1995 only ~ 10 GMSLR estimates were published, with a consequent huge uncertainty on a. Over time period 1898-1975, our study indicates the sea-level acceleration given by Eq. (3), a result that is totally independent from (but fully consistent with) that obtained by *Church and White* [2006] over a comparable time period (the 20th century), namely 0.8 ± 0.8 myc (2σ). Indeed, according to our results in Fig. 3, a meta-analysis could have provided comparable values of sea-level acceleration already since the early 2000's, exploiting information from previously assessed rates of GMSLR from ~ 20 scholarly papers.

5. Conclusion

The IPCC AR5 [*Church et al.*, 2013] has recently concluded that there is high confidence that the rate of sea-level rise has increased during the last two centuries. However, according to AR5, it is only likely (probability $\geq 66\%$) that GMSLR has accelerated since the early 1900s. This latter conclusion was reached exploiting results from a few independent global reconstructions finalized at a direct evaluation of sea-level acceleration. Adopting a totally different perspective, here we have considered an ensemble of previous results that appeared in the literature since 1941 on the *rate* of GMSLR, to which a GIA correction has been applied. By a straightforward application of the LS and GLS methods, we have shown that collectively the 36 studies selected point to a time variation of the rate of GMSLR (i.e. a sea-level acceleration), although the evaluation of this important climate variable was not within their scope. This result has been confirmed by a meta-analysis. Even though our arguments are mostly based on heuristics, they bring new evidence of a sea-level acceleration during 20th century, independently corroborating the IPCC AR5 evaluations and recently published sea-level reconstructions [*Jevrejeva et al.*, 2014; *Hogarth*, 2014; *Choblet et al.*, 2014].

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Table 1. Estimates of global sea-level acceleration a from studies published since 1992. P and σ_a are the analysis time span and the uncertainty on the acceleration, respectively. The data are chronologically displayed in Fig. S1.

n.	Author(s)	year of publication	P year-year	a myc	σ_a myc
1.	*Douglas*	1992	1905-1985	-1.1	1.2
2.	*Douglas*	1992	1850-1991	0.1	0.8
3.	*Church and White*	2006	1870-2001	1.3	0.6
4.	*Church and White*	2006	1900-2000	0.8	0.8
5.	*Jevrejeva et al.*	2008	1700-2002	~ 1	–
6.	*Church and White*	2011	1880-2009	0.9	0.3
7.	*Ray and Douglas*	2011	1900-2000	0.0	0.2
8.	*Olivieri and Spada*	2013	1820-2010	0.98	0.23
9.	*Olivieri and Spada*	2013	1840-2010	0.42	0.24
10.	*Jevrejeva et al.*	2014	1807-2009	2	1
11.	*Wenzel and Schröter*	2014	1900-2000	0.42	0.92
12.	*Choblet et al.*	2014	1900-2000	1.5	–
13.	*Hogarth*	2014	1900-2000	1.0	0.8
14.	*Hay et al.*	2015	1901-1990	1.7	0.3
15.	*This study*	?	1898-1975	0.54	0.27

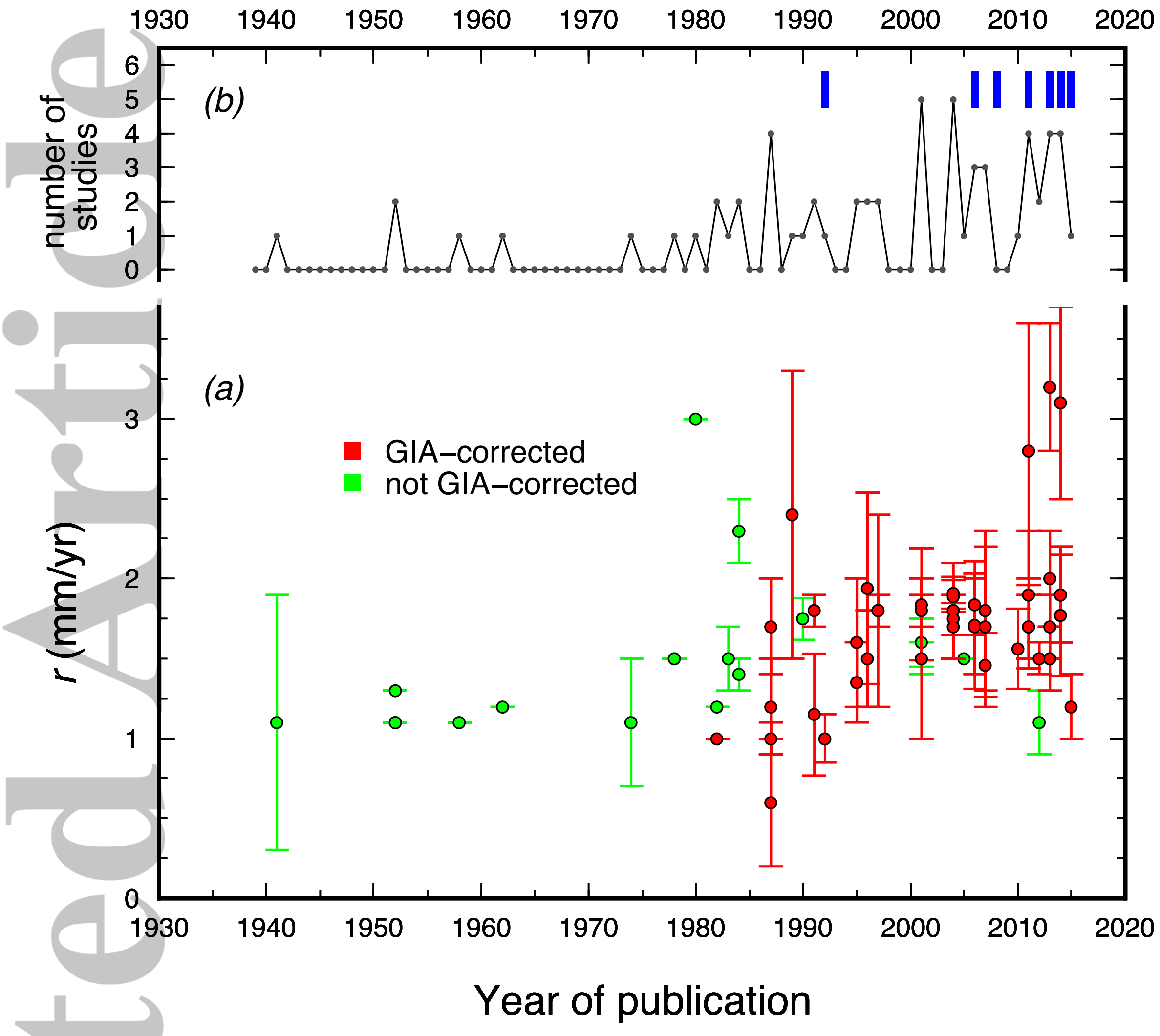

Figure 1. *(a)* Rates of GMSLR (r) from 62 peer-reviewed academic journals published since *Gutenberg* [1941], based on our systematic review (see Tables S1 and S2); GIA-corrected (from 44 studies) and un-corrected estimates (from 18 studies) are shown by red and green symbols, respectively. *(b)* Number of published studies per year in which r has been estimated. Blue bars on top mark the years when at least one study dedicated to sea-level acceleration has been published.

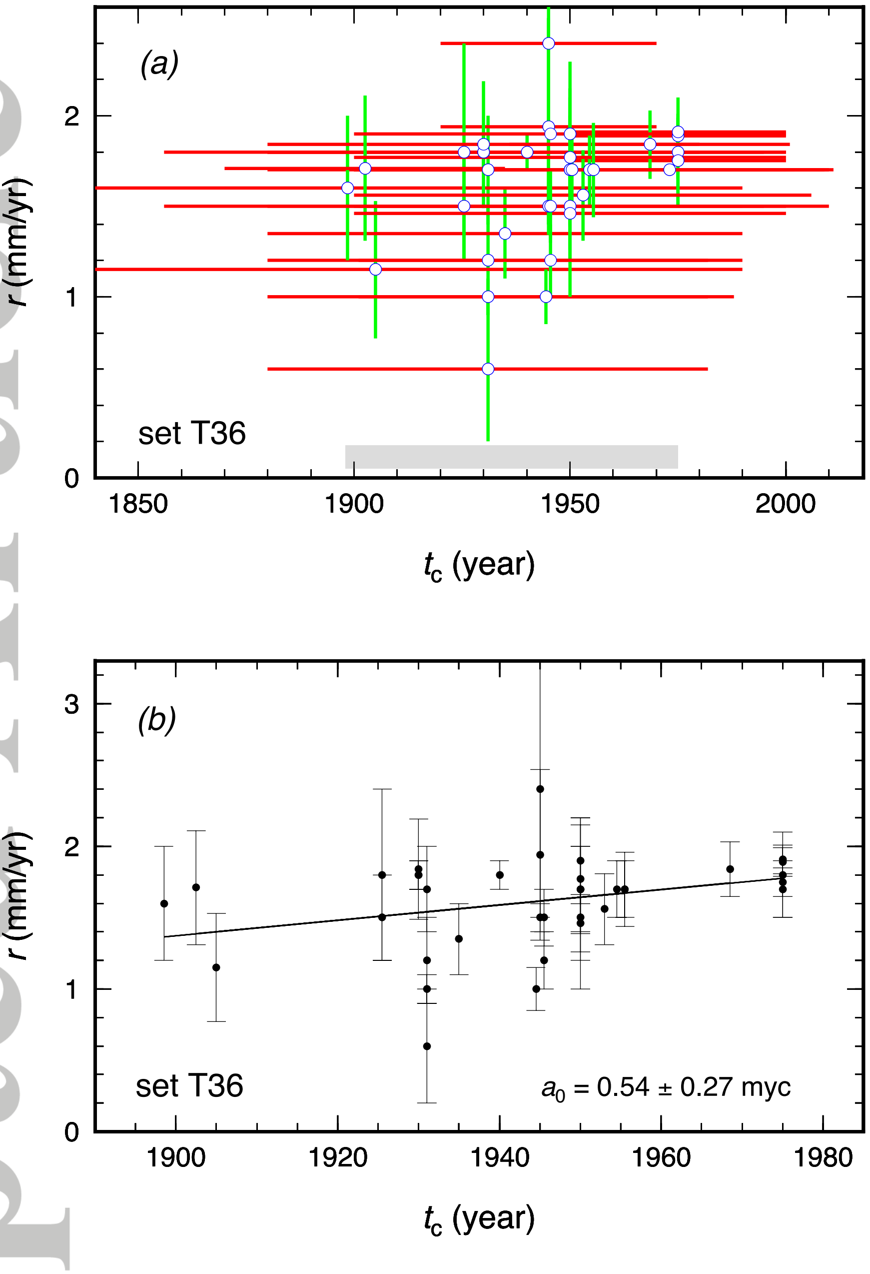

Figure 2. *(a)* Rates of GMSLR for set T36 as a function of t_c, the midpoint of the time-interval (t_1, t_2) over which r is evaluated in each of the studies (red bars). Error bars σ_r are shown in green. *(b)* Line that best fits the T36 r values, whose slope defines the sea-level acceleration during time period $P_0 = $ (1898-1975) identified by the whole range of t_c values (shaded rectangle in *(a)*).

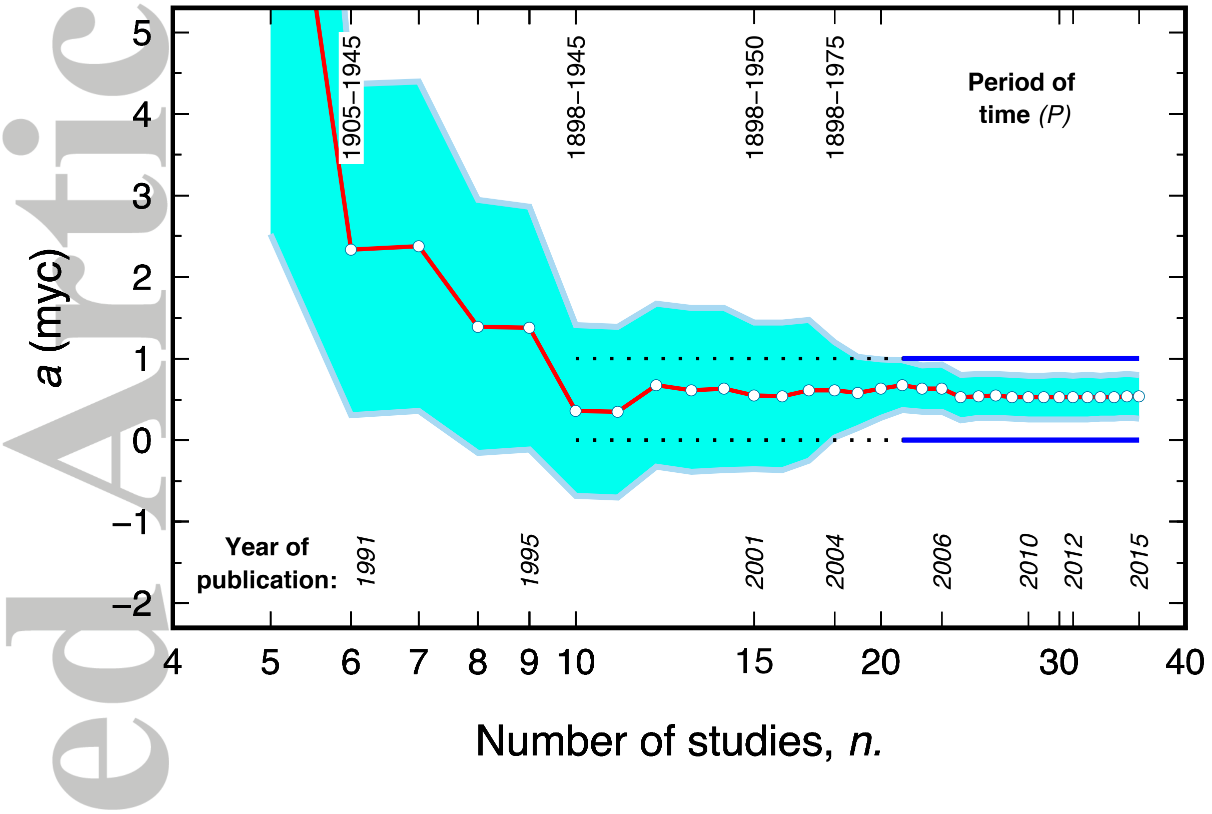

Figure 3. Sea-level acceleration a (white circles) and its 1σ uncertainty (cyan) determined by considering an increasing number of published studies (n) extracted from set T36 in chronological order. The year of publication of the studies and the length of the time period P to which the computed acceleration refers are shown at the bottom and the top, respectively.