



Sea level budget over 2003-2008: A reevaluation from GRACE space gravimetry, satellite altimetry and Argo

A. Cazenave, K. Dominh, S. Guinehut, E. Berthier, W. Llovel, G. Ramillien,
M. Ablain, G. Larnicol

► To cite this version:

A. Cazenave, K. Dominh, S. Guinehut, E. Berthier, W. Llovel, et al.. Sea level budget over 2003-2008: A reevaluation from GRACE space gravimetry, satellite altimetry and Argo. Global and Planetary Change, Elsevier, 2009, 65 (1-2), pp.83-88. .

HAL Id: hal-00401223

<https://hal.archives-ouvertes.fr/hal-00401223>

Submitted on 22 Jul 2009

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47

**Sea level budget over 2003-2008:
a reevaluation from GRACE space gravimetry,
satellite altimetry and Argo**

**A. Cazenave¹, K. Dominh¹, S. Guinehut², E. Berthier¹, W. Llovel¹,
G. Ramillien¹, M. Ablain² and G. Larnicol²**

- 1. LEGOS, OMP, Toulouse**
- 2. CLS, Ramonville St Agne**

**Submitted
to
Global and Planetary Change**

August 2008

48 **Abstract**

49
50 From the IPCC 4th Assessment Report published in 2007, ocean thermal expansion contributed by
51 ~50% to the 3.1 mm/yr observed global mean sea level rise during the 1993-2003 decade, the
52 remaining rate of rise being essentially explained by shrinking of land ice. Recently published
53 results suggest that since about 2003, ocean thermal expansion change, based on the newly
54 deployed Argo system, is showing a plateau while sea level is still rising, although at a reduced rate
55 (~ 2.5 mm/yr). Using space gravimetry observations from GRACE, we show that recent years sea
56 level rise can be mostly explained by an increase of the mass of the oceans. Estimating GRACE-
57 based ice sheet mass balance and using published estimates for glaciers melting, we further show
58 that ocean mass increase since 2003 results by about half from an enhanced contribution of the
59 polar ice sheets -compared to the previous decade- and half from mountain glaciers melting. Taking
60 also into account the small GRACE-based contribution from continental waters (<0.2 mm/yr), we
61 find a total ocean mass contribution of ~2 mm/yr over 2003-2008. Such a value represents ~80% of
62 the altimetry-based rate of sea level rise over that period. We next estimate the steric sea level (i.e.,
63 ocean thermal expansion plus salinity effects) contribution from: (1) the difference between
64 altimetry-based sea level and ocean mass change and (2) Argo data. Inferred steric sea level rate
65 from (1) (~ 0.3 mm/yr over 2003-2008) agrees well with the Argo-based value also estimated here
66 (0.37 mm/yr over 2004-2008). Furthermore, the sea level budget approach presented in this study
67 allows us to constrain independent estimates of the Glacial Isostatic Adjustment (GIA) correction
68 applied to GRACE-based ocean and ice sheet mass changes, as well as of glaciers melting. Values
69 for the GIA correction and glacier contribution needed to close the sea level budget and explain
70 GRACE-based mass estimates over the recent years agree well with totally independent
71 determinations.

72

73

74 **1. Introduction**

75

76 While global mean ocean heat content (hence thermal expansion) rose regularly since at least the
77 early 1990s as evidenced from in situ ocean temperature data (Antonov et al., 2005; Levitus et al.,
78 2005; Ishii et al., 2005; Guinehut et al., 2004; Willis et al., 2004), new in situ hydrographic
79 observations from the recently deployed Argo system (Roemmich and Owens, 2000) indicate that
80 ocean heat content had a break since 2003 (Willis et al., 2008). If real, this means that, during the
81 last 5 years, ocean thermal expansion has not contributed to sea level rise, unlike during the
82 previous 10-year period where about 50% of the rate of sea level rise could be attributed to ocean
83 thermal expansion (Bindoff et al., 2007). Yet, satellite altimetry observations indicate that global
84 mean sea level has continued to rise since 2003, at a slightly reduced rate however (of 2.5 +/- 0.4
85 mm/yr over 2003-2008, Glacial Isostatic Adjustment -GIA- correction of 0.3 mm/yr applied)

86 compared to the previous decade [see Ablain et al., 2008 for details on the satellite altimetry-
87 based sea level data processing and errors assessment]. As shown in the IPCC 4th Assessment
88 Report (Bindoff et al., 2007), during the period 1993-2003, altimetry-based rate of sea level rise (of
89 3.1 +/- 0.4 mm/yr) can be explained by 1.6 +/- 0.25 mm/yr steric sea level and 1.2 +/- 0.2 mm/yr
90 land ice contributions respectively (note that uncertainties quoted here correspond to the 95% errors
91 range). Thus a new question is raised: could the recent rate of sea level rise (since 2003) be
92 explained by fresh water input to the ocean alone as a result of enhanced land ice (and eventually
93 land waters) contribution? In the present study, we try to answer this question by estimating the
94 ocean mass change contribution to sea level using space gravimetry data from the GRACE mission
95 launched in March 2002. GRACE provides spatio-temporal variations of the Earth gravity at
96 monthly or less temporal resolution and ~300-400 km ground resolution (Tapley et al., 2004).
97 Numerous studies published in the recent years have shown that GRACE can offer useful
98 constraints on ocean mass change (e.g., Chambers et al., 2004; Lombard et al., 2007), on the mass
99 balance of the ice sheets [e.g., Velicogna and Wahr, 2006a,b; Chen et al., 2006a,b; Lutchke et al.,
100 2006; Ramillien et al., 2006) and on land water contribution to sea level (Ramillien et al., 2008).
101 Here we analyse GRACE data over a 5.5 year time span (August 2002 through February 2008) over
102 oceans, land and ice sheets to estimate the total fresh water mass contribution to past few years sea
103 level rise. We discuss the total fresh water input to the oceans comparing ocean mass change and
104 ice sheet contribution inferred from GRACE with recent independent estimates for the mass
105 balances of the ice sheets and mountain glaciers. In addition as shown by Lombard et al.(2007),
106 comparing the altimetry-derived global mean sea level change with GRACE-based ocean mass
107 change provides an estimate of the steric (i.e., thermal expansion plus salinity effect) contribution to
108 sea level. We also follow this approach here and compare altimetry/GRACE-based steric sea level
109 with Argo-based estimate.

110

111 **2. Ocean mass variation from GRACE**

112 We have analysed geoid data from the GRACE space mission to estimate the change in mean mass
113 of the oceans since mid-2002. We follow the same procedure as in Lombard et al. (2007), except
114 that we use here the most recent geoid solutions (RL04 Level-2 products) released by the
115 GeoForschungsZentrum –GFZ- (Flechtner, 2007). This data set covers the period August 2002 to
116 February 2008 (~5.5 years). The geoid solutions consist of spherical harmonics coefficients up to
117 degree and order 120 at monthly interval. To work with geoid anomalies, we remove from each
118 monthly solution, a mean solution averaged over the whole 5.5-year time span. In the geoid solution
119 determination process, an ocean model is removed. As the geoid solution over the oceans represents
120 departure from the model, we add back the initial ocean model. To estimate the ocean mass
121 component, we construct a geographical mask over the whole oceanic domain and compute, at each
122 time step, the convolution product between spherical harmonics of mask and geoid anomalies. We

123 limit the spherical harmonic expansion to degree 50 (corresponding to a ground resolution of
124 ~ 400 km) to minimize the resonance effects affecting higher harmonic degrees [see Swenson and
125 Wahr, 2006). We next express the results in terms of Equivalent Sea Level, noted ESL (see
126 Lombard et al., 2007 for details about the GRACE data analysis).

127 The raw GRACE-based ocean mass time series is dominated by an annual cycle caused by the
128 annual exchange of water between land and oceans (Cazenave et al., 2000). As we are interested
129 here in the interannual fluctuations, we remove the annual cycle. The resulting time series, shown in
130 Fig.1, has a slightly negative slope of $\sim -0.12 \pm 0.06$ mm/yr over the time span January 2003-
131 December 2007 (we consider this time span –called 2003-2008- to work with an integer number of
132 years). It is shown in Fig.1. However, a GIA correction has to be applied to this raw ocean mass
133 time series. In effect, GIA causes a secular change in the mean oceanic geoid that needs to be
134 removed from the GRACE-based raw ocean mass time series to obtain the real water mass change
135 of the oceans. This linear correction is quite large and available from GIA modelling only. It varies
136 from ~ 1 mm/yr to 2 mm/yr (in ESL unit), depending on modelling assumptions (Willis et al.,
137 2008; Tamisiea et al., 2008; Peltier et al., 2008). Lombard et al. (2007) used a GIA correction of 1.7
138 mm/yr following Tamisiea et al. (2008). Willis et al. (2008) used a value closer to 1 mm/yr.
139 Recently Peltier et al. (2008) reevaluated, under various modelling assumptions, the GIA
140 corrections that need to be applied to satellite data (satellite altimetry and GRACE) when
141 determining global mean sea level rise and ocean mass change. They show that Earth rotation
142 effects have strong influence on the ocean mass GIA correction and recommend to use an ocean
143 mass GIA correction of ~ 2 mm/yr that accounts for the rotational effects. Here we use this value.
144 We will see below that such a value allows us to close the sea level budget. Corresponding GIA-
145 corrected ocean mass time series (annual cycle removed plus 12-month smoothing) is shown in Fig.
146 1. We note that during the 2003-2008 period, the ocean mass has increased almost linearly, at a rate
147 of 1.9 ± 0.1 mm/yr . This increase results from fresh water mass input to the oceans as a result of
148 land ice loss and eventually land waters.

149

150 **3. Ice sheet contribution from GRACE**

151 We now estimate the ice sheet contribution from GRACE over time span 2003-2008. Two methods
152 are compared:

- 153 (1) We average the GRACE signal over the whole Earth surface and remove the ocean contribution
154 using the ocean mask as explained in section 2. We also average the GRACE signal over the
155 whole land surface using a land mask (excluding the ice sheets). The difference between the
156 two averages provides an estimate of the ice sheet contribution.
- 157 (2) We average the GRACE signal using dedicated masks for Greenland and Antarctica as
158 explained in Ramillien et al. (2006).

159 Although the two calculations are not independent, they provide an upper bound for the so-
160 called leakage effect, i.e., the contamination from far field gravity signals not due to the ice sheets
161 (at a given location, geoid height not only reflect local mass anomalies but also far field anomalies
162 because of the inverse distance relationship between geoid and mass; such a contamination is
163 amplified over small size regions like Greenland because of the low GRACE resolution, of ~ 400
164 km). We expect that method 1 minimizes the leakage effects.

165 Fig. 2 shows the ice sheet contribution expressed in equivalent sea level estimated by method 1.
166 The raw time series exhibits a slightly positive trend of 0.4 ± 0.1 mm/yr ESL. To this curve we
167 need to add the GIA correction over the ice sheets (as over the oceans, GRACE cannot separate
168 climate-related surface mass change from solid Earth mass change related to GIA). For Greenland,
169 this correction is almost negligible [e.g., Ramillien et al., 2006]. This is not the case however for
170 Antarctica. In Ramillien et al. (2006), we used a GIA correction for Antarctica of 0.5 mm/yr ESL
171 based on Ivins and James (2005) model. Such a value is also that preferred by Barletta et al. (2007)
172 who investigated a large range of upper and lower mantle viscosities to estimate the GIA correction
173 to be applied to GRACE-derived ice sheet mass balance. We use this value here to compute the
174 GIA-corrected time series shown in Fig.2. The resulting trend amounts to 1.0 ± 0.1 mm/yr ESL. It
175 represents the total ice sheet contribution to sea level as estimated from GRACE over the 2003-
176 2008 time span. In terms of ice mass loss, this corresponds to $\sim 360 \pm 36$ Gigatons/year.

177 Results from method 2 are shown in Fig.3a and 3b (Greenland and Antarctica contributions
178 expressed in ESL). For Antarctica, we have applied a GIA correction of 0.5 mm/yr (ESL) as
179 discussed above. In both figures, we compared the GFZ GRACE-based time series with another
180 estimate based on another GRACE product (i.e., from the Groupe de Recherche en Geodesie
181 spatiale –GRGS- group, Biancale et al., 2006), to check the consistency of the estimated trend. For
182 each ice sheet, the two sources of data lead to very similar trends (with differences smaller than
183 0.02 mm/yr). Taking the mean value from the two data sources, we obtain a GRACE-based
184 Greenland contribution to sea level of 0.38 ± 0.05 mm/yr (i.e., -136 ± 18 Gigatons/year ice mass
185 loss) over 2003-2008. The Antarctica contribution (GIA correction applied) is 0.56 ± 0.06 mm/yr
186 ESL over the same period (i.e., -198 ± 22 Gigatons/year ice mass loss). Summing the two ice
187 sheet contributions leads to 0.95 ± 0.08 mm/yr ESL over 2003-2008, in good agreement with the
188 result of method 1. The small difference between the two methods places an upper bound on the
189 leakage effects.

190

191 **4. Total land ice contribution to sea level**

192 *Ice sheets*

193 Several estimates of the ice sheet mass balance from GRACE have been published in the recent
194 years (Velicogna and Wahr, 2006a,b; Chen et al., 2006a,b; Ramillien et al., 2006). Significant
195 uncertainty in trends can be noticed between these different published results. Early results were

196 based on rather short time series. Hence lengthening the time series may lead to different
197 results because of seasonal and interannual variability. As discussed in Cazenave (2006), another
198 cause of discrepancy arises from differences in data processing and methodology developed by the
199 various GRACE project groups when computing the geoid solutions. From most recent published
200 results, including those of the present study, we note that GRACE products from GFZ, GRGS and
201 the ‘Mascons’ approach (the regional method developed by Lutchke et al., 2006) provide rather
202 converging results, at least for Greenland (see also Forsberg, 2008), with current rates of ice mass
203 loss of $\sim 130\text{-}150$ Gigatons/year. Higher rates are found by Velicogna and Wahr (2006a) (210
204 Gigatons/year for Greenland; e.g., Witze, 2008) and Chen et al. (2006a) based on Center for Space
205 Research –CSR– geoids. So far, the reason for this discrepancy remains unclear.

206 From a compilation of published results based on different remote sensing techniques and
207 modelling, Meier et al. (2007) reported for year 2006 contributions (in ESL) of 0.5 ± 0.1 mm/yr,
208 0.32 ± 0.04 mm/yr and -0.15 ± 0.07 mm/yr for Greenland, West Antarctica and East Antarctica
209 respectively, leading to a total ice sheet contribution of $\sim 0.7 \pm 0.15$ mm/yr for that particular year.
210 Recently Rignot et al. (2008) reassessed Antarctic ice mass balance using radar interferometry and
211 surface mass balance modelling. They conclude that East Antarctica has remained almost in balance
212 since 1992 while accelerated ice mass loss is reported in West Antarctica. The net Antarctica
213 contribution for year 2006 amounts to 0.54 ± 0.2 mm/yr. This is three times Meier et al.’s value of
214 0.17 mm/yr, mainly a result of positive mass balance for East Antarctica in the latter study. It is
215 worth to note that our GRACE-based estimate for Antarctica over the past 5 years is in good
216 agreement with Rignot et al. (2008) estimate. These results suggest that recent years ice sheet
217 contribution to sea level has increased compared to the 1990s (Lemke et al., 2007). In the following
218 we consider for the total ice sheet contribution, the average of the two methods presented in section
219 2, i.e., $\sim 1.0 \pm 0.15$ mm/yr for 2003-2008.

220

221 *Glaciers and ice caps*

222 Between 1990 and 2003, the IPCC 4th Assessment Report determined a Glacier and Ice Cap (GIC)
223 contribution to sea level rise of 0.77 ± 0.22 mm/yr (Lemke et al., 2007). There are still very few
224 updated estimates of GIC losses for the most recent years (beyond 2003) due to the difficulty to
225 gather mass balance measurements performed worldwide by different research groups. Kaser et al.
226 (2006) reported a contribution to sea level rise of 0.98 ± 0.19 mm/yr for 2001-2004, slightly larger
227 than during the previous decade. Using the same data as Kaser et al. (2006) and assuming that ice
228 losses by GIC increased linearly with time since year 2000, Meier et al. (2007) found the GIC
229 contribution to be 1.1 ± 0.24 mm/yr ESL for year 2006.

230 The enhanced mass losses from GIC proposed by Meier et al. (2007) is supported by recent
231 evidences of accelerated ice thinning rates in Alaska (Chen et al., 2006c), Svalbard (Kohler et al.,
232 2007) and in Himalaya (Berthier et al., 2007). The acceleration is also clearly demonstrated by the

233 updated (although not yet complete) glacier mass balance measurements collected by the
234 World Glacier Monitoring Service (WGMS, available at <http://www.geo.unizh.ch/wgms/>). Analysis
235 of a subset of thirty reference glaciers spread in nine mountain ranges shows that the three years
236 with the strongest ice losses appear after 2002. The mean mass balance for 2002-2006 (the last four
237 hydrological years available) is two to three times more negative than during the previous 10 years.
238 In the following we consider the value of 1.1 ± 0.24 mm/yr ESL from Meier et al. (2007) as
239 representative of the 2003-2008 time span and use it for the sea level budget.

240

241 **5. Total mass contribution to the sea level budget over 2003-2008**

242 Summing the ice sheet and glacier contributions as discussed above, leads to a total land ice
243 component of 2.1 ± 0.25 mm/yr ESL over 2003-2008. To this value should eventually be added a
244 small contribution from land waters. In a previous study (Ramillien et al., 2008), we estimated to \sim
245 0.17 ± 0.1 mm/yr, the land water contribution to sea level using GRACE data (GFZ geoids,
246 release RL03) over 2003-2006. An updated estimate based on GFZ RL04 GFZ and GRGS GRACE
247 data leads to about the same value over 2003-2008. In the following we use the Ramillien et al.
248 (2008).

249 Comparing the GRACE-based ocean mass trend (1.9 ± 0.1 mm/yr; see section 2) with the total
250 land ice plus land waters contribution estimated independently (2.2 ± 0.28 mm/yr; sections 3 and
251 4) gives satisfactory agreement for a GIA correction of 2 mm/yr. In a way this provides constraints
252 on the GIA correction, suggesting that the upper range of proposed values is indeed indicated. As
253 mentioned above, this upper range is recommended by Peltier et al. (2008) because of Earth rotation
254 effects. The comparison also provides constraints on glacier melting contribution, since with
255 GRACE, we can compute separately ocean mass increase (sum of ice sheet mass loss and land
256 waters) and ice sheet mass balance. Comparing the two provides constraint on glaciers melting. We
257 note that the latter contribution agrees well with published results based on *in situ* observations and
258 remote sensing.

259 Fig.4 compares for the 2003-2008 period, the observed (from T/P and Jason-1 altimetry) sea level
260 curve (from Ablain et al., 2008) to GRACE-based ocean mass change (with a GIA correction of 2
261 mm/yr) and total land ice plus land waters contribution discussed above. We note that land ice plus
262 land waters has contributed for 75%-85% to recent sea level rise, i.e., significantly more than during
263 the decade 1993-2003 (Bindoff et al., 2007).

264

265 **6. Steric sea level inferred from altimetry and GRACE and computed with Argo**

266 As shown in Lombard et al. (2007), it is possible to estimate the steric sea level from the difference
267 between the altimetric (i.e., total) sea level and the GRACE-based ocean mass component.
268 Corresponding steric sea level curve for 2003-2008 is presented in Fig.5 (assuming a GIA
269 correction of 2 mm/yr for the ocean mass estimate). The steric sea level increased on average since

270 early 2003 through 2006, then shows a slightly decreasing trend. The latter behaviour results
271 from the fact that altimetric sea level flattens since 2006 while the ocean mass continues to increase.
272 If this steric sea level behaviour is real, it could be related to the particularly strong recent La Nina
273 cold phase (Kennedy, 2007). The average slope of the steric sea level curve over 2003-2008 is
274 small, on the order of 0.31 ± 0.15 mm/yr. In Fig.5 is also presented the steric sea level computed
275 from the difference between satellite altimetry and total land ice (i.e., ice sheet contribution
276 estimated in this study plus glacier contribution from Meier et al., 2007) plus land waters curve. It
277 is interesting to note that it closely follows the altimetry minus ocean mass curve. Its trend is also
278 similar.

279 We now provide an independent estimate of the steric sea level using temperature and salinity data
280 from Argo profiling floats. When available, delayed-mode data are preferred to real-time ones (i.e.
281 for half of the floats) and only measurements with Argo quality control flags at '1' are used. As
282 real-time quality controlled checks applied on the Argo data set are very simple and automated,
283 additional quality controls were first performed following the method described in Guinehut et al.
284 (2008). It compares collocated sea level anomalies from altimeter measurements with steric height
285 anomalies calculated from the Argo temperature and salinity profiles. By exploiting the correlation
286 that exists between the two data sets (Guinehut et al., 2006), along with mean representative
287 statistical differences between the two, the altimeter measurements are used to extract random or
288 systematic errors in the Argo float time series (drift, bias, spikes, etc). About 4% of the floats were
289 deleted by this method.

290 Steric heights at the surface are then computed relative to the 900-m depth from Argo temperature
291 and salinity profiles. The 900-m depth was chosen as a compromise between data coverage and
292 maximum sampled depth to provide optimum spatial and temporal coverage. Steric changes below
293 900-m do contribute to the sea level budget on multi-decadal time scales but observations and
294 models suggest that major contributions come from the upper ocean [e.g., Antonov et al., 2005,
295 Wunsch et al., 2007].

296 Argo floats profiles being discrete measurements in time and in space, steric sea level grids at $1/3^\circ$
297 resolution are constructed at monthly interval. Mapping is based on an optimal interpolation method
298 (Bretherton et al., 1976), using a temporal correlation scale of 45 days and a spatial correlation scale
299 that varies with latitude, from 1500 km at the equator to 700 km at 50°N (larger values are used in
300 the zonal direction than in the meridional one). In order to take into account errors associated with
301 mesoscale variability aliasing, noise-to-signal ratio is fixed to 2.0 for each in-situ measurement.
302 Besides, a contemporaneous Argo climatology representing the time-mean is removed from the
303 individual steric height prior to mapping. Finally, monthly steric height anomaly grids are globally
304 averaged to produce steric sea level time series.

305 In order to precisely quantify the impact of Argo data sampling and methodology used to calculate
306 the globally averaged values, the AVISO multi-mission combined sea level products (Ducet et al.,

2000) are interpolated at the time and location of each Argo float profile. Sea level maps are then reconstructed using the same mapping technique as for steric maps. This allows us to estimate the impact of the variable Argo coverage. At the beginning of 2002, Argo sampling covers about 40 % of the ocean. It reaches around 70 % in 2003, then 80 % at the beginning of the year 2004. After mid-2006, more than 90 % of oceanic areas are sampled. Here we consider Argo data over 2004-2007 only because of the still poor 2003 coverage. The globally averaged steric sea level computed from the gridded data is finally compared altimetry-based sea level (SSALTO/DUACS multi-mission combined products, Ducet et al., 2000). The two curves compare very well over 2004-2008 with a 2.4 mm rms difference, the trend being only slightly reduced by 0.02 mm/year. Fig 5 presents the Argo-based steric sea level curve (seasonal cycle removed; as for ocean mass variations, the steric sea level curve for the upper 900-m depth is dominated by an annual cycle due to seasonal heating and cooling of the upper ocean). The curve is rather flat over the 2004-2008 time span. Corresponding linear trend is small and on the order of 0.37 ± 0.1 mm/year. Even if the year to year variability does not match exactly the altimetry/GRACE steric sea level curve (possibly a result of the data processing and deep ocean contribution), it is remarkable to obtain such an agreement. These two independent estimates of steric sea level trend presented in this study are slightly higher than Argo-based values from Willis et al. (2008). Nevertheless, these results strongly indicate a pause in the rate of steric sea level rise in the past few years. The independent estimate based on GRACE and satellite altimetry data indicate that it is not due to any Argo instrumental problem.

327

328 7. Conclusion

329 From the results presented in this study, we see that confronting independent estimates of ocean and
330 land contributions to sea level with altimetry results leads to a rather coherent picture for recent
331 years variations. This can be summarized as follows: since 2003, sea level has continued to rise but
332 with a rate (of 2.5 ± 0.4 mm/yr) somewhat reduced compared to the 1993-2003 decade (3.1 ± 0.4
333 mm/yr). Over 2003-2008, the GRACE-based ocean mass has increased at an average rate of ~ 1.9
334 mm/yr (if we take the upper range of possible GIA corrections as recommended by Peltier et al.,
335 2008). Such a rate agrees well with the sum of land ice plus land water contributions (i.e., GRACE-
336 based ice sheet mass balance estimated in this study, GRACE-based land waters plus recently
337 published estimates for the current glacier contribution). These results in turn offer constraints on
338 the ocean mass GIA correction, as well as on the glacier melting contribution.

339 The steric sea level estimated from the difference between altimetric (total) sea level and ocean
340 mass displays increase over 2003-2006 and decrease since 2006. On average over the 5 year period
341 (2003-2008), the steric contribution has been small (on the order of 0.3 ± 0.15 mm/yr), confirming
342 recent Argo results (this study and Willis et al., 2008).

343

344

345 **Acknowledgments**

346 The Argo data were collected and made freely available by the international Argo project (a pilot
347 program of the Global Ocean Observing System) and the national programs that contribute to it
348 (<http://www.argo.ucsd.edu>, <http://argo.jcommops.org>). The altimeter products were produced by
349 SSALTO/DUACS and distributed by AVISO with support from CNES.

350 We thank R. Peltier and Luce Fleitout for helpful discussions about the GIA correction.

351

352

353

354 **Table 1:** Sea level rise and the different contributions over 2003-2008 (numbers are from the
 355 present study, except for glaciers and ice caps)

356

357

358

Data source	Rate (mm/yr)
Sea Level (altimetry) 2003-2008	2.5 +/- 0.4
Ocean mass (GRACE) 2003-2008	1.9 +/- 0.1
Ice sheets (GRACE) 2003-2008	1. +/- 0.15
Glaciers and Ice Caps 2003-2008 Meier et al. (2007)	1.1 +/- 0.24
Terrestrial Waters 2003-2008	0.17 +/- 0.1
Sum of ice and waters	2.2 +/- 0.28
Steric sea level (altimetry minus GRACE) 2003-2008	0.31 +/- 0.15
Steric sea level (Argo) 2004-2008	0.37 +/- 0.1

359

360 **References**

361

362 Ablain M., Guinehut S., Valladeau G., DoMinh K. and Cazenave A. (2008), A new assessment of
363 global mean sea level from altimeters highlights a reduction of global slope from 2005 to 2008 in
364 agreement with in-situ measurements, submitted to *Ocean Sciences*.

365 Antonov J., S. Levitus, T.P. Boyer (2005), Thermosteric sea level rise, 1955-2003, *Geophys. Res.
366 Lett.* 32, doi:10.1029/2005GL023112

367

368 Barletta V.R., Sabadini R. and Bordoni A. (2008), Isolating the PGR signal in the GRACE data :
369 impact on mass balance estimates in Antarctica and Greenland, *Geophys. J. Int.*, 172, 18-30.

370

371 Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P., & Chevallier, P. (2007). Remote
372 sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India).
373 *Remote Sensing of Environment*, 108(3), 327-338, doi:10.1016/j.rse.2006.11.017.

374

375 Biancale, R., J.-M. Lemoine, G. Balmino, S. Loyer, S. Bruisma, F. Perosanz, J.-C. Marty and P.
376 Gégout (2006), 3 years of geoid variations from GRACE and LAGEOS data at 10-day intervals
377 from July 2002 to March 2005, CNES/GRGS product, data available on CD-ROM, also on BGI
378 web page: <http://bgi.cnes.fr/>.

379

380 Bindoff N., Willebrand J., Artale V. , Cazenave A., Gregory J. , Gulev S., Hanawa K., Le Quéré C.,
381 Levitus S., Nojiri Y., Shum C.K., Talley L., Unnikrishnan A. (2007) Observations: oceanic climate
382 and sea level. In: *Climate change 2007: The physical Science Basis. Contribution of Working
383 Group I to the Fourth Assessment report of the Intergovernmental Panel on Climate Change*
384 [Solomon S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller
385 (eds.)]. Cambridge University Press, Cambridge, UK, and New York, USA.

386

387 Bretherton, F.P., R.E. Davis, and C.B. Fandry (1976), A technique for objective analysis and
388 design of oceanographic experiments applied to MODE-73, *Deep-Sea Res.*, 23, 559-582.

389 Cazenave, A., F. Remy, K. Dominh and H. Douville (2000), Global ocean mass variations,
390 continental hydrology and the mass balance of Antarctica ice sheet at seasonal timescale, *Geophys.
391 Res. Lett.*, Vol. 27, No. 22, 3755-3758.

392

393 Cazenave A., How fast are the ice sheets melting? (2006), *Science*, 314, 1250-1252.

394

395 Chambers, D.P., J. Wahr and R. S. Nerem (2004), Preliminary observations of global ocean mass
396 variations with GRACE, *Geophys. Res. Lett.*, Vol. 31, L13310.

397

398 Chen, J.L., C.R. Wilson and B.D. Tapley (2006a), Satellite gravity measurements confirm
399 accelerated melting of the Greenland ice sheet, *Science*, 313, 1958.

400

401 Chen J.L., Wilson C.R., Blankenship D.D. and Tapley B.D. (2006b), Antarctic mass rates from
402 GRACE, *Geophys. Res. Lett.*, 33, doi:10.1029/2006GL026369.

403 Chen, J.L., Tapley, B.D., & Wilson, C.R. (2006c). Alaskan mountain glacial melting observed by
404 satellite gravimetry. *Earth and Planetary Science Letters*, 248(1-2), 368-378.

405

406 Ducet, N., P.-Y. Le Traon, and G. Reverdin (2000) Global high resolution mapping of ocean
407 circulation from TOPEX/Poseidon and ERS-1 and -2. *J. Geophys. Res.*, 105, 19477-19498.

408 Flechtner F. (2007), AOD1B product description document for product releases 01 to 04, GRACE
409 327-750, CSR Publ. GR-GFZ-AOD-001 Rev. 3.1, University of Texas at Austin, 43 pp.

410

- 411 Forsberg R. (2008), Greenland ice sheet mass balance from GRACE, European Science
412 Fondation workshop on Greenland ice sheet variability.
413
- 414 Guinehut, S., P.-Y. Le Traon, G. Larnicol, and S. Phillips (2004): Combining ARGO and remote-
415 sensing data to estimate the ocean three-dimensional temperature fields. *J. Mar. Syst.*, 46, 85-98.
416
- 417 Guinehut S., P.-Y. Le Traon and G. Larnicol (2006), What can we learn from global
418 altimetry/hydrography comparisons?, *Geophys. Res. Lett.*, 33, L10604,
419 doi:10.1029/2005GL025551.
420
- 421 Guinehut S., C. Coatanoan, A.-L. Dhomps, P.-Y. Le Traon and G. Larnicol (2008), On the use of
422 satellite altimeter data in Argo quality control, submitted to *J. Atmos. Oceanic. Technol.*
- 423 Ishii M., M. Kimoto, K. Sakamoto, and S.I. Iwasaki (2006), Steric sea level changes estimated from
424 historical ocean subsurface temperature and salinity analyses. *Journal of Oceanography*, 62(2) 155-
425 170.
426
- 427 Ivins E.R. and James T.S. (2005), Antarctic glacial isostatic adjustment: a new assessment, *Antarctic*
428 *Science*, 17 (4), 541-553.
- 429 Kaser G., Cogley J.G., Dyurgerov M.B., Meier M.F. and Ohmura A. (2006), Mass balance of
430 glaciers and ice caps: consensus estimates for 1961-2004, *Geophys. Res. Lett.*, 33, L19501,
431 doi:10.1029/2006GL027511.
- 432 Kennedy J. (2007), La Nina 2007. Integrated Climate Programme (IPC) 2007-2012, Product E1 (ii),
433 Hadley Center MetOffice (UK).
434
- 435 Kohler, J., James, T.D., Murray, T., Nuth, C., Brandt, O., Barrand, N.E., & Aas, H.F. (2007),
436 Acceleration in thinning rate on western Svalbard glaciers. *Geophys. Res. Lett.*, 34(L18502), doi:
437 10.1029/2007GL030681.
438
- 439 Levitus S., J.I. Antonov, and T.P. Boyer (2005), Warming of the World Ocean, 1955- 2003.
440 *Geophys. Res. Lett.* , 32(L02604) doi:10.1029/2004GL021592.
- 441 Lemke et al. (2007), In: Climate change 2007: The physical Science Basis. Contribution of
442 Working Group I to the Fourth Assessment report of the Intergovernmental Panel on Climate
443 Change [Solomon S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L.
444 Miller (eds.)]. Cambridge University Press, Cambridge, UK, and New York, USA.
445
- 446 Lombard A., Garcia D., Cazenave A. and Ramillien G., Fletcher, R. Biancale and M. Ishii (2007),
447 Estimation of steric sea level variations from combined GRACE and satellite altimetry data, *Earth*
448 *Planet. Sci. Lett.*, 254, 194-202.
- 449 .
- 450 Lutchke, S.B., H.J. Zwally, W. Abdalati, D.D. Rowlands, R.D. Ray, R.S. Nerem, F.G. Lemoine,
451 J.J. McCarthy, and D.S. Chinn (2006), Recent Greenland ice mass loss by drainage system from
452 satellite gravimetry observations, *Scienceexpress*, 10.1126/science.1130776.
453
- 454 Meier, M.F., Dyurgerov, M.B., Rick, U.K., O'Neel, S., Pfeffer, W.T., Anderson, R.S., Anderson,
455 S.P., and Glazovsky, A.F. (2007), Glaciers dominate eustatic sea-level rise in the 21st century.
456 *Science*, 317(5841), 1064-1067
457
- 458 Peltier R., Drummond R. and Lutchke S. (2008), On the origins of Earth rotation anomalies: new
459 insights on the basis of both 'old' data and GRACE data, submitted.
460

- 461 Ramillien G., Lombard A., Cazenave A., E. Ivins, M. Llubes, F. Remy and R. Biancale
462 (2006), Interannual variations of ice sheets mass balance from GRACE and sea level, *Global and*
463 *Planetary Change*, 53, 198-208.
- 464
465 Ramillien G., Bouhours S., Lombard A., Cazenave A., Flechtner F. and Schmidt R. (2008), Land
466 water contributions from GRACE to sea level rise over 2002-2006, *Global and Planetary Change*,
467 60, 381-392.
- 468 Rignot, E., Bamber, J.L., Van den Broecke, M.R., Davis, C., Li, Y., Van de Berg, W.J., & Van
469 Meijgaard, E. (2008). Recent Antarctic ice mass loss from radar interferometry and regional climate
470 modelling. *Nature Geoscience*, 1, 106 – 110.
- 471 Roemmich D. and Owens W.B. (2000), the ARGO project: Global ocean observations for
472 understanding for understanding and prediction of climate variability, *Oceanography*, 13 (2), 45-50.
473
- 474 Swenson, S. and J. Wahr (2006), Post-processing removal of correlated errors in GRACE data,
475 *Geophys. Res. Lett.*, 33, L08402, doi:10.1029/2005GL025285.
476
- 477 Tamisiea, M.E., J.X. Mitrovica, R.S. Nerem, E.W. Leuliette, and G.A. Milne (2008), Correcting
478 satellite derived estimates of global mean sea level change for glacial isostatic adjustment, *Geophys.*
479 *J. Int.*, in press.
- 480
481 Tapley B.D., S. Bettadpur, J.C. Ries, P.F. Thompson and M. Watkins (2004), GRACE
482 measurements of mass variability in the Earth system, *Science*, 305, 503-505.
- 483
484 Velicogna I. and Wahr J. (2006a), Revised Greenland mass balance from GRACE, *Nature*, 443,
485 329.
- 486 Velicogna I. and Wahr J. (2006b), Measurements of time-variable gravity show mass loss in
487 Antarctica, *Scienceexpress*, 10.1126/science.1123785.
- 488 Willis J.K., D. Roemmich, B. Cornuelle (2004), Interannual variability in upper ocean heat content,
489 temperature, and thermosteric expansion on global scales, *J. Geophys. Res.* 109,
490 doi:10.1029/2003JC002260.
- 491 Willis J. K., Chambers D.T. and Nerem R. S. (2008), Assessing the globally averaged sea level
492 budget on seasonal to interannual time scales, in press, *J. Geophys. Res.*
- 493
494 Witze A. (2008), Loosing Greenland, *Science*, 452, 798-802.
- 495
496 Wunsch, C., R.M. Ponte and P. Heimbach (2007), Decadal Trends in Sea Level Patterns: 1993–
497 2004, *Journal of Climate*, 20 (24), doi: 10.1175/2007JCLI1840.1.
- 498
499

Figure Captions

501

502 **Fig.1:** Ocean mass change from GRACE over 2003-2008. The open circled curve is the raw time
503 series. The black triangles curve corresponds to the GIA corrected time series.

504

505 **Fig.2:** Total ice sheet contribution to sea level estimated from GRACE over 2003-2008 (method 1;
506 see text). The lower curve (crossed solid line) corresponds to raw data. The upper curve
507 (dotted line with crosses) is the GIA corrected curve.

508

509 **Fig.3:** (a) GRACE-based contribution of Greenland ice loss to sea level (2003-2008). The curve
510 with open circles corresponds to GFZ geoids. The curve with black squares corresponds to
511 GRGS geoids.

512 (b) Same as (a) but for Antarctica. A GIA correction of 0.5 mm/yr ESL has been applied.

513

514 **Fig.4:** Upper curve (crossed line) : altimetry-based sea level curve; Middle curve (open circles) :
515 total land ice contribution using the GRACE-based ice sheet mass balance (this study) and
516 Meier et al. (2007) glaciers contribution; Lower curve (black triangles) : GRACE-based
517 ocean mass change (GIA correction applied).

518

519 **Fig.5:** Steric sea level. Upper curve (black triangles): estimated from the difference between
520 altimetry and GRACE-based ocean mass. Middle curve (open circles) : estimated from the
521 difference between satellite altimetry and total land ice plus land waters contribution; Lower
522 curve : ARGO-based estimate (this study).

523 Fig.1

524

525

526 mm

527

528

529

530

531

532

533

534

535

536

537

538

539



540

541 Fig.2

542

543

544

545 mm

546

547

548

549

550

551

552

553

554

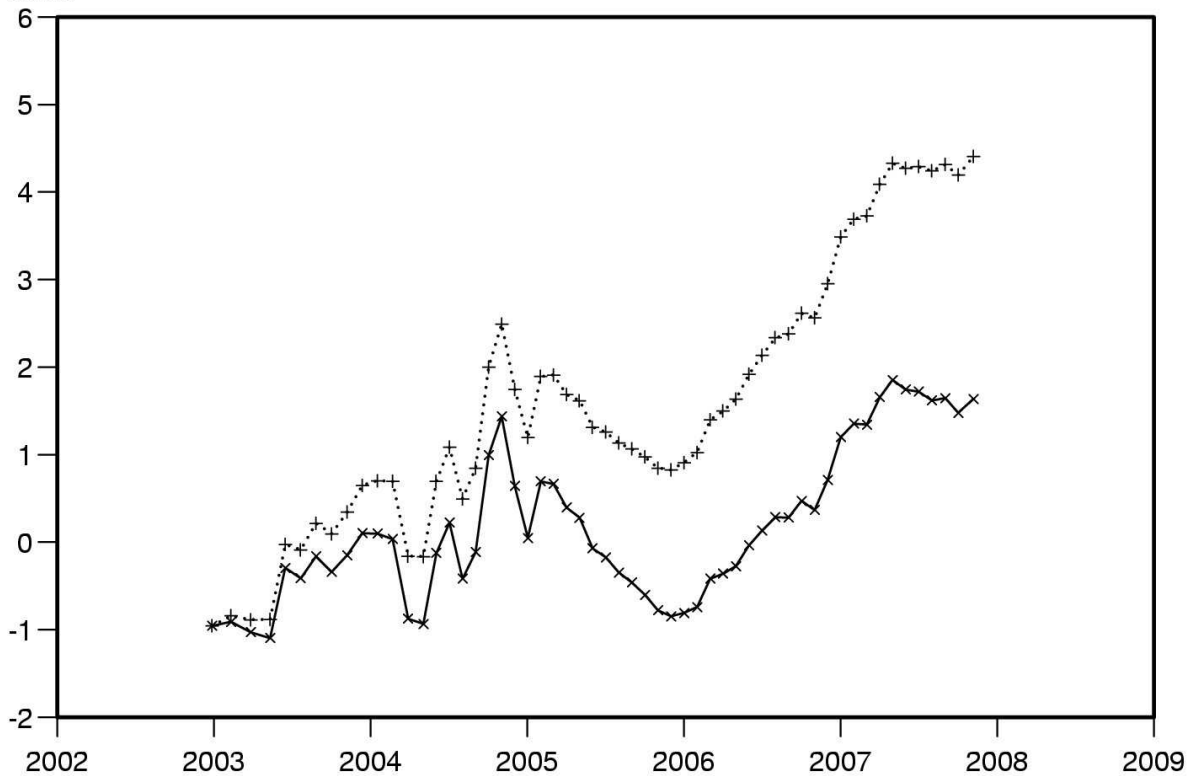
555

556

557

558

559



559 Fig.3a

560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596

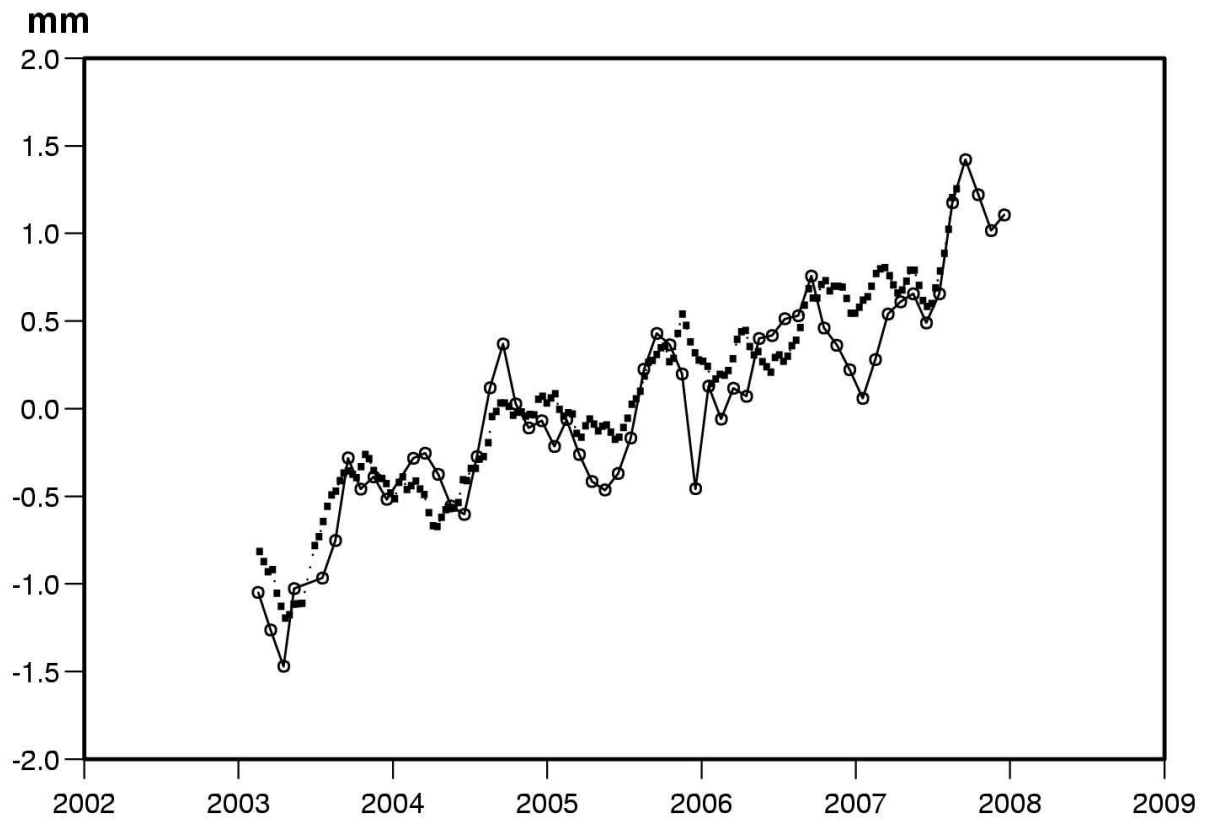
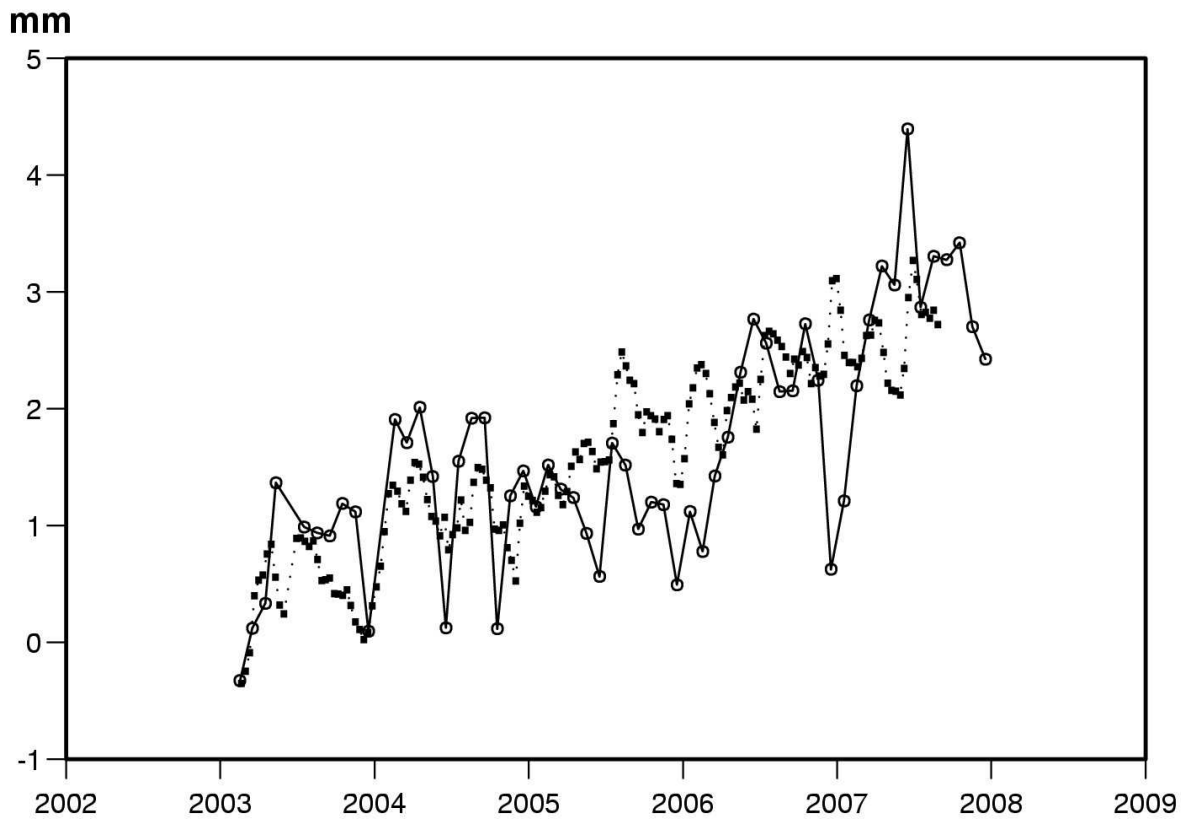


Fig.3b



597 Fig.4

598

599

600

601

602

603

604

605

606

607

608

609

610

611

612

613

614

615

616 Fig.5

617

