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Interactive comment on "Uncertainty in Satellite estimate of Global Mean Sea Level changes, trend and acceleration" *by* Michaël Ablain et al.

Anonymous Referee #2

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General comments

In this paper the uncertainty in the satellite estimate of Global Mean Sea Level changes, particularly referring to the trend and the acceleration has been evaluated. I have read it with attention, finding that its quality is quite good, in my opinion. The English form is generally good but at some sections it needs to be further improved. Moreover, the research group appears to be qualified in the field of satellite oceanography. Nonetheless this, a moderate revision is still necessary for a further improvement of the paper's quality (see specific comments). The topic of Global Mean Sea Level and its relationships with climate changes has been deeply studied in marine geophysics and satellite oceanography (Ablain et al., 2015; 2017; Abraham et al., 2013; Allan et al., 2014; Aucan et al., 2017; Baki Iz et al., 2018; Beckley et al., 2010; 2017; Boening et al., 2012; Cazenave et al., 2014; Chambers et al., 2010; Chen et al., 2017a; 2017b; Church and White, 2006; 2011; Church et al., 2013; Clark and Primus, 1987; Conrad and Hager, 1997; Curry, 2018; Dahlen, 1976; Dangendorf et al., 2017; Davis and Mitrovica, 1996; Desai et al., 2015; Desbruyeres et al., 2016; Dieng et al., 2017; Esselborn et al., 2018; Farrell and Clark, 1976; Fasullo et al., 2013; 2016; Frederikse et al., 2017a; 2017b; 2018; Gardner et al., 2013; Gornitz et al., 2019; Gregory et al., 2013; Haigh et al., 2014; Hamlington and Thompson, 2015; Hamlington et al., 2013; 2016; 2017; Handoko and Hariyadi, 2018; Hay et al., 2015; Herring et al., 2019; Kay et al., 2014; Kendall et al., 2005; Kidwell et al., 2017; Lickley et al., 2018; Melachroinos et al., 2013; Merrifield et al., 2009; Milne and Mitrovica, 1996; Mitchum, 2000; Mitrovica and Milne, 2003; Mitrovica et al., 2001; Nerem and Fasullo, 2018; Nerem et al., 1999; 2010; 2018; Prandi et al., 2009; Ray et al., 2013; Shepherd et al., 2018; Slangen et al., 2016; 2017; Swart et al., 2015; Spada, 2017; Spada and Galassi, 2016; Tamisiea, 2011; Thompson et al., 2016; Trenberth et al., 2016; Vaughan et al., 2013; Wahr et al., 2015; Wang et al., 2017; Watkins et al., 2015; Watson et al., 2015; Wiese et al., 2016; Wouters et al., 2013). Due to the exceptional abundance of recent scientific literature addressing this research topic, I suggest perhaps to the authors to expand the discussion of their results, taking into account some of the scientific papers listed in the attached references, which have not considered in detail. This could be a general issue to be addressed in the revision of the manuscript. Moreover, the relationships among the sea level changes and the subsidence of the basin, both to a regional and to a local scale have not been analyzed. I suggest perhaps to add in the discussion a short paragraph (half one page) clarifying which are the relationships existing between the oceanographic aspects and the geological processes controlling the sea level fluctuations. This discussion will represent a main added value further improving the quality of the paper. In particular, I think that the relationships between the water column and the height of the sea bottom, as controlled by subsidence, both isostatic and tectonic, need to be clarified. I suggest to the authors to carefully avoid the English grammar repetition and to avoid to be redundant, as it happens in some sections of this manuscript.

Specific comments I suggest to eliminate the quotations of references in the abstract of the paper. Usually, the abstract does not include any quotation. I suggest to put the quotation of references in the paper in a chronological order, not alphabetical one, if not strictly required from the journal. The discussed needs to be expanded taking into account recent literature and geological aspects, as mentioned in the general comments. The conclusions need to be consequently expanded. The captions to figures need to be carefully revised and corrected. Abstract Row 17 . . ...anthropogenic activity, or estimating the Earth's energy imbalance. Previous authors have estimated the uncertainty. . .. and have shown that it amounts to. . ... Row 19 In this study, we extend our previous results providing a comprehensive description of the uncertainties in the satellite GMS record. We analyzed . . ... and estimated. . ..ten days. Row 22 Three types of errors have been modeled (drifts, biases, noises) and combined together to derive a realistic estimate of the GMSL error variance-covariance matrix. Rows 23-24 We derived a 90% confidence envelop of the GMSL record on a 10-day basis from the error variance-covariance matrix. Row 25 Then we used a least squared approach . . .. Row 27 Over 1993-2017 we have found a GMSL trend. . . Rows 29-30 I suggest to eliminate this sentence. Moreover, in the abstract there is the repetition of the term "estimating". Try to avoid it.

1. Introduction Rows 32-33 The sea level change is a key indicator of global climate change, which integrates changes in several components of the climatic system as a response to climatic variability, both anthropogenic and natural. Rows 39-41 Six research groups (AVISO/CNES, SL_cci/ESA, University of Colorado, CSIRO, NASA/GSFC, NOOA) have processed the sea level raw data provided by satellite altimetry to estimate the GSML series on a 10-day basis (Figure 1) Rows 41-45 There is a repetition of the terms difference and different. Try to re-write this paragraph avoiding the repetition. Row 45 different interpolation methods applied by several groups (Masters et al., 2012; Henry et al., 2014). Rows 45-49 This spread is smaller than the real uncertainty in the sea level trend, because all the research groups have used similar methods and corrections to process the raw data and thus several sources of

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systematic uncertainty are not accounted for in the spread. Rows 50-54 In a previous study Ablain et al. (2009) have proposed a realistic estimate of the uncertainty in the GMSL trend over 1993-2008, using an approach based on the error budget. They have identified the radiometer wet tropospheric correction as one of the main sources of error. They have also proposed the orbital determination. . .. . . Row 54 When all the terms were accounted for, they have found . . ... Rows 56-58 In the framework of the ESA Sea Level Climate Change Initiative (SL_cci), significant improvements have been obtained estimating the sea level from space (Ablain et al., 2015; Quartly et al., 2017; Legeais et al., 2018) to get closer to the GCOS requirements. Rows 61-64 During the second altimetry decade (2002-2014) Ablain et al. (2015) have estimated that the uncertainty of the GMSL trend was lower than. . .. . . Rows 65-67 In previous studies the uncertainty in GMSL has been estimated for long-term trends (periods of 10 years or more, starting in 1993), for inter-annual time scales (between 1 and 5 years) and annual time scales (Ablain et al., 2009; 2015). Rows 67-74 This estimation of the uncertainty at three time-scales is a valuable first step, but it is not enough, as it does not fully meet the needs of the scientific community. In many climatic studies the GMSL uncertainty is required at different time scale and span within the 25-year altimetry record. In sea level budget studies based on the evolution of GMSL components, these estimates have been carried out at monthly time scale. In this way, the GMSL monthly changes have been interpreted in terms of changes of oceanic masses (GRACE mission). Rows 74-80 This is also the case of studies estimating the Earth's energy imbalance with the sea-level budget approach (Meyssignac et al., 2018). In the studies on the detection and the attribution of climate change (Slangen et al., 2017), the uncertainty in the trend estimates is needed, but over different time spans that that ones addressed by Ablain et al. (2009; 2015) and by Legeais et al. (2018). The uncertainty on different metrics is often needed. Dieng et al. (2017) and Nerem et al. (2018) have recently estimated the acceleration in the GMSL over 1993-1997, finding a small acceleration (0.08 mm/yr2) over the 25 year long altimetry record. Rows 79-80 I suggest to eliminate this sentence, it is quite redundant. Rows 81-87 In this paper we focus on the uncertainty in the GMSL record arising from instrumental errors in the satellite altimetry. The uncertainties of the measurements have been quantified in the GMSL record. This is an important information for the studies in the detection and attribution of the climatic changes, estimating the rise of global mean sea level as a response to the anthropogenic activity. In the detection-attribution studies the response of the GMSL to the anthropogenic activity needs to be separated from that one to climatic variability, representing an additional source of uncertainty. Rows 87-89 I suggest to eliminate these two sentences. They are quite redundant. Rows 98-101 We used an error budget approach to a global scale on a 10 day basis in order to estimate the error variance-covariance matrix. We considered all the major sources of uncertainty in the altimetry measurements, including the wet tropospheric correction, the orbital solutions and the inter-calibration of satellites. We have also taken into account the time correlation between the different sources of uncertainty (section 2). The errors have been separately characterized for each altimetry mission, since they have been affected by different sources of errors (section 2). Rows 105-106 I suggest to eliminate this sentence, it is also very redundant.

1. GMSL data series Rows 110-117 Each group processes the 1-Hz data with geophysical corrections to correct the altimetry measurement for various aliasing, biases and drifts, caused by different atmospheric conditions, sea states, ocean tides and other causes (Ablain et al., 2009). They spatially average the data over each 10-day orbital cycle to provide GMSL estimates on a 10-day basis. The differences among the GMSL estimates from several groups arise from data editing, from difference in the geophysical corrections and from differences in the used method to spatially average the individual measurements during the orbital cycles (Masters et al., 2012; Henry et al., 2014). Rows 117-121 Recently, the comparisons of the GMSL time series derived from satellite altimetry with independent estimates are based on the tide gauge records (Valledeau et al., 2012; Watson et al., 2015) or on the combination of the contribution to the sea level from thermal expansion, land ice melt and land-water storage (Dieng et al., 2017). They have shown that there was a drift in the GMSL record over the

period 1993-1998. This drift is caused by an erroneous onboard calibration correction on TOPEX altimeter side-A (noted TOPEX-A).

2. Altimetry GMSL error budget Rows 138-140 This section describes the different errors that affect the altimetry GMSL record. It builds on the GMSL error budget presented in Ablain et al. (2009) and extends this work taking into account the new altimeter missions (Jason-2, Jason-3) and the recent findings on altimetry error estimates. Row 144 . . ... and by the correlation time-scale (λ). Row 147 Add a point at the end of the sentence. Row 149 The biases can arise .. Row 159 The drifts may occur in the GMSL record. . .. Rows 163-170 This drift has been corrected by using several empirical approaches (Ablain, 2017; Beckley et al., 2017; Dieng et al., 2017), that are all affected by a significant uncertainty. We estimated this uncertainty to be. . ... with a comparison between an independent GMSL estimate based on tide gauge records (Ablain, 2017). For the TOPEX-B record, no GMSL drift has been reported, but Ablain et al. (2012) showed significant sigma-0 instabilities in the order of 0.1 dB, which generate through the sea-state bias correction an uncertainty. . ...(February 1999 – April 2002). Concerning the ITRF realization Couhert et al. (2015) have shown that. . .. . .. Rows 176-183 The residual time correlated errors are separated into two different groups, depending on their correlation time scales. The first group gathers errors with short correlation time scales, i.e. lower than two months and between two months and one year. The second group gathers errors with long correlation time scales between 5 and 10 years. In the first group the errors are mainly due to the geophysical corrections (ocean tides, atmospheric corrections), to the altimeter corrections (sea-state bias correction, altimeter ionospheric corrections), to the orbital calculation and to the potential altimeter instabilities (altimeter range and sigma-0 instabilities). At time scales below one year, the variability of the corrections' time series is dominated by errors, such that the variance of the error in each . . ... Rows 184-186 For errors with correlation time scales lower than 2 months, we estimated the standard deviation (σ) of the error from the correction's time series filtered with a 2-month high-pass filter. Since the standard deviation of the errors depends on the different altimeter missions, the standard de-

viation has been separately estimated for each altimeter mission. Rows 196-204 In the second group of residual time correlated errors, the errors are due to the onboard microwave radiometer calibration, yielding instabilities in the wet troposphere correction and also to the orbital calculation (Couhert et al., 2015). Since these errors are correlated at a time scale longer than 5 years, they can not be estimated with the standard deviation of the correction time series, too short (25-year long) to sample the time correlation. For this group of residual-time-correlated errors we used simple models to represent the time correlation of the errors. For the wet troposphere correction, several studies (Legeais et al., 2014; Thao et al., 2014; Fernandes et al., 2015) have identified long-term differences among the computed corrections from the different microwave radiometers and from different atmospheric re-analyses (Dee et al., 2011).

3. The GMSL error variance-covariance matrix Rows 221-222 In this section we derived the error variance-covariance matrix $(\sum)oftheGMSLfromtheerrorbudgetdescribedinthesection2.WeassumedthatalltheerrorsourcesshowninTable1areindepe$

...

Row 231 alongtime Row 234 ....but not in the mean time GMSL Row 236 This is the reason because Row 238 For the drifts .....takes the shape

4. GMSL uncertainty envelope Row 258 We estimated......... Rows 270-275 In Figure 4 we superimposed the GMSL time series (average of the GMSL time series in Figure 1) and the associated uncertainty envelop. For the TOPEX-A period we tested three different curves with three different corrections based on the removal of the Cal-1 mode (Beckley et al., 2017), on the comparison with tide gauges (Watson et al., 2015; Ablain, 2017) or based on a sea level closure budget approach (Dieng et al., 2017). The uncertainty envelop is centered on the record corrected for TOPEX-A drift with the correction based on Ablain et al. (2017). As it has been expected, all the empirically corrected GMSL records are within the uncertainty envelop.

5. Uncertainty in GMSL trend and acceleration Rows 279-281 The variance-covariance

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matrix can be used to derive the uncertainty on any metric based on the GMSL time series. In this section we used the error variance-covariance matrix to estimate the uncertainty on the GMSL trend and acceleration over any period of 5 years and more within 1993-2017. Rows 282-287 Recently, several studies (Watson et al., 2015; Dieng et al., 2017; Nerem et al., 2018; WCRP Global Sea Level Budget Group, 2018) have found a significant acceleration in the GMSL record from satellite altimetry (after correction for the TOPEX-A drift). The occurrence of an acceleration in the record should not change the estimation of the trend when calculated with a least squared approach. However, it can affect the estimation of the uncertainty on the trend. To cope with this issue, we address here at the same time both the estimation of the trend and acceleration in the GMSL record. In order to obtain this objective we used a second order polynomial as a predictor. Rows 300-304 The most common method to estimate the GMSL trend and acceleration is the Ordinary Least Squares (OLS) estimator in its classical form (Cazenave and Llovel, 2010; Masters et al., 2012; Dieng et al., 2015; Nerem et al., 2018). This is also the most common method to estimate trends and acceleration in other climate essential variables (Hartmann et al., 2014 and references therein). Rows 311-314 To address this issue, we used a more general formalism to integrate the GMSL error in the trend uncertainty estimation, following Ablain et al. (2009), Ribes et al. (2016) and IPCC AR5 (Hartmann et al., 2014; see in particular Box 2.2 and Supplementary Material). Row 327 Eliminate the space Rows 341-344 and Rows 344-346 Check the English form Rows 354-355 The periods for which the acceleration in sea level is significant at the 90% confidence level are shown in Fig. 8. Rows 362-363 It is unclear which is the relationship between the acceleration of Global Mean Sea Level and the volcanic eruptions (Mount Pinatubo). Rows 364-371 The period for which the trend in sea level is significant at the 90% confidence level is shown in Fig. 9. In periods when the acceleration is not significant, the second order polynomial that we used as a predictor to estimate the trend and the acceleration does not hold anymore in principle. For these periods we should turn out a first order polynomial. The use of a first order polynomial does not affect the trend estimates, but only the trend uncertainty estimates. We checked for differences in the trend uncertainty when using either second order or first order polynomial predictors. We found that these differences are negligible (not shown). Fig. 9 indicates that for periods of 5 years and longer, the trend in GMSL is always significant at 90% CL over the whole record. At the end of the record the trend tends to increase. This is consistent with the acceleration plot in Figure 6. 6. Conclusions Row 379 . . .. . .measurement also increases and the description of the errors improves. Rows 383-385 The uncertainty of the GMSL here computed shows the reliability of altimetry measurements in order to accurately describe the evolution of the GMSL on all time scales from 10 days to 25 years. It also shows the reliability of altimetry measurements in order to estimate the trends and the accelerations of the sea level. Row 387 . . ..we estimated. . .. . . Rows 391-394 In this study several assumptions have been made, that could be improved in the future. Firstly, the modeling of altimeter errors should be regularly revisited and improved to take into account a better knowledge of errors. . .. . Concealing the mathematical formalism, the OLS method. . .. .

CAPTIONS TO FIGURES (from January 1993 to December 2017). I suggest to correct in all the captions. Figure 1: Evolution of the GMSL series (corrected for TOPEX-A drift by using Ablain et al., 2009 TOPEX-A correction) from six different groups (AVISO/CNES, CSIRO, University of Colorado, SL_cci/ESA, NASA/GSFC, NOOA). The SL_cci/ESA covers a period from January 1993 to December 2016, while all the other products cover the full 25-year period (from January 1993 to December 2018). Seasonal (annual and semi-annual) signals have been removed and a 6-month smoothing has been applied. An averaged solution has been computed from the six groups. GMSL time series have the same average on the 1993-2015 period (common period) and the averaged solution starts at zero in 1993. The averaged solution without TOPEX-A correction has also been represented. A GIA correction of 0.3 mm/year has been subtracted to each dataset. Figure 2: Error variance-covariance matrix of altimeter GMSL on the 25-years period (from January 1993 to December 2017). Figure 3: Evolution in time of GMSL measurement uncertainty within a 90% confidence level

(1.65 σ) on the 25-years period (from January 1993 to December 2017). Figure 4: Evolution of the AVISO/GMSL with different TOPEX-A corrections. On the black, red and green curves, the TOPEX-A drift correction has been respectively applied based on Ablain (2017), Watson et al. (2015), Dieng et al. (2017) and Beckley et al. (2017). The uncertainty envelope, as well as the trend and acceleration uncertainties are given to a 90% confidence level (1.65 σ). Seasonal (annual and semi-annual) signals removed and 6-month smoothing have been applied. GIA correction has also been applied. Figure 5: GMSL trend uncertainties (mm/yr) estimated for all altimeter period within a 25-years period (from January 1993 to December 2017). The confidence level is 90 % (1.65 σ). Each colored pixel respectively represents the half-size of the 90 % confidence range in the GMSL trend. The values are given in mm/y. The vertical axis indicates the length of the period (ranging from 1 to 25 years) considered in the computation of the trend, while the horizontal axis indicates the center date of the period (for example 2000 for the 20-year period 1990-2009). Figure 8: GMSL acceleration using the AVISO GMSL time series corrected for the TOPEX-A drift using the correction proposed by Ablain (2017): the acceleration in the shaded areas is not significant (lower than the acceleration uncertainties at the 90% confidence level). The length of the window (in years) is represented on the vertical axis and the central date of the used window is represented on the horizontal axis.

Technical corrections Row 288 . . . no observations Row 455 SEA LEVEL BUDGET. Why capitals? Check and correct. Row 478 Marine Geodesy, 35 (suppl. 1), 20-41 Row 503 Marine Geodesy, 35 (suppl. 1), 42-60.

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