Correspondence

Chinese Science Bulletin

Reply to: Parker A. Comment on "Low-frequency sea level variation and its correlation with climate events in the Pacific"

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First, we would like to thank Parker for his discussion and comments on our work. Parker's main concern [1] is that the sea level is oscillating with important multi-decadal periodicities but absolutely not positively accelerating. He also argued that the global mean sea level (GMSL) acceleration computed by Jin et al. [2] seemed too large. His similar concern had also appeared in the comment of local sea level rise on Long Island, New York [3]. The most important difference between these two commented papers is that the former computes the sea level acceleration globally, while the latter locally. Parker quoted both, individual tide gauges and the time series of GMSL by satellite radar altimeter from the University of Colorado CU Sea Level Research Group.

Individual tide-gauge records with enough length and quality can be used to compute the local sea level accelerating trend. However, the length should be longer than 60 years [4] to avoid large oscillations due to long-term tidal effects, which has also been confirmed by Parker himself [5]. As we known, individual tide-gauge records only represent the mean sea level variation within localized area. Parker presented the sea level records of several tide gauges in his Figure 1. The length of sea level time series are all longer than 100 years, and the 2nd order coefficients computed from the time series have both positive and negative values. The results show the largest positive acceleration in San Francisco, CA of +0.007 mm/a^2, and the largest negative acceleration in Honolulu, HI of −0.006 mm/a^2. These phenomena demonstrate that the local sea levels are accelerating or decelerating in different sea areas. Nevertheless, the GMSL accelerating trend is still unknown from his Figure 1. Either by tide gauges, or by satellite radar altimetry, many researches have achieved the conclusion that regional mean sea level trends are geographically dependent. Wood-

worth et al. [6] had pointed out that most of the tide-gauge data from Europe and North America display evidence for a positive acceleration, but the magnitude of the acceleration varies between stations. There are also a few of stations which display negative accelerations. From the most recent results published by AVISO (http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/) and that shown in Figure 1, we can see large difference, especially between eastern and western parts of the Pacific Ocean. Another fact is that the magnitude of the acceleration/deceleration depends on the time period of observations.

For comparison, we select the tide gauges whose periods are longer then 60 years from the Revised Local Reference (RLR) dataset provided by PSMSL (http://www.psmsl.org/data/obtaining/) [7], and remove the tide gauges whose spare time is greater then 30% to ensure the stability. Then considering the seasonal signals, the sea level records on each selected tide gauge are fitted by the following linear regression model:

$$y = a + bt + ct^2 + d\cos(2\pi t) + e\sin(2\pi t) + f\cos(4\pi t) + g\sin(4\pi t), \tag{1}$$

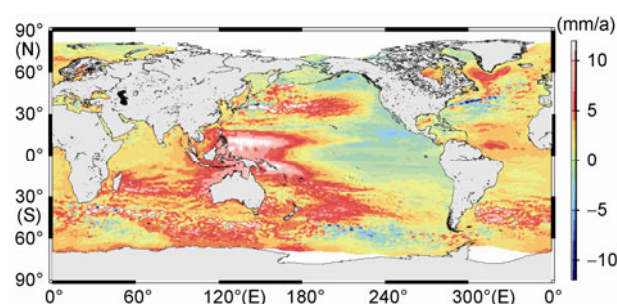where y is the sea level record, t is the observed time, a is

Figure 1   Regional mean sea level trends from Oct 1992 to Apr 2012.

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the residual bias, *b* is the rate of sea level change, *c* is the accelerating rate of sea level change, *d*, *e* are the annual cycle parameters of sea level change, *f*, *g* are the semi-annual cycle parameters of sea level change.

The number of the selected tide gauges is 226, among which, there are 84 stations having negative accelerating rates (Figure 2(a)) and 142 stations having positive accelerating rates (Figure 2(b)). If we simply average the accelerating rates on all stations, the global mean accelerating rate is 0.005 mm/a^2. Since the distribution of the tide gauges with period longer than 60 years is very sparse in global ocean, to obtain the trend of GMSL by tide gauges, one should firstly divide all valid tide gauges into several geographic groups, and then average the sea level trends from tide gauges in each group, and finally, average the group mean trends globally [4]. So, we apply the weighted average by the fitting error of each station in each 10°×10° cell firstly, and then the global mean accelerating rate is achieved to be 0.012 mm/a^2 by averaging the values of all cells in globe. Also from the pure tide gauge data, Jevrejeva et al. [8] provided evidence that global sea level acceleration up to the present was about 0.010 mm/a^2 and appeared to have started at the end of the 18th century; Woodworth et al. [9] pointed out that an acceleration was indeed observed in both tide gauge and saltmarsh data at different locations around the world, yielding quadratic coefficients of order 0.005 mm/a^2, with the most rapid changes rate of the sea level rise occurring around the end of the 19th century. All these results are consistent with our result within the error range [2].

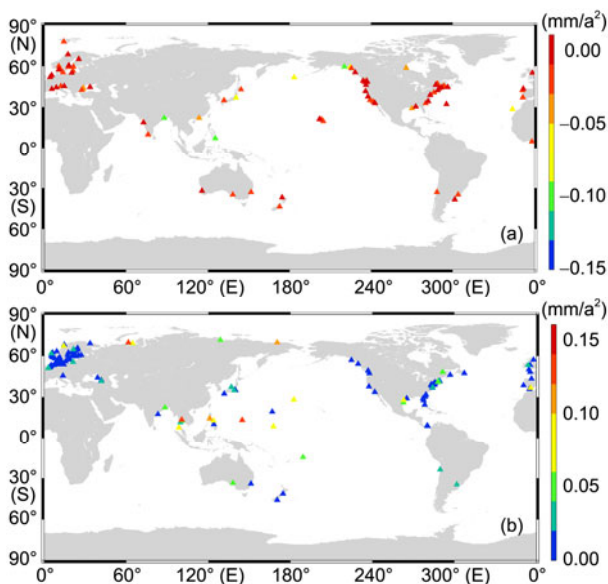Even if the tide-gauge data are averaged in global scale for a particular month to obtain the GMSL time series, the result shows a much larger seasonal variations than that observed by satellite altimetry during the same interval. If the seasonal signal is removed from tide-gauge data, the obtained GMSL time series still does not measure the same variability as observed by satellite altimetry [10]. The time series of GMSL computed by simply average or weighted average using regional groups of tide-gauge data only represent coastal and island sea level change, but not the open ocean sea level change. Another approach to determine the time series of GMSL is to combine the globally distributed satellite altimeter data together with the coastal and island tide-gauge data. This approach was first developed by Chambers et al. [10] for inter-annual sea level variability and extended by Church et al. [11] to examine sea level trends. Many researchers reconstructed the historical time series of GMSL change using this approach, but with various sets of EOFs [12–15]. All of them confirmed the possibility and stability of this approach through comparisons between the reconstructed GMSL trend and the results from tide gauge or satellite altimetry individually, but few of them discussed the accelerations. Among these researchers, Church and White [16,17] updated their reconstructions to estimate the GMSL trend in the period of 1880 to the present, and the significant accelerations of 0.013±0.006 mm/a^2 and 0.009±0.004 mm/a^2 during the 20th century were detected respectively, which are also consistent with our result within the error range [2].

Another dataset used in the comment is the GMSL time series by satellite altimeter data from 1993 to the present. Using the GMSL time series, Parker computed the 2nd order coefficients of –0.006 mm/a^2 to show a negative acceleration. However, Niedzielski and Kosek [18] pointed out that over the GMSL time series from T/P, Jason-1 and Jason-2 altimeter observations of the period from January 1993 to April 2010, it was impossible to detect any acceleration in sea level rise with probability close to 1. Expect for only two exceptions, when the time spans are approximately 400 and 500 satellite cycles, acceleration can be detected with at least 0.4 probability. That is to say, using short period of time series, the accelerating trend of GMSL is hard to detect.

Due to the lack of globally distributed sea level data with enough length and quality, it is now still controversial whether the GMSL is accelerating or not. This is also the reason why so many researches seek for the combination of tide gauge and satellite altimeter data. But, some problems in the reconstruction still need to be solved and the uncertainty is still large. For instance, the lower spatial resolution of grid sea level change by satellite altimetry data, the datum inconsistency of tide gauges, the sparseness of tide gauges in early years, and so on. All of these problems should be carefully considered to obtain precise and stable GMSL time series with enough length to detect the accelerating trend in future.

Figure 2   Distribution and sea level accelerating rates of tide gauges with period longer than 60 years. (a) The 84 tide gauges that have negative accelerating rate; (b) 142 tide gauges that have positive accelerating rate.

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