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COMMENTARIES

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Commentary on 'Coastal Planning Should Be Based on Proven Sea Level Data' by A. Parker and C.D. Ollier (Ocean & Coastal Management, 124, 1–9, 2016)

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ABSTRACT

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A recent paper by A. Parker and C.D. Ollier (*Ocean & Coastal Management,* 124, 1–9, 2016), concerned with the use of 'proven' sea-level data for coastal planning, contained a number of incorrect or misleading statements about sea-level data sets and measurement methods. In this commentary, we address aspects of sea-level records that could have been misunderstood by readers of that paper. While we agree with the main point made by the authors, that the best possible sea-level data are required by coastal planners, we suggest that planners should base their work on wider and better informed sources of sea-level information.

ADDITIONAL INDEX WORDS: *Sea-level changes, tide gauge records, vertical land movements, satellite altimetry*.

INTRODUCTION

We refer to a recent paper by Parker and Ollier published in *Ocean & Coastal Management* (Parker and Ollier, 2016, hereafter PO16), which includes a number of incorrect or misleading statements about sea-level data sets and measurement methods. The paper is difficult to read in places, so we cannot comment on all of the authors' remarks. Instead, we focus on a number of their main statements that we believe are incorrect. As a result, we hope that coastal planners, who were the target audience for PO16, will have a better appreciation of several features of sea-level records.

COMMENTARY

Average Sea-Level Trends Obtained Using Records of Different Lengths

The PO16 paper is concerned with the measurement of the rates of change of sea level, primarily using historical tide gauge records from the Permanent Service for Mean Sea Level (PSMSL, 2016) data set (Holgate *et al*., 2013). Tide gauges measure relative sea level, *i.e*. the level of the sea relative to the height of benchmarks on the nearby land. Therefore, their records can contain contributions from changes in land level, as well as from changes in the level of the sea itself.

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In the abstract and Section 6 of PO16, it is stated that the average sea-level trend for 570 tide gauge records 'of any length' (which we have concluded means records of approximately 30 years or more) is 1.04 mm/y, whereas if 100 records with at least 80 years of data are used, then one obtains an average trend of 0.25 mm/y. Unless we misunderstand, the inference by the authors is that longer and more reliable records result in lower trends and that there is thereby an implication of little historical sea-level rise.

It is seen later that we agree with these two values of average trend but find the interpretation is incorrect. These different average values are quite consistent if one bears in mind the spatial–temporal composition of the PSMSL data set, which has been discussed by many authors (*e.g*., Woodworth, 1991; Church *et al*., 2004; Holgate *et al*., 2013; Pugh and Woodworth, 2014; Shennan, Long, and Horton, 2015). Such a composition is quite evident from a consultation of the PSMSL web site (PSMSL, 2016). The PSMSL has its origins in a decision made in 1933 to collect sea-level data for studies of vertical land movements (primarily glacial isostatic adjustment, GIA) in Europe, rather than for the climate studies in which it is usually employed nowadays (Rossiter, 1963). Data from Scandinavia have always formed a large part of the data set, and Scandinavia is a region with high rates of negative relative sea-level change due to GIA.

Table 1 explains the issue. At the time of writing, there were 1445 records in the revised local reference (RLR) data set of the PSMSL (the data set used by PO16). The number of stations we

Table 1. *Overview of PSMSL data.*

A	B	C	D	E	F	G	H	I	J
>160	3	1.30	3	1.30	−0.08	2	2.20	1.54	0.66
>140	14	1.59	14	1.59	0.21	13	2.22	1.65	0.57
>130	16	1.66	16	1.66	0.05	15	2.11	1.72	0.39
>120	21	0.72	21	0.72	−0.67	20	1.35	0.71	0.64
>100	54	0.58	53	0.57	−0.88	48	1.82	0.71	1.11
>80	104	0.24	103	0.23	−1.27	88	1.45	0.37	1.08
>60	181	0.42	179	0.42	−0.99	148	1.75	0.74	1.02
>40	432	1.01	429	1.01	−0.69	320	2.06	1.03	1.03
>30	589	1.08	586	1.08	−0.63	406	2.16	1.18	0.98

A = required number of years of data in PSMSL station records (up to 2014), B = number of station records in the PSMSL data set given that requirement, C = average of the observed sea-level trends (trends computed over their entire record lengths) of the records in B, D = number of stations in B with GIA values available from the Peltier (2004) model, E = average of the observed sea-level trends (computed over their entire record lengths) of the records in D, F = average GIA model trend for the stations in D, G = number of the station records in B that have at least 15 years of data from 1993 and on, H = average of the observed sea-level trends (computed for 1993 and on only) of the records in G, I = average of the observed sea-level trends (computed over their entire record lengths) of the records in G, J = recent change in the average sea-level trend (H–I).

quote in Tables 1 and 2 are slightly larger than those quoted by PO16 because a more recent version of the data set is used; this has no effect on our findings. If one requires a record to contain more than, say, 30 or 80 years of data, then one obtains 589 or 104 records, respectively, as shown (Table 1, column B). Their average trend is 1.08 or 0.24 mm/y (column C), respectively, measured over their entire record length, which is essentially the same as reported by PO16. However, the 80-year value in particular is much lower than it would have been otherwise because many of these sites with long records are in regions with a high negative rate of relative sea-level change due to GIA. Column D shows the number of stations in column B for which we have an estimate of relative sea-level change from a modern geodynamic model of GIA; estimates are available for almost all stations, as shown by the number of stations in columns B and D being almost the same, as are the averages of the observed sea-level trends in columns C and E. Column F shows the average of the GIA model trends for relative sea-level change for the same stations as in column D. It demonstrates that the lower average rate of observed relative sea-level change for record lengths of approximately 60 to 120 years, as shown in column E, is due to GIA. That many sites with these record lengths are in a region where GIA is important, namely, Scandinavia, is no surprise, as demonstrated by the maps of Figure 1. By contrast, the stations with the longest records (>130 years) are located primarily along the Atlantic coastline of NW Europe, far from the formerly glaciated regions, and they do not experience high negative rates of relative sea-level change due to the GIA process.

The same conclusion is drawn by selecting records in terms of their minimum time span instead of minimum number of years of available data, there being potential differences between the two selections because of data gaps. Figure 2 shows that average tide gauge trends, plotted in terms of the minimum time span of selected records, compares well to averaged GIA rates at the same locations. This again emphasises the importance of taking vertical land movements into account

Table 2. *Overview of data for average rate of sea-level change.*

	K	L	M	N	O
1992	113	−0.06	111	−0.08	−1.36
2014	181	0.42	179	0.42	−0.99

K = number of station records with more than 60 years of data up to either 1992 or 2014, L = average of the observed sea-level trends of the records in K up to either 1992 or 2014, M = number of stations in K with GIA values available from the Peltier (2004) model, N = average of the observed sea-level trends of the records in M up to either 1992 or 2014, O = average GIA model trend for the stations in M.

when studying sea-level information from a spatially and temporally changing distribution of stations. GIA is not the only geological process that can lead to vertical land movement, but it is the main one (considered globally) and is the only process for which suitable geodynamic models exist.

The GIA estimates of relative sea-level change used here are taken from the ICE-5G (VM2) model described in Peltier (2004), made available to the PSMSL by Prof. W.R. Peltier (Toronto University) and obtainable from the PSMSL web site (PSMSL, 2016). When one adjusts for GIA at most stations, with records of reasonable length, then rates on the order of 1 to 2 mm/y are obtained, as has been shown by a large number of authors over the years (*e.g.*, Douglas, 2001). We do not dwell here on the preferred global-average 20th-century values of trend after adjustment for GIA but leave that to study groups such as the Intergovernmental Panel on Climate Change Fifth Research Assessment (IPCC AR5; Church *et al.*, 2013); the general point we wish to make on the importance of GIA to the observed trends in the longer records is clear. The PO16 paper does not refer to GIA, which is surprising given that one of its authors had a distinguished career in coastal geology and geomorphology.

Average Sea-Level Trends Measured in the Periods up to 1993 or 2014

In Section 6 of PO16, there is mention of an average rate of sea-level change of 0.23 mm/y obtained from 100 records with 60 years of data before the 'satellite altimeter era' (p. 5), which we take to mean before 1993. That is compared to a rate of 0.25 mm/y from 170 stations with at least 60 years of data in their records up to 2014. The implication is that there is no recent acceleration in the rate of sea-level rise.

We do not agree with the logic for, and the result of, this comparison (if we understand their text correctly), as Table 2 explains. Column K gives the number of records selected if one requires more than 60 years of data up to either 1992 or 2014 (113 and 181, respectively). These are again approximately the same number of records as used by PO16, but unlike those authors, we find that the average rate increases from –0.06 to 0.42 mm/y between the two selections (column L), or by about 0.5 mm/y, rather than near zero. A main point of PO16 is that the differences in the two values of average trends (*i.e.* our Table 2, column L) are either zero or small, so they assert that there has been no recent acceleration of sea-level change.

There are two possible reasons for a slightly larger average trend for the second selection. One possible reason is that the additional stations included in the average by allowing extra data up to 2014 clearly introduce more recent data, so their

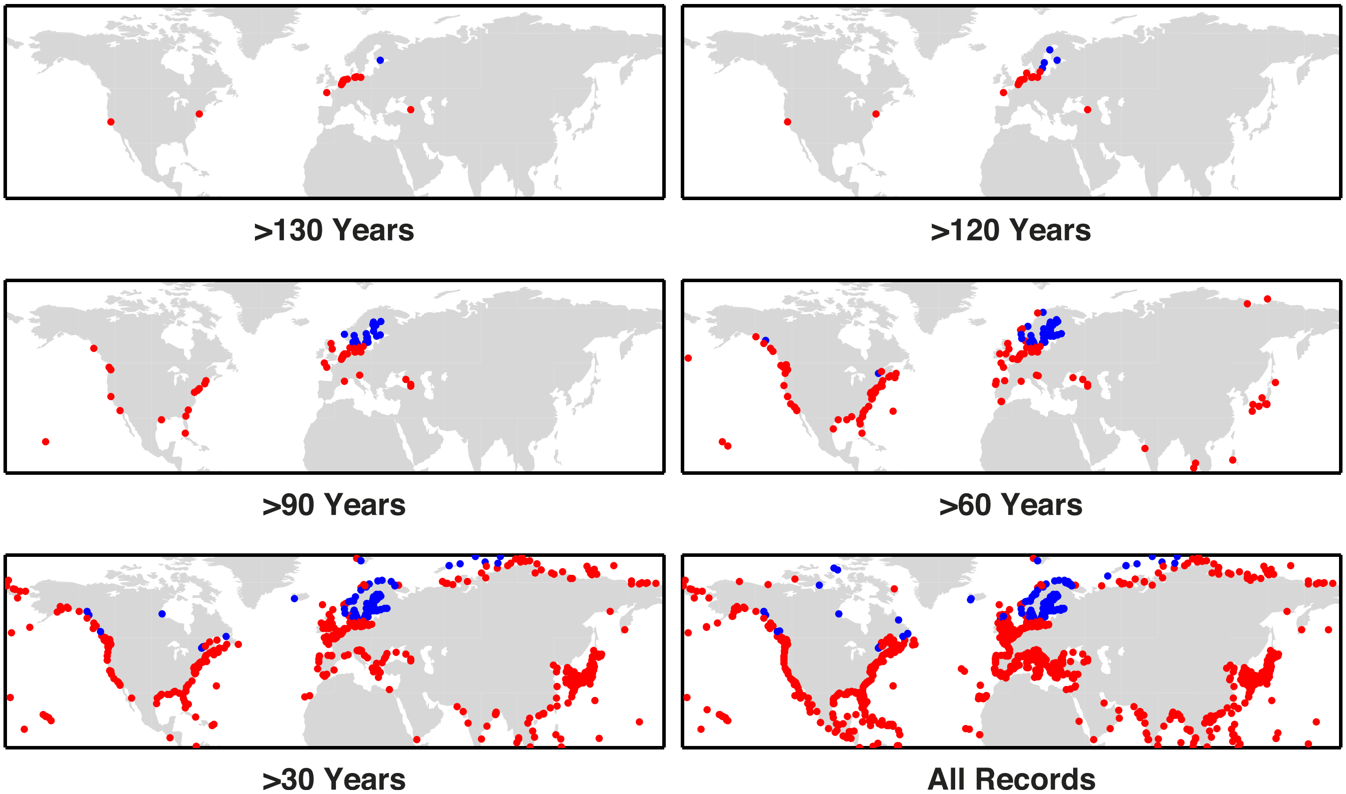

Figure 1. Spatial coverage of the PSMSL RLR data set in terms of the number of years of data in each record. Red dots are used except for stations with rates of relative sea-level change due to GIA in the Peltier (2004) model of −1 mm/y or more negative (blue dots). Only the Northern Hemisphere is shown to emphasise the contributions of NW European and Scandinavian records. There are relatively few long PSMSL records from the Southern Hemisphere; see Holgate *et al*. (2013) and PSMSL (2016) for more information. (Color for this figure is available in the online version of this paper.)

trends tend to be higher because of recent climate change (see 'Recent Changes in the Average Sea-Level Trend'). A more important reason is that the additional stations will be largely from outside Scandinavia, again resulting in a higher rate of relative sea-level change than before; columns M and N show that almost all stations in column K have available estimates of relative sea-level change due to GIA from the Peltier (2004) model, while column O shows the average GIA model rate for

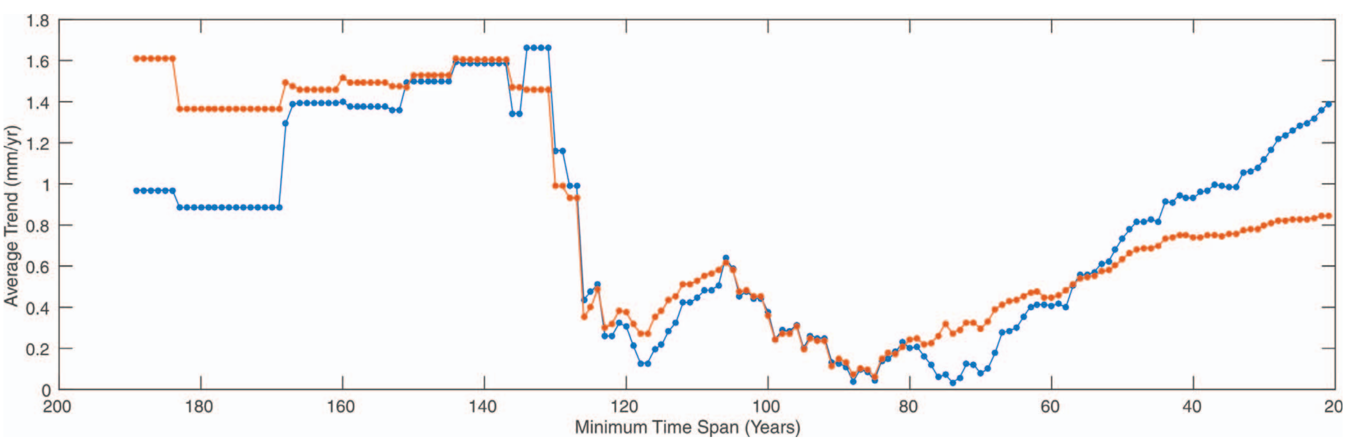

Figure 2. Average tide gauge trends (blue) for stations in the PSMSL RLR data set in terms of minimum time span of the selected records. These are compared to relative sea-level trends at the same locations due to GIA from the Peltier (2004) model (orange). An offset of 1.4 mm/y has been added to the GIA rates so that the two curves overlap in the plot. (Color for this figure is available in the online version of this paper.)

these stations. Column O demonstrates that the second selection (up to 2014) results in a more positive average trend simply because of the GIA contributions to the different sets of stations.

Comparing rates for long records (more than 60 years) up to either 1992 or 2014, with almost a factor of 2 difference in the number of stations in the two selections, is tantamount to comparing apples and oranges. When different sets of records are used, then inevitably there will be different averages in sea-level trends because of spatial variability in ocean circulation and because of spatial variability in vertical land movements arising from a number of geophysical processes, such as GIA and the solid Earth's adjustment to present-day glaciological and hydrological change (Tamisiea and Mitrovica, 2011). Even if the same records had been used, but with a different end year, the comparison would still not have been useful, because the rates are bound to be similar if the added number of years is small compared to the overall record length. The real issue with regard to a recent acceleration is whether the rates for the same stations have changed since 1993, as discussed in the next section.

Recent Changes in the Average Sea-Level Trend

Columns G to J of Table 1 are concerned with average rates of sea-level change since 1993. This is the start of the extra period of data that the authors of PO16 used in their comparison of trends mentioned earlier (*i.e.* data between 1993 and 2014). It happens to be a reasonable point at which to define a start of recent sea-level rise (*e.g.*, Holgate and Woodworth, 2004) and is the start of the era of precise satellite altimetry, which is discussed later.

Column G shows the number of PSMSL tide gauge records with at least 15 years of data since 1993 (which we consider a reasonable requirement to derive a reasonably accurate trend in this short period) for each of the selections of minimum number of years in the overall record (column B). Column H gives the average rates in the recent period, with values of about 2 mm/y for each selection (these rates are uncorrected for GIA) but again with lower values when selecting a minimum number of 60 to 120 years because of the spatial–temporal coverage of the records (Figure 1) and the important role of GIA, as explained earlier. Column I gives the average rate for their overall records, and column J lists the difference H minus I, giving a crude estimate of the recent change in the average sea-level trend. It can be seen that rates for the recent epoch are in excess of the long-term ones by roughly 1 mm/y.

This recent acceleration is consistent with that concluded by individual researchers (*e.g.*, Holgate and Woodworth, 2004) and by study groups such as the IPCC AR5 (Church *et al.*, 2013), and it contradicts the conclusions of PO16, based on the authors' earlier apples-and-oranges comparison, that 'every single tide gauge and the global the naive average [*sic*] show the sea level is stable' (p. 6).

Altimeter Data Calibration

The PO16 authors reserve much of their criticism for satellite altimeter data. In their Section 1, one reads 'In the Global Mean Sea Level (GMSL) computation [from altimeter data] the calibration of the altimeter sea level measurements is performed against a network of tide gauges (University of Colorado sea level research group, 2015). This permits the discovery and monitoring of drift in the satellite and sometimes in the tide gauge measurements. While GMSL measurements are continuously calibrated against a network of tide gauges, it is stated that the GMSL result cannot be used to predict relative sea level changes along the coasts. The purpose of this statement is to discourage comparison of the purely speculative GMSL with actual measurements along the coast' (p. 2).

The last sentence is nonsense. A more substantial point to make is that in the methods developed by Mitchum (2000) and Leuliette, Nerem, and Mitchum (2004), and employed by the University of Colorado (Professors Leuliette, Nerem, and Mitchum, *personal communication*), the 'calibration' does not amount to a hard constraint of the altimetry to the tide gauges but rather is a monitoring and consistency check.

The University of Colorado web page (University of Colorado, 2016) explains explicitly 'Changes to the altimeter can be monitored by comparing the altimeter-derived sea surface heights to sea surface heights measured at tide gauges. This technique is not used to calibrate the altimeter in any way, but it is valuable in diagnosing and correcting altimeter drift'. This issue has been misrepresented (Mörner, 2004) and explained and refuted (Nerem *et al.*, 2007) before now, and it is disappointing to see it recycled again.

The Merits of Absolute Sea Level vs. Relative Sea Level

The abstract of PO16 states that absolute sea level 'is a rather abstract computation, far from being reliable, and is preferred by activists and politicians for no scientific reason' (p. 1). This is incorrect. There are several important areas of sea-level research that require absolute, rather than relative, levels to be studied; three examples can be mentioned here. One is that altimeter data are geocentric (absolute) measurements, which must be combined with tide gauge data in a unified sea-level system with the use of global navigation satellite system (GNSS) equipment at the gauges, again so as to compare apples with apples. A second is that the determination of land movements by altimetry and GNSS and tide gauges in combination inevitably leads the scientist to work with absolute sea levels. Wöppelmann and Marcos (2016) give an excellent description of this topic. A third example is in the pursuit of worldwide height system unification, whereby all future heights will be measured in a geocentric reference frame by techniques such as GNSS and altimetry and all countries will use a unified datum, which is in effect the geoid (Woodworth *et al.*, 2012). We know of no 'activists and politicians'.

PO16 is correct that there are still inaccuracies with GNSS measurements on the order of 1 mm/y (see Figure 14 of Wöppelmann and Marcos, 2016) and improvements and investments are required to make progress on this. For example, the Global Sea Level Observing System (GLOSS) network still requires GNSS to be installed at many of its tide gauges (IOC, 2012). This topic has been discussed previously in papers in this journal (*e.g.*, Houston and Dean, 2012).

Altimeter, Tide Gauge, and GNSS Data Complementarity

The PO16 authors go on to say that 'GPS and the satellite altimetry do not help to clarify the influence climate change has on sea levels. It will be show [*sic*] that the GPS is returning a vertical velocity at the tide gauge with errors larger than the average rate of rise at the tide gauges while the GMSL is a non-reliable computation. The pattern of sea levels is already very clear from the analysis of the relative sea level measured by the tide gauges of sufficient quality and length' (p. 2). This is also incorrect. Precise altimeter measurements over the open ocean and tide gauge measurements at the coast have together demonstrated how regional ocean circulation and sea level fluctuate in response to meteorological and oceanographic forcings, which are part of the evolving climate system. In addition, altimeter rates of sea level are largely consistent with tide gauge rates at the coast (Holgate and Woodworth, 2004). Altimetry has revolutionised the study of oceanography during the past few decades (Pugh and Woodworth, 2014).

As for GNSS (*i.e.* global positioning system, GPS), it is true as mentioned earlier that rates of vertical land movement measured by this technique have uncertainties that are larger than desired at individual sites but that, as a collection, they are consistent with the other parts of the measuring system (see 'The Merits of Absolute Sea Level *vs*. Relative Sea Level'). The PO16 authors demonstrate this clearly by including maps from the web sites of the PSMSL (2016) and Système d'Observation du Niveau des Eaux Littorales (SONEL, 2016). The maps included in their Figure 2 show the complementarity between tide gauge and GNSS measurements, while Wöppelmann and Marcos (2016) discuss in detail the complementarity among all three techniques.

Section 7 of PO16 goes on to again recycle the criticisms of the altimeter record that were raised years ago and readily demolished at the time (Nerem *et al*., 2007). Conventional nadir-pointing precise altimetry is now a mature technique with a record of two and a half decades. A large community of scientists from many countries is engaged in altimetry studies, and there is a consensus concerning the interpretation of altimetric signals and in the validity of sea-level products. However, technology never stands still, and altimetry is again evolving rapidly, with new radar techniques that are enabling altimetry to become even more useful close to the coast (Vignudelli *et al*., 2011). Even if the PO16 authors were not enthusiasts of conventional altimetry, these are exciting technical developments, of great interest to coastal scientists, that one would have thought to be worthy of mentioning in their paper.

Coastal Planning for Future Sea-Level Rise

Section 9 of PO16 claims that 'computer model projections' of future sea level are 'flawed' (p. 9). This claim is based solely on a report by participants in the highly questionable 'Nongovernmental International Panel on Climate Change' (Carter *et al*., 2014) and a quotation from a paper by economist R.S. Pindyck (Pindyck, 2013a,b), which is a critique of integrated assessment models (IAMs, of which physical climate models form a part). Pindyck's criticisms relate mainly to the 'cascade of uncertainty' that occurs when many models are combined into an integrated model, rather than to the deficiencies of any single model. PO16 (p. 9) implies that 'the models' to which Pindyck refers are physical climate models, but they are not. In fact, Pindyck is referring to IAMs. In his paper, Pindyck (2013a,b) states explicitly, 'My criticism of IAMs should *not* be taken to imply that because we know so little, nothing should be done about climate change right now, and instead we should wait until we learn more. Quite the contrary. One can think of a GHG abatement policy as a form of insurance: society would be paying for a guarantee that a low-probability catastrophe will not occur (or is less likely)' (line 16, line 870). While Pindyck's main concern at the time was the mitigation of greenhouse gas emissions, these words could equally be applied to adaptation to sea-level rise. We suggest that coastal planners and policymakers would ignore sea-level projections such as those of the IPCC AR5 at their peril.

CONCLUSIONS

Overall, while we are appreciative of the importance of good sea-level data to coastal studies, and while we agree with the title of PO16 and recognise that the paper had the objective of encouraging the availability of even more good data, we cannot let that paper pass without pointing out the many errors in it. In particular, we reject the assertions in PO16 that techniques such as altimetry and GNSS have nothing to offer to coastal sea-level research. The sea-level literature is replete with examples of how different techniques (instrumental, archaeological, and geological) can complement one another; there are far too many to list here.

Finally, we wish to briefly explain why these comments were submitted to the *Journal of Coastal Research*. A version of the present commentary was submitted to *Ocean & Coastal Management* but was required by the editor to have a number of edits that we could not accept, while a lengthy reply by the authors of PO16 was to be published almost verbatim. In our opinion, PO16 was not peer-reviewed adequately; otherwise, many of our earlier points would have been addressed and corrected before publication. In addition, it should have been edited throughout for good scientific English. One of us (Hunter, 2014) had been involved in comments on a previous debatable paper by one of the authors of PO16 (Parker, Saad Saleem, and Lawson, 2013) with a similar experience of editorial standards that could, in our opinion again, be improved upon.

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