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Key Points:

- Tide-gauge comparisons suggest TOPEX altimeter data have a small (±5 mm) U-shaped 1 mm/yr drift
- Likely cause is an internal calibration-mode range correction, corrupted by a degraded point target response
- Two revised altimeter time series show global mean sea level rising around 3 mm/yr for two decades, but recently increasing

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On the "Cal-Mode" Correction to TOPEX Satellite Altimetry and Its Effect on the Global Mean Sea Level Time Series

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Abstract Comparison of satellite altimetry against a high-quality network of tide gauges suggests that sea-surface heights from the TOPEX altimeter may be biased by ±5 mm, in an approximate piecewise linear, or U-shaped, drift. This has been previously reported in at least two other studies. The bias is probably caused by use of an internal calibration-mode range correction, included in the TOPEX "net instrument" correction, which is suspect owing to changes in the altimeter's point target response. Removal of this correction appears to mitigate most of the drift problem. In addition, a new time series based on retracking the TOPEX waveforms, again without the calibration-mode correction, also reduces the drift aside for a clear problem during the first 2 years. With revision, the TOPEX measurements, combined with successor Jason altimeter measurements, show global mean sea level rising fairly steadily throughout most of 24 year time period, with rates around 3 mm/yr, although higher over the last few years.

1. Introduction

The TOPEX/Poseidon (T/P), Jason-1, Jason-2, and Jason-3 satellite altimeter missions have provided a continuous and near-global time series of sea level measurements, now extending to over 24 years. Among the myriad applications of this time series, the determination of global mean sea level with a precision necessary to monitor subcentimeter change is probably the most difficult. Many of the challenges that must be overcome are reviewed by Fu and Haines (2013) and Ablain et al. (2017). As those authors emphasize, comparison of altimeter measurements against independent measurements of local sea level at tide gauges plays a critical role in establishing the validity of the altimetric time series.

There are two main approaches to tide-gauge validation of satellite altimetry. In one, a small set of heavily instrumented stations are set up under the satellite flight path, and the altimeter and in situ sea level measurements, as well as other ancillary measurements (e.g., wet tropospheric path delay), are compared. For the T/P and Jason satellites, project teams from NASA and CNES (Bonnefond et al., 2010; Haines et al., 2010; Ménard et al., 1994), as well as international collaborators (Mertikas et al., 2010; Watson et al., 2011) maintain a set of four such stations. In the second approach, many dozens of tide gauges from the global international network are employed (Mitchum, 1998). These stations of opportunity are less well instrumented and are usually not directly in the overflight path, but they are invaluable because of the statistical power of averaging over many independent measurements.

In several cases, the tide-gauge validation systems now in place have indeed uncovered spurious drifts in the altimeter measurements. In each case, the NASA and CNES project teams have been able to locate the underlying reasons for the discrepancies and correct the problems. Several cases have involved drifts in the onboard water-vapor radiometers used to correct altimeter ranges for wet path delay, and these problems have been resolved by independent calibration of the radiometers (e.g., Brown et al., 2007; Ruf, 2002). A more unusual case occurred early in the T/P mission when a spurious drift was found to be due to an error in software used to correct altimeter ranges for oscillator drift (Nerem, 1997); see the discussion by Fu and Haines (2013).

Recently, based on their comparisons of altimetry and tide gauges, Watson et al. (2015) called attention to a possible spurious (apparently piecewise linear) drift during the first 6 years of the T/P mission. The problem was actually evident in some earlier tide-gauge comparisons (e.g., Leuliette et al., 2004; Valladeau & Ablain, 2011; Valladeau et al., 2012), but it was Watson et al. who emphasized its impact for monitoring recent changes in global mean sea level. As we show below, it seems likely that the drift is an artificial one introduced into the system as an independent correction based on an internal instrument calibration. It affects only the TOPEX altimeter onboard the T/P spacecraft.

Our discussion here is based primarily on T/P altimeter data available from the "Merged Geophysical Data Records B" (MGDR-B), as distributed by the NASA and CNES project teams (Benada, 1997). As of this writing, the MGDR-B data are still the most recent release from the project. Our few adjustments to these data, involving mostly improved geophysical corrections, are noted below.

The following two sections discuss the origin of the suspect TOPEX correction. Section 5 examines the altimeter and tide-gauge comparisons with and without the correction. We also test a newly retracked TOPEX time series, which addresses, at least in part, the likely ultimate cause of the problem. These findings allow us to assess the reliability of three varieties of the TOPEX time series. Based on the revised TOPEX altimetry, in combination with data from the successor Jason satellites, a new global mean sea level time series is presented in section 6.

2. TOPEX Calibration Mode

Like radar altimeters before (e.g., Townsend, 1980) and since (e.g., Desjonquères et al. 2010), the TOPEX instrument had an internal calibration tracking mode that was designed to detect any significant drift in the altimeter range owing to thermal or other changes in the internal hardware components of the system. TOPEX had two calibration modes for both the Ku-band and C-band radars (Marth et al., 1993). So-called "Cal-1" was designed to detect internal path delays which would directly translate into errors in range. "Cal-2" mode was designed to characterize the response of the receiver, which is useful for monitoring backscatter, but that mode does not directly concern us here. Both calibration modes were run in succession twice a day for the duration of the mission.

During the Cal-1 calibration process, transmission and reception by the radar antenna is blocked, while a part of the transmitter output is instead routed directly to the receiver by way of a digitally controlled attenuation and delay line. Since the received signal is then no longer an ocean reflection, it consists of a single "point target" component. Monitoring of this signal over time allows any changes in internal altimeter delay (as well as gain) to be detected. The subsequently estimated range drift errors for TOPEX were produced by Hayne et al. (1994a), who describe further details of the calibration procedure. Since the estimated range error is purportedly a result of a drifting path delay inside the altimeter, it is a function of time only and does not involve characteristics of the reflecting ocean surface such as significant wave height.

One serious issue with the TOPEX Cal-1 mode was the rather large quantization increments used for the telemetry; the equivalent quantization in range was 7.3 mm. (Note that this large quantization error did not occur in normal altimeter tracking.) Hayne et al. developed a smoothing technique which they thought suppressed this error to a more manageable level of about 1 mm. There was also an observed temperature dependence which they allowed for.

Hayne et al. (1994a) presented the Cal-1 mode drift estimates for the first 75 repeat cycles (i.e., the first 2 years) of the TOPEX mission. Hancock et al. (1999) and Lockwood et al. (2006) extended the time series to the end of the mission. The entire time series is available on a NASA Wallops Flight Center website (current address: topex.wff.nasa.gov), and the data are shown here in Figure 1. The drift estimates have a large U-shaped character until TOPEX was switched to its redundant Side-B altimeter at repeat cycle 236 (9 February 1999), at which point there is an offset of approximately 6 mm and the estimates are more linear with only a small trend. Just before the T/P satellite was moved into its interlaced orbit, starting at repeat cycle 364 (August 2002), the standard deviation of the individual cycle estimates grew markedly larger and the cycle means became more erratic. A good explanation for this apparent change in noise level is lacking. Lockwood et al. (2006) speculated that the cause lay with a component of the microwave transmission unit (MTU) that had nonlinear thermal characteristics in a certain temperature range. In fact, similar behavior had been observed in some prelaunch testing of the instrument, but it was not considered a critical problem since the range repeatability remained within instrument specifications. The erratic nature of the range

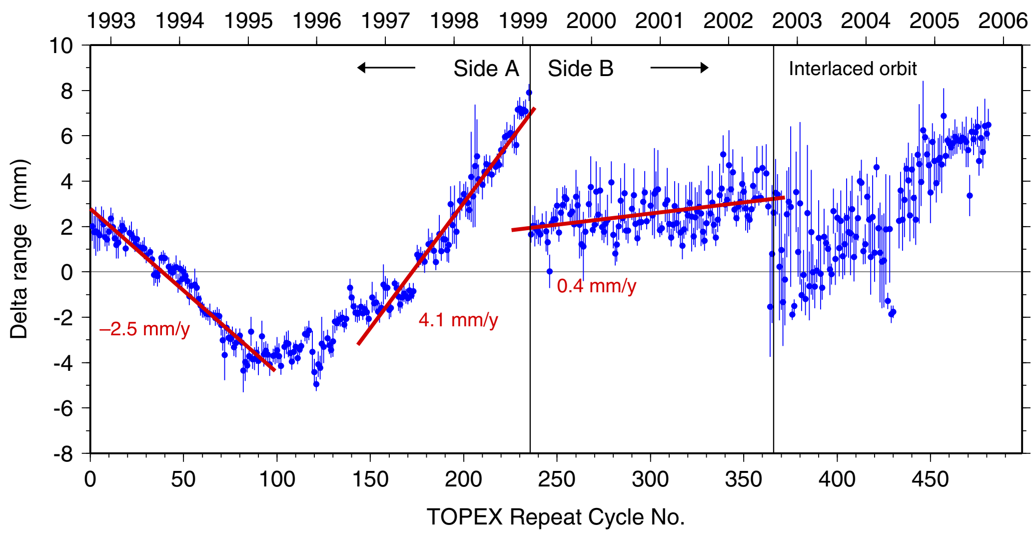

Figure 1. Combined (Ku-band and C-band) range error from the calibration-mode tracking of the TOPEX altimeter, as determined by Hayne et al. (1994a) and subsequently updated by them to cover the duration of the mission. Bottom horizontal axis marks off the 9.9156 day T/P repeat cycles. Error bars represent the standard deviation of the internal calibrations taken during each T/P repeat cycle; there were generally 20 in each cycle. Red lines mark linear fits to selected segments of the data. For the whole Side-A period (1993–1999, cycles 11–235), the fitted trend is +0.8 mm/yr.

corrections did become less pronounced after cycle 460, but the satellite remained operational for only another 20 cycles after that point.

By way of comparison to a modern altimeter, Figure 5 of Desjonquères et al. (2010) shows the calibration-mode drift estimates for the Poseidon-3 altimeter aboard the Jason-2 satellite. Over 40 cycles, the drift was negligible, about 0.5 mm. Subsequent unpublished CNES project reports also show very little drift for either Jason-1 or Jason-2.

Beginning with the TOPEX MGDR-B release (but not before), the data of Figure 1 were combined with several other corrections (these include corrections derived by Hayne et al., 1994b, as well as the oscillator drift error plus a fixed bias offset) which together formed a "net instrument correction" that was applied to the altimeter range measurement. Therefore, nearly all TOPEX users over the past two decades have likely been using the cal-mode range correction in their work.

There are at least two reasons why this range correction could be problematic, especially for the Side-A altimeter. By design, the TOPEX calibration loop bypassed the normal signal pathways as near as possible to the antenna so it was truly measuring the internal path delay in the altimeter system. There is a remote possibility that the inferred drift in path delay was actually caused by components of the calibration loop itself. Although a drift in calibration-loop hardware is conceivable, a second explanation involving changes in radar response characteristics seems more likely. In fact, Hancock et al. (1999) warned that "We have less confidence in the later (Side-A corrections) due to the (unquantifiable at this time) effect of the change in the altimeter's point target response." The following section discusses this matter.

3. TOPEX Point Target Response Changes

The receiver's response to the calibration-loop signal provides a direct measure of the altimeter's point target response (PTR). This response differs from the response during normal altimeter tracking of the signal from the ocean surface which involves a triple convolution of the PTR with the response from a flat target and with the elevation density function of the ocean (Hayne, 1980). In principle the PTR takes the classical sinc^2 functional form, with a central peak and a series of much smaller and symmetric sidelobes on either side. There is clear evidence that the TOPEX Side-A PTR changed over time. The first indication of this was an anomalous increase in significant wave height (SWH) beginning in 1997 and worsening with time (see Figure 2). The changes in PTR are the reason the altimeter was switched from Side-A to the redundant

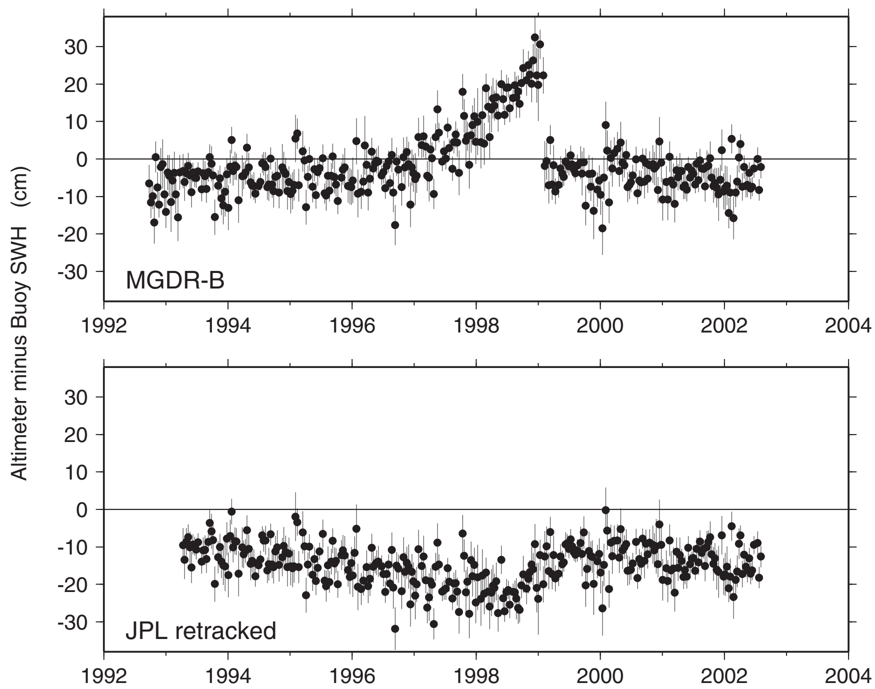

Figure 2. Comparisons of TOPEX significant wave heights against independent buoy data, essentially following the procedure used by Mitchum (2000) for comparing altimeter sea-surface heights against tide-gauge data. A mean altimeter-minus-buoy difference across all buoys is formed for each repeat cycle. (top) Original altimetric waves heights as collected by TOPEX and reported on the MGDR-B data records. Figure is slightly modified from Ray and Beckley (2012). (bottom) Similar analysis using identical buoy data for the retracked TOPEX data of Callahan et al. (2016).

Side-B at the beginning of repeat cycle 236. The Side-B altimeter in general showed better signal characteristics with no evident changes throughout the remainder of the mission.

Changes in the PTR sidelobes have a pronounced effect on altimeter measurements, especially at small SWH, since they tend to change the leading edge of the radar waveform, from which both SWH and range (and thus sea-surface height, SSH) are estimated. For TOPEX, the sidelobe changes caused a noticeable "shoulder" at the beginning of the waveform (Hancock et al., 1999). Moreover, since the observed surface return is the convolution of the true return and the PTR, estimates of SSH, off-nadir pointing angle, and SWH are all affected.

Note that the Cal-1 range correction applied in the MGDR-B data was not designed to correct for a changing PTR; the correction strictly addresses the issue of possible internal path delay changes. In fact, the corrections shown in Figure 1 are based on an assumption of a fixed PTR. Fortunately, the calibration runs that were obtained twice each day throughout the lifetime of Side-A do provide (somewhat suboptimal) evidence for how the PTR changed.

The observed changes in the TOPEX PTR are documented in some detail in the report of Hancock et al. (1999). Figure 3 shows how the magnitude of the first few PTR sidelobes (relative to the central peak) is thought to have changed over the course of the mission. The sidelobes were not symmetric for either altimeter, but more importantly the changes over time for Side-A were also not symmetric; for example, sidelobe -2 increased more than $+2$, while $+3$ increased more than -3. The first sidelobes have greatest impact on the parameters estimated from the waveforms, and while sidelobe -1 showed a gradual increase to cycle 140, then a rapid acceleration afterward, sidelobe $+1$ showed a curious drop-off, followed by gradual, then rapid, increases. Hancock et al. (1999) also noted the complete disappearance of sidelobes ± 5 (their Figures 3–19).

Changes in the PTR cause changes in estimated SSH in two ways: (a) there is the direct change in altimeter-estimated range solely by how the PTR convolves with the true surface reflection and (b) there is a change in sea-state bias correction implied by the changes in estimated SWH. Hayne and his colleagues developed

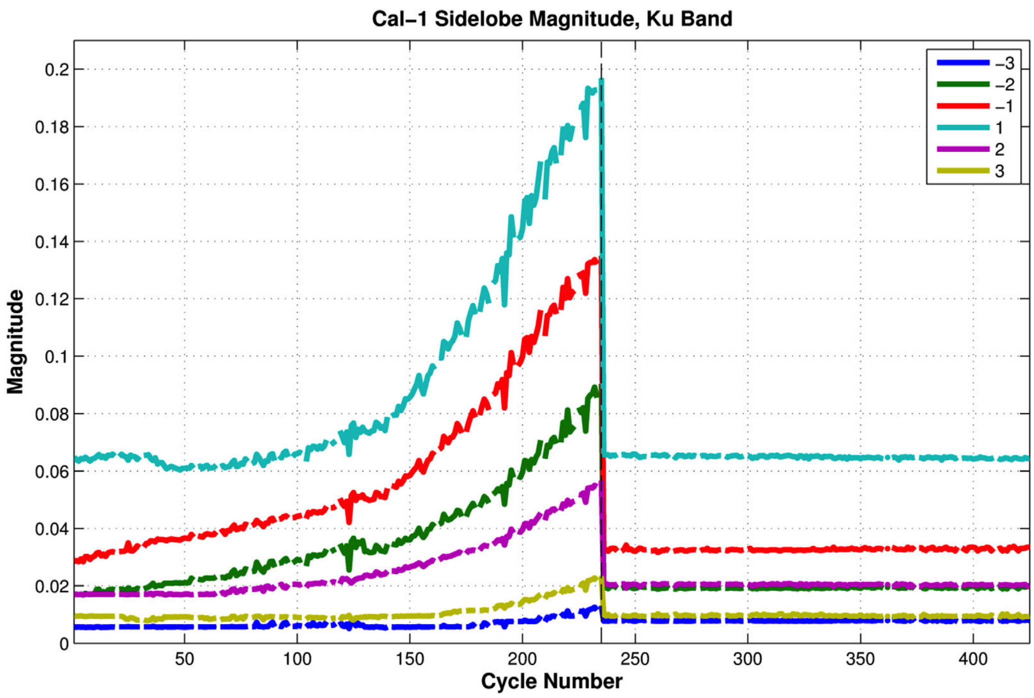

Figure 3. Amplitudes of the first ±3 side lobes of TOPEX, as inferred from the Cal-1 mode internal calibration data. Amplitudes are scaled relative to the central peak. The Side-A data show small changes in the side lobes almost from the beginning of the mission, while Side-B shows no changes during its approximately 6 years of operation. Note that in addition to the general increase, there is a "hump" in the first ~50 cycles for side lobe +1.

several models for the changes in Side-A PTR and computed simulations of both SSH effects (a) and (b). Their initial results showed that by cycle 250, the error in estimated SWH over an ocean with a "typical" 2 m SWH would amount to about +50 cm; the error in estimated SSH would be about +10 mm; the error in SSH after sea-state bias correction would be around 5 mm, and less than that for SWH between 3 and 6 m (see Figures 3–28 of Hancock et al., 1999). Thus, the overly large sea-state bias correction implied by the overestimated wave heights tend (mostly) to cancel the errors in range. This result led most TOPEX users to make no changes to normal processing of the Side-A SSH data. (In contrast, studies of ocean waves were justified in adjusting the TOPEX SWH data in some manner; e.g., Queffeulou, 2004; Queffeulou & Bentamy, 2007.)

Unfortunately, as Hancock et al. (1999) discuss, subsequent simulations by Hayne and colleagues were less reassuring, with significantly larger errors in implied SSH. Some of the simulated errors in SWH, however, turned out much larger than those observed in the real altimeter data (as in Figure 2), so the final conclusions about the effects of the changing PTR were not especially firm.

This may be a case where the tide-gauge comparisons provide the more definitive assessment of these errors, which is not a completely satisfactory situation. The tide-gauge results are the topic of section 5.

4. Three Varieties of TOPEX

In the tests to follow, we use the 1993–2016 times series of SSH data from TOPEX, Jason-1, and Jason-2, but with three different varieties of TOPEX data, as follows:

1. NASA MEaSUREs version 3.2, which includes the Cal-1 mode correction as it was included in the MGDR-B data.
2. NASA MEaSUREs version 3.2, but with the Cal-1 mode correction unapplied (to both Side-A and Side-B).
3. A newly retracked TOPEX version 5.0 data set, produced at the Jet Propulsion Laboratory (Callahan et al., 2016). The Cal-1 correction is also not used with these data.

We briefly summarize a few aspects of these three data sets, especially as they relate to the calibration-mode problem at hand.

4.1. MEaSUREs Altimetry

MEaSUREs (Making Earth System data records for Use in Research Environments) is a NASA project designed to reprocess historical remote sensing data to the strictest standards needed for climate research. The reprocessed altimeter data employed here are version 3.2, available from the JPL Physical Oceanography Distributed Active Archive Center (PODAAC; https://doi.org/10.5067/ALTCY-TJ123). Details related to altimeter range corrections, data quality flags, and editing recommendations are documented in product handbooks associated with the data sets at PODAAC.

Relative to MGDR-B data, the most important update to the data is significantly more accurate satellite ephemerides, based on an improved (and time-varying) geopotential model and improved modeling of tracking station displacements (Lemoine et al., 2010). We also employed updated ocean-tide models and a small correction to the TOPEX dry-troposphere correction, both of which have implications for 59 day oscillations in altimetric global mean sea level (e.g., Masters et al., 2012; Ray, 2013). A location-dependent correction for glacial isostatic adjustment has been applied to the data; it affects the trend in global (strictly, between latitudes $\pm 66°$) mean sea level by $+$ 0.25 mm/yr, a value that agrees well with that computed by Tamisiea and Mitrovica (2011). Sea-state bias corrections are based on work of Tran et al. (2010). Updated wet-troposphere corrections are from Brown et al. (2009). Note that no waveform retracking was performed for MGDR-B data; the data are essentially those output from the onboard tracker, although with adjustments as provided in the "net instrument" correction.

Inter-mission biases between TOPEX Side-B and Jason-1 and between Jason-1 and Jason-2 were determined directly from the collinear SSH data collected during the Jason-1 and Jason-2 verification campaigns, during which approximately 6 months of overlapping simultaneous measurements were collected. So these inter-mission biases are well determined. The bias between Side-A and Side-B is far more problematic since obviously no data could have been collected from both altimeters simultaneously. Nonsimultaneous data are available, both from the Poseidon altimeter aboard T/P and from the ERS-2 satellite, but Poseidon data were collected only about 10% of the time and differences between TOPEX data and ERS-2 data appear too noisy to constrain accurately the A-B bias (e.g., E. Leuliette, personal communication, 2017). The A-B bias can evidently be determined only from the tide-gauge comparisons. This matter is discussed below in section 5. All inter-mission biases are tabulated in Table 1.

4.2. Retracked TOPEX Altimetry

This paper is not the proper vehicle for an extensive discussion of TOPEX waveform retracking, which will appear elsewhere. Nonetheless, a brief discussion is still needed in the context of the cal-mode adjustments as well as the final results on implied sea level.

TOPEX retracked v5.0 measurements (Callahan et al., 2016) incorporated several refinements to the retracking process (Rodriguez, 1988) and are based on the best available assessment of the Cal-1 PTR information. Unfortunately, there are at least three problems with the PTR calibration data: (1) the TOPEX altimeter signal was contaminated by small signal leakages (Hayne et al., 1994b) that affected both the calibration and regular measurements; (2) the calibration data were obtained with only one sample per sidelobe rather than as

Table 1
Estimates of Altimeter Bias[a] and Drift[b] for TOPEX Side-A, Side-B, Jason-1, and Jason-2

	Bias (mm)			Drift (mm/yr)			
	A–B	B–J1	J1–J2	A	B	A/B	A/B/J1/J2
MEaSUREs	8 ± 2	−22	0	1.02	0.53	0.56	0.24
MEaSUREs w/o Cal-1	5 ± 2	−25	0	0.25	0.23	−0.45	−0.02
Retracked TOPEX w/o Cal-1	0 ± 2	−2	0	0.15	−0.30	−0.32	0.08

[a]Formal error bars for the two biases relative to Jason-1 are near-zero because of the large number of collinear measurements collected during the verification campaigns.
[b]Drift estimates involving TOPEX begin at 1993.0, but at 1994.5 for the retracked TOPEX data. Uncertainties on drift estimates are approximately ± 0.4 mm/yr, independent of time span (Mitchum, 2000).

a full sweep of the PTR—see, for example, Figures 3–19 of Hancock et al. (1999)—so the information is not very robust; (3) in calibration mode the tracking was centered near waveform gate index 78.5, while real ocean tracking was centered at 32.5, and some postmission engineering modeling suggested that PTR changes could have manifested themselves somewhat differently at these different gates. Especially problem (2) limited the usable PTR measurements to the first ± 6 sidelobes of the PTR, while it has been found in retracking tests that ± 30 sidelobes are needed. Because of this, the PTR used in the retracking was extended by a theoretical sinc-function parameterization, adjusted to the observed asymmetry of the two sides of the measured PTR. The variation of the first ± 3 sidelobes of the PTR was shown above in Figure 3.

The retracking process aims to use the actual characteristics of the radar found from calibration data with the observed signal to extract the correct range, SWH, and off-nadir angle. (For TOPEX the retracking amplitude and noise level were not directly used.) If an incorrect—theoretical or fixed initial—PTR is used with the Side-A data, incorrect values will be retrieved. While the most noticeable effect of higher sidelobes will be to produce spuriously high SWH estimates, effects on range and off-nadir angle (from the waveform tail) are more subtle but still important for centimeter-level precision.

Other features of the v5.0 retracking were: The preflight waveform weights (to correct for the shape of the low-pass filter) were used. A fixed skewness of 0.1 (as for Jason) was used. The key new feature was that the noise estimate was moved earlier in the waveform (gates 5–7 scaled versus 7–12) to avoid contamination as the Side-A PTR changed beginning from as early as cycle 100.

The retracked SWH data are compared against buoy data in Figure 2. The inordinately large wave heights of the original Side-A data have been much reduced, although it appears to be slightly overcompensated with SWH now too small during 1997 and part of 1998. (Note that any systematic offset over the whole time series between the altimetry and the buoy network, which is clearly evident in the figure, is not germane to the present discussion. In any event, such a constant offset is partly a function of buoy calibrations—see discussions by Challenor & Cotton, 2001; Ray & Beckley, 2012; Swail et al., 2010.)

For the tests below, the same geophysical and media corrections were applied to the retracked data as were applied to the MEaSUREs data. The retracked sea-state bias corrections were based on the retracked SWH data and were computed with a nonparametric model kindly provided by D. Vandemark (personal communication, 2016), who analyzed the retracked data for this purpose.

Note that if the cal-mode range correction for Side-A is suspect because of the PTR changes, as we have implied above, it is still suspect for the retracked TOPEX data as well. Thus, in our tests of the two revised TOPEX time series, including the retracked time series, no cal-mode range correction is applied.

5. Tide-Gauge Comparisons

Mitchum (1998, 2000) laid out the basic method for estimating altimeter errors via comparison to the large tide-gauge network that we apply in this paper. Briefly, this work showed that at any particular tide gauge, the altimeter/tide-gauge differences are composed of (a) relatively high-frequency noise due to incomplete cancellation of true ocean signals because of the separation between the tide-gauge location and the altimeter's footprint and (b) low-frequency signals due to altimeter drift error and vertical land motion of the tide gauge. The low-frequency errors cannot be separated without independent information, but the high-frequency noise can be substantially suppressed by averaging data over a large number of tide gauges. The low-frequency noise is reduced by correcting the tide-gauge data using estimates of vertical land motion. In this paper, we applied the improved ULR5 (University of La Rochelle Consortium) GPS velocity field land-motion corrections (Santamaría-Gómez et al., 2012) implemented as described by Doran (2010).

The tide-gauge series used in our analyses are quality controlled on an annual basis. An important source of error in the tide-gauge series is from level shifts due to problems in tying to a proper vertical zero point. These errors show up as step functions in the altimeter/tide-gauge difference series and can affect the low-frequency error estimates from the difference series. Note, however, that no adjustments to the tide-gauge data are made based on the altimeter data. Rather, any indication of such an error at any tide gauge is evaluated by examination of the tide-gauge leveling records and by comparisons to neighboring tide gauges. When doing these evaluations, we are careful to avoid flagging stations simply on the basis of low-

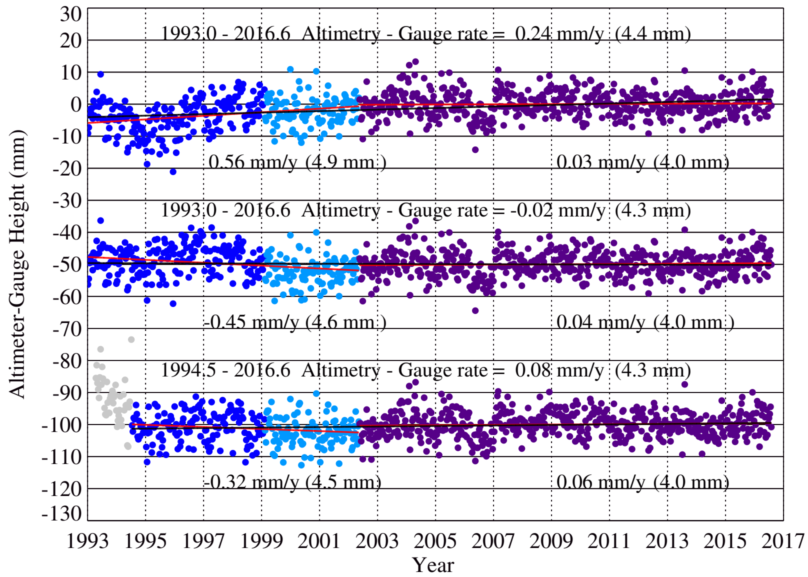

Figure 4. Altimeter minus tide-gauge mean height residuals for the T/P, Jason-1, and Jason-2 sea-surface height time series, following methodology of Mitchum (2000). Linear rates and standard deviation of residuals (in brackets) are reported for TOPEX Side-A (dark blue) and Side-B (light blue), and for Jason-1 and −2 combined (purple). (top) MEaSUREs v3.2, which has TOPEX cal-mode range correction applied to both TOPEX Side-A and Side-B. (middle) MEaSUREs v3.2 with TOPEX Side-A and Sied-B cal-mode correction un-applied. (bottom) TOPEX heights based on retracked waveform data, with no cal-mode correction applied. Early cycles (gray dots) are excluded from all our comparison statistics.

frequency differences, as these are the types of signals that we are attempting to evaluate using the tide gauges.

The net result is that the tide gauges can be considered a reliable independent check on the stability of the altimeter time series, likely to within an uncertainty (1-σ) of about ±0.4 mm/yr on a linear trend (Mitchum, 2000). This ±0.4 mm/yr uncertainty was determined by propagating errors all through the comparison steps, beginning with an estimate of the altimeter/tide-gauge difference for each pass series. The largest contributor to the uncertainty is from possible errors in our corrections for land motion at tide gauges, including the related errors from uncertainties in the terrestrial reference frame. This uncertainty is independent of the time span of the data. That is, it cannot be reduced by employing a longer time series, but only by improving our knowledge of the tide-gauge land motions.

Our adopted network here comprises 64 tide gauges distributed throughout the global ocean, with 38 located at small open-ocean islands. The network lacks adequate coverage in the southern hemisphere: only nine gauges are in latitudes south of 20°S.

It is critical in these kinds of tide-gauge comparisons that the altimeter and tide-gauge data be handled consistently, as we have previously emphasized (Ray et al., 2010). Thus, for purposes of these comparisons (and only these comparisons), we did not adjust the altimeter data for long-period ocean tides, the ocean pole tide, or atmospheric loading, since none of these adjustments were applied to the tide-gauge data.

The main results of the tide-gauge comparisons for our three altimeter time series are shown in Figure 4, which displays altimeter-minus-gauge SSH differences averaged over each 10 day repeat cycle. A preliminary analysis of this kind was used for each time series to determine the TOPEX A-to-B bias, using a technique that minimizes the discontinuity in the difference time series at the A-B transition. Because there is some subjectivity in how this is determined—for example, how many cycles are examined on either side of the A-B transition—the uncertainty in this bias estimate is based more on judgment than on rigor; the values for each time series are included in Table 1. Note that an uncertainty in the A-B bias of ±2 mm affects estimates of the 1993–2016 linear trend by ±0.11 mm/yr. For the retracked TOPEX data, it appears that no A-to-B bias is required; the difference time series already appears continuous across the transition. That point alone is a mark of some progress.

Based on the data of Figure 4, the drift estimate for the MEaSUREs v3.2 SSH time series from 1993.0 to 2016.6 is $+0.24\pm0.4$ mm/yr. Thus, if the tide gauge is considered "ground truth," the rise of global mean sea level as estimated from the altimetry is slightly too high. Most of this drift can be attributed to the large positive drift ($+1.02$ mm/yr) observed in TOPEX Side-A. The cause of this Side-A drift appears suspiciously related to the cal-mode range correction applied to the altimetry, because the pronounced quadratic signature in the Side-A altimeter-gauge differences is highly correlated (0.72) with the cal-mode correction shown in Figure 1, and as discussed above, we already have good reason to be suspicious of the correction. When the correction is not applied to TOPEX (Figure 4, middle) the resultant 1993.0–2016.6 drift estimate is reduced to -0.02 ± 0.4 mm/yr due to a marked drift-rate reduction in Side-A from 1.02 to 0.25 mm/yr. The standard deviation of residuals from the linear fit for Side-A is also reduced from 5.1 to 4.6 mm. A drift rate reduction is also observed in TOPEX Side-B from $+0.53$ to $+0.23$ mm/yr, resulting in an overall TOPEX trend reversal from $+0.56$ to -0.45 mm/yr. A similar TOPEX drift estimate of -0.32 mm/yr is observed in the TOPEX retracked series (Figure 4, bottom) without any bias adjustment to align Side-A and Side-B.

One evident problem with the retracked data lies at the beginning of the time series, where the tide gauges suggest that the retracked SSH is significantly biased high. These anomalous data persist through about cycle 66, or mid 1994; they are colored gray in Figure 4 and are not used in our statistics. An explanation for the early anomalous data is lacking, although the retracking results may have been affected by the odd behavior of sidelobe $+1$, evident in Figure 3, whose magnitude curiously dropped between cycles 40–50 before later increasing.

Based on the tide-gauge comparisons of Figure 4, both the MEaSUREs time series, without the cal-mode range correction, and the retracked TOPEX data (excluding the initial cycles) are more reliable than the standard MGDR-B data.

6. Implications for Global Mean Sea Level

The time series of global mean sea level computed from our three altimeter time series are shown in Figure 5. The estimation procedure for these global means closely follows Beckley et al. (2010). The seasonal cycle (annual plus semiannual) has been removed. The data were smoothed over a 60 day window in order to suppress the 59 day noise that is generated by errors related in various ways to the precession of the satellite orbit plane (relative to the sun). It is clear from Figure 5 that the two revised time series are less linear than the original time series, reflecting the revisions to the TOPEX data.

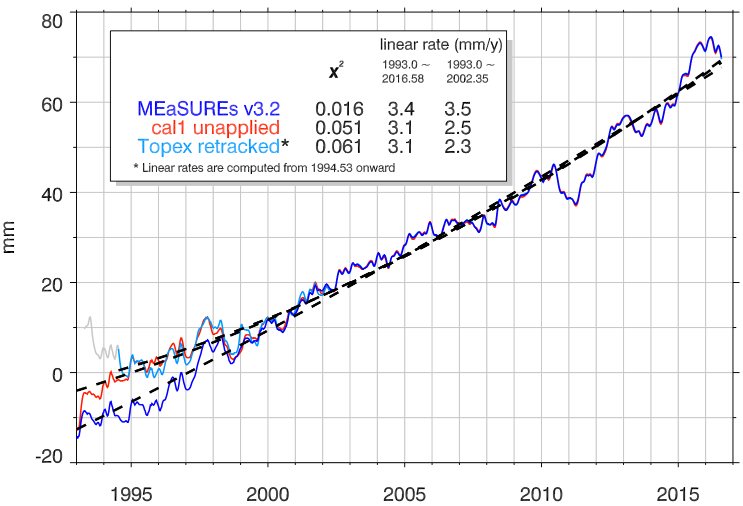

Figure 5. Global mean sea level from T/P, Jason-1, and Jason-2 altimetry. All three curves use identical Jason data. The TOPEX data are: (dark blue) standard MEaSUREs altimeter data, updated from the MGDR-B data release; (red) the same except without application the cal-mode range correction of Hayne et al. (1994a); (light blue) the version-5 retracked data (Callahan et al., 2016), again without application of the cal-mode range correction, and with the early suspect data shown in light gray. Black dashed lines are quadratic fits to the three SSH curves.

Estimated trends from the sea level time series are shown in Table 2, for both the whole time series and the series before the TOPEX-Jason transition in mid-2002. (For completeness, the estimated linear trend over the period 2002.4–2016.6 is 3.46 ± 0.44 mm/yr, identical for all three time series since all three use the same Jason-1 and Jason-2 data.)

The quoted uncertainties in Table 2 represent 1-σ standard errors and account for serial correlation in the time series. Error estimation in this context was recently discussed in detail by Fu (2016), who employed generalized least squares (i.e., a full Toeplitz weight matrix) based on an autocovariance determined from the residuals of an initial, unweighted fit. In our case, we instead employ ordinary least squares (OLS). So long as errors have zero mean, OLS still leads to unbiased trend estimates, although the generalized approach can be more efficient if the adopted error autocovariance is adequately known (e.g., Brockwell & Davis, 1996). As is well known, OLS does lead to biased (too small) standard errors, so we adjusted the standard errors as follows: The time series were first resampled by a factor of 6 to avoid the induced autocorrelation from our 60 day smoothing. The initial OLS standard errors were then augmented by a scalar factor

Table 2
Estimated Trends in Global Mean Sea Level

	Linear (mm/yr)[a]		Quadratic (mm/yr^2)
	1993.0–2002.4	1993.0–2016.6	1993.0–2016.6
MEaSUREs	3.52 ± 0.24	3.41 ± 0.15	0.016 ± 0.023
MEaSUREs w/o Cal-1	2.53 ± 0.28	3.09 ± 0.19	0.051 ± 0.020
Retracked TOPEX w/o Cal-1[b]	2.36 ± 0.36	3.14 ± 0.22	0.061 ± 0.025

[a]Quoted standard errors do not account for possible systematic errors as bounded by tide-gauge comparisons, which are approximately 0.4 mm/yr (Mitchum, 2000).
[b]Retracked TOPEX data before 1994.5 not employed in fitting.

appropriate for an assumed first-order autoregressive AR(1) noise process (e.g., Foster & Brown, 2015; Lee & Lund, 2004). An AR(1) process appears here to be an adequate characterization of the noise since the first few lags i of the sample autocorrelation of the residuals were found to decay like $(\rho_1)^i$, as is expected for AR(1). For the whole T/P-Jason time series, Fu (2016) found a standard error in his estimated linear trend of 0.10 mm/yr (whereas if serial correlation is neglected it was 0.025 mm/yr). Our original, unadjusted MEaSUREs time series is closest to the data used by Fu, and for that series we get a standard error of 0.15 mm/yr, or about 50% larger than his. The standard errors rise slightly for our revised time series, probably owing to larger residual variances, for reasons we address presently. Analysis of residuals suggests a correlation time scale of about 400 days; Fu found 480 days.

Note that the trend standard errors in Table 2 do not account for possible systematic errors. As discussed above, these are thought to be bounded at about ±0.4 mm/yr based on the altimeter/tide-gauge comparisons (Mitchum, 2000), a limit that is dominated by uncertainties in the vertical land motion at the tide gauges. The Mitchum methodology eliminates possible tide-gauge stations from the analysis that show abrupt offsets, often associated with earthquakes, and strongly nonlinear difference series, which are taken to be due to nonlinear vertical land motion. This selection process allows modeling of the land motion errors as long-term linear errors. Therefore, as Fu (2016) emphasizes, the land motion error is a systematic constant throughout the whole time series and applies equally to segments of the time series, thus canceling if one is searching for changes in trend. There are, of course, other possible contributors to systematic error, including uncertainty in the A-B bias estimates discussed above.

As seen in Table 2, a linear rate reduction of 0.3 mm/yr (3.4–3.1 mm/yr) is observed over the 1993.0–2016.6 time span when the cal-mode range correction is not applied to TOPEX, with a larger rate reduction of 1.0 mm/yr over the shorter 1993.0–2002.4 TOPEX period. A similar rate reduction of 0.3 mm/yr is observed in the TOPEX retracked solution albeit over the shorter 1994.5–2016.6 period, and thus with a more significant reduction of 1.2 mm/yr over the abbreviated 1994.5–2002.4 TOPEX period. Watson et al. (2015) reported a reduction of 0.6 mm/yr (3.2 to 2.6 mm/yr) from 1993 to mid-2014 after adjusting each of the TOPEX, Jason-1 and Jason-2 SSH time series for drift and bias estimates derived from their altimeter/tide-gauge comparisons. The bulk of their reduction they concluded was due to the large positive drift estimated for TOPEX Side-A, exceeding 1.5 mm/yr in their analysis. This adjustment is larger than the implied adjustment to our time series, since a linear fit to the cal-mode correction for Side-A (cycles 11–235) is 0.8 mm/yr (see Figure 1).

Because TOPEX spans the initial decade of the altimeter time series, one important consequence of our suggested SSH adjustments is a revision to the linearity of the full 20+ year time series, a point that Watson et al. (2015) emphasized. There is clearly more curvature in the new time series of Figure 5 than in the original. Fitting a quadratic polynomial to the full time series of Figure 5 yields the estimated coefficients given in the final column of Table 2. (Our time span for the retracked time series again starts at 1994.5.) Thus, both revised TOPEX time series reflect an increasing rate of sea level rise, both with an acceleration marginally significant at the 2-σ level. Watson et al. (2015) found their quadratic coefficients also larger after drift adjustment, although none of their coefficients (for a slightly shorter time series) was statistically significant.

In fact, an assumed quadratic model is probably not the best choice. When a more general polynomial is fit to the time series and the order of that polynomial is selected according to the Akaike Information Criterion

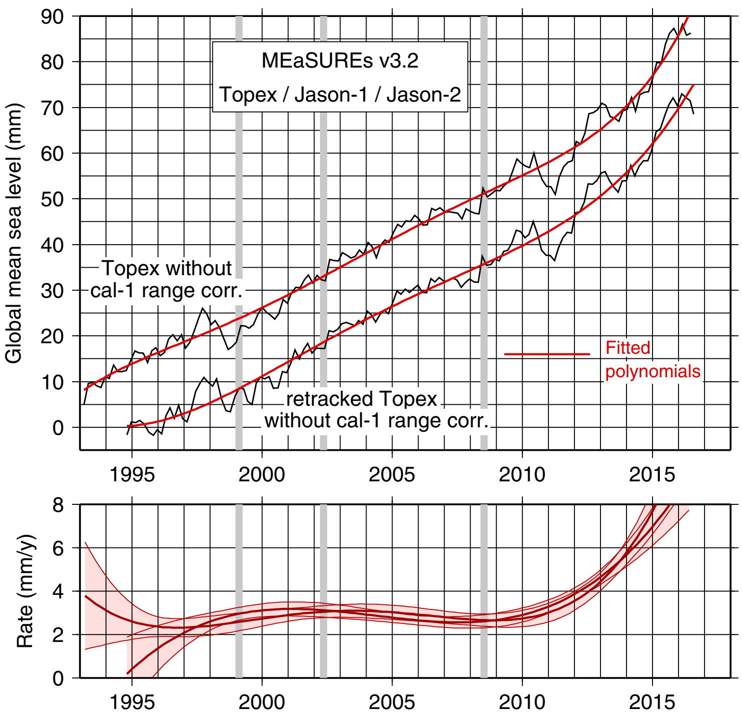

Figure 6. (top) Global mean sea level (black) from TOPEX, Jason-1, and Jason-2 altimetry, for the two time series with revised TOPEX data, seasonal cycle removed. The two curves are offset by 15 mm for plotting purposes. Red curves are polynomials fitted to the sea level curves. Grey vertical bars mark transitions between altimeters: A-B, B-J1, J1-J2. (bottom) Derivatives, analytically evaluated, for the fitted polynomials of top plot. Background shading represents ± 1-σ. Implied rates of sea level rise hovered around 3 mm/yr for most of the two-decade time series, but the rates have markedly increased over the past few years.

(AIC) (von Storch & Zwiers, 1999), we find that a quintic polynomial is preferred for the revised no-cal-mode series and a quartic polynomial is preferred for the (slightly shorter) retracked series. Figure 6 plainly reveals the reason: the AIC is minimized when accounting for an increased rate over the past few years. The derivatives of the fitted polynomials, shown in the bottom plot, suggest rates of sea level rise hovering around 3 mm/yr throughout most of the two-decade time series, although the rates are in disagreement during the Side-A era, mostly because of the retracking issues of the early cycles. The sea level rate over the past few years has markedly increased to over 6 mm/yr. We should probably stress the obvious point that a fitted polynomial is not a physical model, so it reveals nothing about rates after 2016, nor does it shed light on causative mechanisms, which for the more recent few years may well be related to unusually strong La Niña and El Niño events (Fasullo et al., 2013; Piecuch & Quinn, 2016). The recent high sea level rates do correspond to an increasing rate of mass influx into the ocean, as revealed by GRACE gravity measurements—see, for example, Figure 2 of Leuliette (2015)—as well as an increasing rate of thermal expansion (Cheng et al., 2017).

7. Discussion

Watson et al. (2015) called attention to anomalous divergences between TOPEX Side-A sea-surface heights and their network of tide gauges adopted for altimeter validation. The problem had been noted earlier by Valladeau and Ablain (2011) and Valladeau et al. (2012), with some subtle indicators of it seen even earlier (e.g., Leuliette et al., 2004). Recent analyses by Dieng et al. (2017) employing a mass budget closure approach have come to a similar conclusion. Watson et al. subsequently used the tide-gauge data to adjust the altimetry for a supposed piecewise linear drift over time. That procedure is defensible, but we do not favor or advocate it. Our philosophy of "calibration/validation" is to treat the tide gauges only as a validation tool, not to be used for calibration, aside from the one exception of determining a possible bias between the Side-A and Side-B altimeters of TOPEX when (unlike subsequent transitions to Jason altimetry) no simultaneous collinear altimeter measurements were possible. Our approach is to use tide gauges only as an indicator of possible problems, which should be subsequently traced back to the altimeter system and corrected, if possible. Such an approach had already proven beneficial, repeatedly so, earlier in the TOPEX mission (Fu & Haines, 2013) and has also proven repeatedly beneficial for other satellite altimeters (Brown et al., 2007; Ollivier et al., 2012).

For the case at hand, it appears that the TOPEX problems highlighted by Watson et al. (2015) were probably caused in large part by use of an internal calibration-mode range correction which was included in the "net instrument" correction on the MGDR-B data. The correction is probably in error owing to the changes in TOPEX PTR that was itself responsible for other errors, especially in estimated wave heights. Those PTR-induced errors became sufficiently large to warrant switching the altimeter to Side-B in 1999.

The overly large SWH data returned by TOPEX between 1997 and 1999 (Figure 2, top) led to overly large corrections for sea-state bias. It is interesting to note that if the SWH are adjusted, for example, following Queffeulou (2004), then the correspondingly adjusted sea-state bias corrections lead to a sea level series fairly similar to our two revised TOPEX series over the 1996–1999 period, although not before that. Such an approach cannot be recommended, however, because the changes in PTR also affected the radar range directly and not just through the effect on sea-state bias.

The cal-mode range corrections (Hayne et al., 1994a) were designed to correct for changes in internal path delay and were never designed to correct for changes in the altimeter PTR; in fact, as noted, the corrections likely became unsound once the TOPEX PTR began changing. Thus, *not* applying the cal-mode range corrections to TOPEX appears warranted, especially since the corrections clearly correlate with the implied errors in TOPEX—i.e., with the differences between TOPEX SSH and tide gauges (Figure 4, top). Now according to Figure 3, the PTR on Side-B was well behaved and apparently invariant over time. Thus, a case can be made for applying the cal-mode range correction to Side-B while not applying it to Side-A. We have not done that here, however, for several reasons: (1) The noise inflation after cycle 363, combined with residual questions about the 7 mm discretization problem, brings some level of suspicion to the whole procedure; (2) Table 1 shows that the Side-B drift is marginally reduced without the correction, 0.53 versus 0.23 mm/yr; (3) The overall trend in the Side-B correction of 0.4 mm/yr, across 3.5 years, is in any event relatively small; and (4) We prefer to maintain, if possible, consistent data processing steps across the entire TOPEX mission.

Not applying the cal-mode corrections to the original TOPEX data leads to one of our revised time series examined here. In principle, that revised SSH time series is still flawed owing to the PTR changes, unless the range errors were canceled out by the overly large sea-state bias corrections. That cancellation was indeed thought to be the case, as early simulations by George Hayne and his colleagues indicated. Subsequent simulations, however, were less reassuring, suggesting the need for caution (Hancock et al., 1999). Therefore, it has always seemed that retracking TOPEX altimetry while attempting to account for the changes in PTR would be a valuable endeavor. Whether sufficient data had been collected during the mission to allow the changes in PTR to be truly understood is a separate issue, which a more extensive discussion of the retracking results will address. We have examined here recent retracking results (Callahan et al., 2016) and they do lead to superior agreement with the tide-gauge data, aside from a clear problem in the early repeat cycles. The retracked data are not perfect—Figure 2 (bottom) suggests a residual bias in significant wave height—but the fact that the retracked data appear to require no bias adjustment between Side-A and Side-B is a mark in its favor.

Removal of the cal-mode range correction is similar, although not identical, to the drift correction that Watson et al. (2015) applied to their TOPEX time series. As those authors noted, their adjusted TOPEX data (they also adjusted Jason data) lead to a two-decade SSH time series less linear, with slightly more positive curvature, than their original time series. This is also the case when the TOPEX data are not corrected by the cal-mode range correction. The case for an "unabated sea-level rise" (Watson et al., 2015) over the whole satellite era thus appears compelling, and that case can be made on the basis of the altimeter data alone, without recourse to drift corrections based on tide-gauge data. The tide gauges still act as an essential validation tool, giving us independent evidence for a stable, multidecade measurement.

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