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Unabated global mean sea-level rise over the satellite altimeter era

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The rate of global mean sea-level (GMSL) rise has been suggested to be lower for the past decade compared with the preceding decade as a result of natural variability[1], with an average rate of rise since 1993 of +3.2 ± 0.4 mm yr^{-1} (refs 2,3). However, satellite-based GMSL estimates do not include an allowance for potential instrumental drifts (bias drift[4,5]). Here, we report improved bias drift estimates for individual altimeter missions from a refined estimation approach that incorporates new Global Positioning System (GPS) estimates of vertical land movement (VLM). In contrast to previous results (for example, refs 6,7), we identify significant non-zero systematic drifts that are satellite-specific, most notably affecting the first 6 years of the GMSL record. Applying the bias drift corrections has two implications. First, the GMSL rate (1993 to mid-2014) is systematically reduced to between +2.6 ± 0.4 mm yr^{-1} and +2.9 ± 0.4 mm yr^{-1}, depending on the choice of VLM applied. These rates are in closer agreement with the rate derived from the sum of the observed contributions[2], GMSL estimated from a comprehensive network of tide gauges with GPS-based VLM applied (updated from ref. 8) and reprocessed ERS-2/Envisat altimetry[9]. Second, in contrast to the previously reported slowing in the rate during the past two decades[1], our corrected GMSL data set indicates an acceleration in sea-level rise (independent of the VLM used), which is of opposite sign to previous estimates and comparable to the accelerated loss of ice from Greenland and to recent projections[2,10], and larger than the twentieth-century acceleration[2,8,10].

The satellite-era time series of GMSL is a seminal climate data record[2,3] that describes one of the most robust manifestations of climate change. Accurate estimates and projections of the rate of sea-level rise, and any acceleration or deceleration thereof are of major importance for evaluating model projections and for adaptation planning, particularly for low-lying highly populated, highly productive and environmentally sensitive areas[11]. The accuracy of these GMSL estimates from data over the past two decades is dependent on the determination of fixed and time-variable systematic errors within and between each of the three successive satellite altimeter missions (TOPEX/Poseidon[12] (T/P), Jason-1 (ref. 13) and OSTM/Jason-2 (ref. 14)) used in GMSL studies. Validation of the record (often termed bias drift estimation; that is, estimating drift of the altimeter sea surface height system) requires comparison of the altimeter and tide gauge (TG) sea levels over a network of TG sites (for example, refs 5–7). This approach has been used previously to successfully diagnose algorithm and instrumental errors[4,15,16] and, after correction, drift estimates have been small and have not been used to further adjust (or calibrate) the observational records[3]. However, past implementations of this approach have limitations dominated by uncertainty in their adopted VLM at TGs (refs 5,7). The validation is also sensitive to a typically poor spatial distribution of suitable TGs, and earthquake deformation at individual TGs (ref. 17).

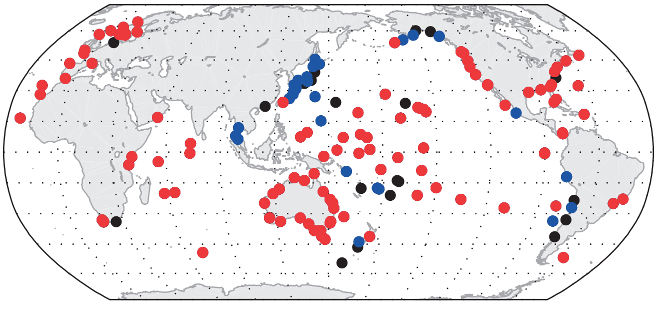

Figure 1 | Map of the initial 122 TGs used in this analysis. Additional quality control procedures (for example, obvious nonlinear VLM) eliminate TGs shown in black, and the earthquake threshold eliminates TGs in blue. The remaining TGs in red are used for bias drift estimation. Distributions by mission are shown in Supplementary Fig. 2.

Here we develop an alternative method that addresses these limitations. We expand the network of TGs used (with respect to that used by ref. 7) by a factor of ~2 to 96 TGs (Fig. 1), using high-rate hourly data. Unlike previous work[5,6], for each TG we compute bias drift and residual ocean tide at multiple offshore comparison points (CPs) for each satellite pass, using up to the maximum of four passes surrounding each TG. We correct bias drift estimates for VLM using new data from the expanding network of GPS stations co-located with or near to TGs. These VLM trends are derived from homogeneously reprocessed GPS data (updated from ref. 18), or where they are not available, we use VLM derived from a model of glacial isostatic adjustment[19] (GIA) combined with estimates of present-day elastic effects derived from the GRACE mission[20]. Accurate GPS estimates of VLM are preferable to those from GIA models as GIA is only one component of VLM, and, for many TGs, may not be the dominant signal[18]. Of our final TGs, 69% have one or more GPS estimates of VLM within 100 km (see Supplementary Methods). We model co-seismic earthquake deformation to exclude TGs with vertical motion above a specified

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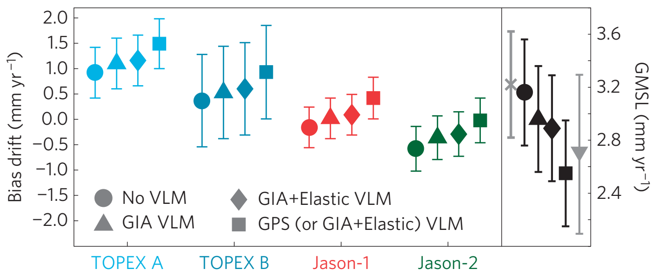

Figure 2 | Individual mission bias drift estimates (left panel) and GMSL trends (right panel), as a function of VLM applied. GMSL trends are the unadjusted consensus altimeter estimate[2] (grey 'X'), adjusted altimeter trends from this study (black lines; VLM applied as per legend), and TG-derived trend (grey inverted triangle; corrected for GPS-based VLM, see text for details). All uncertainty estimates are 1 sigma.

threshold (Fig. 1) and use a data-driven weighting strategy aimed at reducing sensitivity to TG data contaminated by nonlinear VLM or unresolved datum errors. We apply these advances to the most recently updated altimeter data set (1993 to mid-2014) that is processed as homogeneously as possible, with each mission using consistent orbits (see Methods), with respect to the same reference frame as the GPS-derived estimates of VLM (ITRF2008; ref. 21).

Our bias drift results (Fig. 2) reveal non-zero rates, in contrast to previously published results (for example, refs 5,22), which prompts a re-evaluation of the GMSL record. Of greatest significance to the estimation of the trend in GMSL is that the largest bias drift is found within the ~6 year TOPEX side A record ($+0.9 \pm 0.5\,\mathrm{mm\,yr^{-1}}$ to $+1.5 \pm 0.5\,\mathrm{mm\,yr^{-1}}$, depending on the VLM correction used). In contrast, the bias drift for OSTM/Jason-2 (using GPS VLM) is small. The difference between our bias drift estimates for any pair of satellite missions is robust to the range of available VLM corrections (that is, no VLM correction, GIA alone, GIA plus elastic response to present-day mass redistribution, or GPS that reverts to GIA plus elastic where GPS is unavailable, Fig. 2). If we apply our bias drift estimates to derive an adjusted GMSL series, the previously reported deceleration[1], estimated here as $-0.057 \pm 0.058\,\mathrm{mm\,yr^{-2}}$ (over 1993–2014), becomes an acceleration of $+0.041 \pm 0.058\,\mathrm{mm\,yr^{-2}}$ (Fig. 3), independent of the VLM applied. Neither of these is significantly different from zero, however, the revised estimate is significantly different from the earlier estimate derived from data unadjusted for the effects of bias drift. Contributions to GMSL from land water storage changes (and to a lesser extent changes in thermal expansion of the oceans) are estimated to have decelerated over 1994 to 2012, related to natural climate variability[1]. This decline may have been partially neutralized as excess water on the continents has returned to the ocean resulting in more rapid sea-level rise over the past three years. Any hydrologic contribution to an acceleration, as in ref. 1, is in addition to the altimeter adjustment discussed here. Our computed acceleration is higher than the observed twentieth-century acceleration[2,8,23] but in reasonable agreement with an accelerating contribution from the Greenland and West Antarctic ice sheets over this period[2,24], and the Intergovernmental Panel on Climate Change projections[2,10] of acceleration in sea-level rise during the early decades of the twenty-first century of about $+0.07\,\mathrm{mm\,yr^{-2}}$.

For all missions, the bias drift is sensitive to the applied VLM correction (Fig. 2). Application of the different VLM estimates (as above) has the net effect of making all bias drift estimates progressively more positive (Fig. 2), with estimates that include GPS-based VLM ~$0.57\,\mathrm{mm\,yr^{-1}}$ higher than the equivalent not corrected for VLM. This result is compatible with a previous simulation study[25] that reported an upper bound of the effect of $+0.6\,\mathrm{mm\,yr^{-1}}$. Our GPS VLM velocities compare favourably to those from ref. 25, with a mean difference (ours minus ref. 25) of $-0.13\,\mathrm{mm\,yr^{-1}}$ (weighted-root-mean-square difference of $0.7\,\mathrm{mm\,yr^{-1}}$) computed from 71 common sites (noting that a lower mean VLM has the effect of a positive shift in the estimated bias drift and thus a decrease in the adjusted rate of change in GMSL). Applying a further correction for VLM due to elastic deformation brings the GIA-only solution into slightly closer agreement with that based on GPS (Fig. 2).

If we apply what we consider as the best estimates of mission-specific systematic error (bias drift) to each of the missions (1993 to mid-2014), the linear rate of GMSL is reduced from $+3.2 \pm 0.3\,\mathrm{mm\,yr^{-1}}$ (unadjusted) to $+2.9 \pm 0.4\,\mathrm{mm\,yr^{-1}}$ (adjusted, GIA plus elastic VLM), to $+2.6 \pm 0.4\,\mathrm{mm\,yr^{-1}}$ (adjusted, GPS-based VLM; Figs 2 and 3). Note that all GMSL trend estimates include corrections for the expansion of the ocean basins due to GIA (ref. 19) of $+0.33\,\mathrm{mm\,yr^{-1}}$ and corrections for the impact of atmospheric pressure. Our results from the adjusted GMSL series are in closer agreement with the rates derived from the ERS-2 and Envisat missions (median values of $+2.6 \pm 0.2\,\mathrm{mm\,yr^{-1}}$ and $+2.9 \pm 0.2\,\mathrm{mm\,yr^{-1}}$, respectively[9], see Supplementary Discussion regarding differences in data period and the treatment of uncertainty), and the trend in GMSL computed from TGs alone ($+2.7 \pm 0.6\,\mathrm{mm\,yr^{-1}}$, updated from ref. 8 with the same GPS-based VLM applied, noting significant difference in the TG network used (up to 400 TGs; ref. 8) compared with that used to compute bias drift estimates (96 TGs)). They are also consistent with the updated estimate of the sum of observed contributions to GMSL over 1993 to the end of 2009 ($+2.8 \pm 0.5\,\mathrm{mm\,yr^{-1}}$, ref. 2).

We also applied our method to the along-track altimeter data provided by the University of Colorado (CU, 2014_v5; ref. 3). Unadjusted GMSL trend and acceleration estimates for the CU data were within $0.02\,\mathrm{mm\,yr^{-1}}$ and $0.018\,\mathrm{mm\,yr^{-2}}$ of our results, and adjusted estimates were within $0.06\,\mathrm{mm\,yr^{-1}}$ and $0.004\,\mathrm{mm\,yr^{-2}}$ (Fig. 3). A range of additional sensitivity tests including multi-mission ensemble and misclosure analyses, as well as exclusion tests eliminating various subsets of the TG network and altimeter record, further demonstrate the robustness of our results (see Supplementary Discussion for further detail). Most notably, results using our bias drift estimates remain unchanged to within approximately $0.2\,\mathrm{mm\,yr^{-1}}$ following the removal of the top 20% of the highest-weighted (lowest-uncertainty) CPs, suggesting that our data-driven weighting approach (see Methods and Supplementary Methods) is not sensitive to a small subset of the TG network.

We are unable to definitively attribute the bias drift observed in the early TOPEX record to any one cause. A number of factors are likely to contribute and their interaction is complex (see Supplementary Discussion). One possibility is the performance degradation of the point-target response associated with the side A electronics of the TOPEX altimeter that led to the switch to side B in February 1999 (refs 8,16,26). This degradation, as well as leakages in the waveforms, affected the derived altimeter to sea surface range, significant wave height and wind speed. Correction of these issues related to the point-target response combined with homogeneous 're-tracking' of the altimeter waveforms (commensurate with that of later missions[27,28]) may resolve the dominant bias drift for the TOPEX mission. Removing 1.5 years of data from the end of side A has the effect of reducing the side A bias drift (using GPS-based VLM) by ~37% to $+0.96 \pm 0.68\,\mathrm{mm\,yr^{-1}}$ (having the effect of lifting the adjusted GMSL rate for all estimates by about $0.1\,\mathrm{mm\,yr^{-1}}$). We also note that the TOPEX side A drift is unlikely to be linear; however, applying a more sophisticated piecewise linear model has little effect on resultant GMSL trend and acceleration terms (see Supplementary Discussion). In addition to re-tracking, the drift characteristics of the microwave radiometer on-board T/P remain problematic[29]. Similarly, the positive bias drift for Jason-1 ($+0.42 \pm 0.41\,\mathrm{mm\,yr^{-1}}$, using GPS-based VLM) may be associated

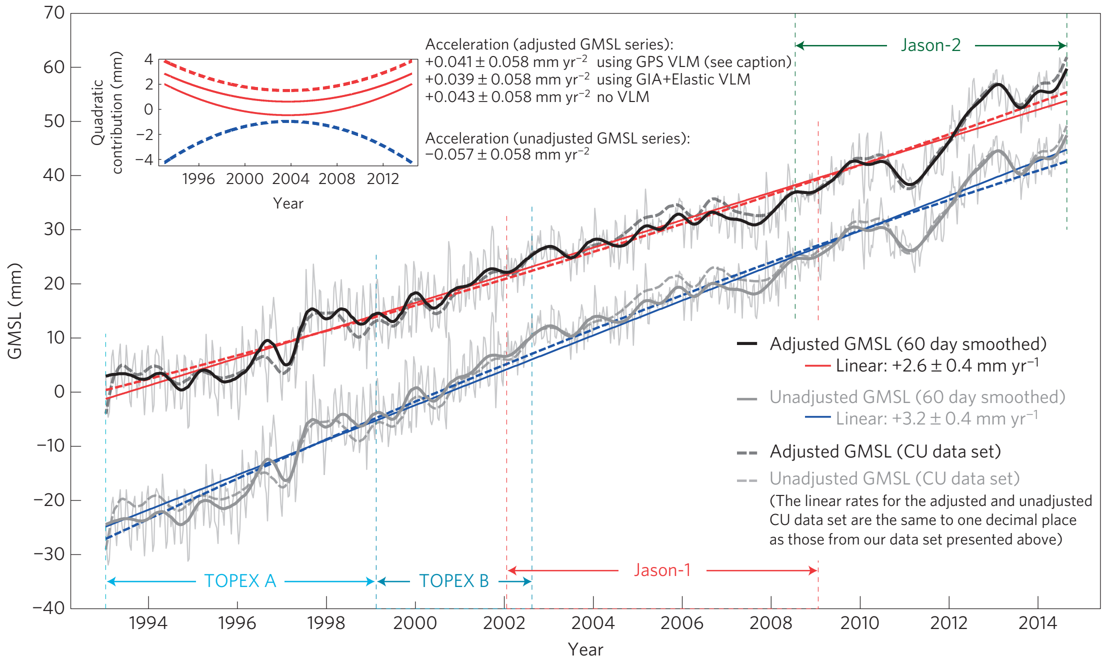

Figure 3 | Adjusted and unadjusted satellite altimeter GMSL time series (each arbitrarily offset and corrected for ocean-basin expansion). Adjusted series use GPS-based VLM estimates (where unavailable for a specific TG, GIA+Elastic VLM is substituted). GMSL (annual and semi-annual periodic terms removed) is shown as cycle-by-cycle estimates (thin grey line) and after filtering (60-day low-pass Butterworth filter, thick line). Linear and linear-plus-quadratic fits are shown as continuous and dashed lines, respectively. The inset shows quadratic components (arbitrarily offset and symmetric about midpoint) highlighting that the adjusted acceleration is invariant to VLM treatment. Equivalent series derived from the CU data set are shown for comparison (thick dashed lines).

with residual drift in the enhanced Jason-1 radiometer data product (see Supplementary Methods and Discussion).

It is likely that a component of bias drift for each altimeter mission is spatially variable, evidenced by, for example, the observed ~1 mm yr^{-1} differences between different orbit solutions[4,9]. However, at this time we have not yet been able to resolve mission-specific regional bias drifts because of insufficient and irregular spacing of TGs. Refined estimates of VLM would be possible with co-located GPS measurements at all TG locations (ongoing deployments are still required in this regard[18]), and longer GPS series would allow for nonlinear VLM to be removed from TGs meaning some gauges that are excluded at present could be reinstated in the bias drift solution. Such efforts will assist in resolving differences between the various VLM data sets/models presented here. In the absence of further observations earlier in time, techniques such as ours remain limited by the need to extrapolate GPS VLM and the elastic term added to GIA VLM over the full altimeter period. Further reduction in the uncertainty of bias drift estimates also requires improved understanding of residual oceanographic signals present in the altimeter minus TG time series.

Critically, bias drift (that is, mission-specific error in the trend) and relative bias estimates (that is, intra- or inter-mission offset or error in the mean) are specific to the choice of altimeter data processed (orbit, sea-state bias, radiometer corrections and so on), and should not be used or applied outside this context—hence, our decision to use a standard and accepted altimeter processing approach based on the latest release of geophysical data record (GDR) products and corrections to ensure our bias drift estimates are as widely applicable as possible. For example, differences in the processing used to generate the data provided by the University of Colorado (for example, see ref. 3) yielded bias drift estimates that differed by as much as 0.5 ± 0.7 mm yr^{-1} for TOPEX side A. However, the r.m.s. of differences between the adjusted CU and our adjusted GMSL time series (Fig. 3) is only 1.3 mm, with adjusted trends agreeing to within 0.06 mm yr^{-1}, and adjusted accelerations to within 0.004 mm yr^{-2}. Given the importance of the altimeter record, we encourage further attempts to estimate bias drifts and to identify and correct the underlying issues leading to these drifts. In the meantime, we recommend that the archived altimeter data should not be adjusted with our bias drifts but that users of altimeter estimates of GMSL should be aware of the potential need to adjust for small but significant biases, particularly in the early part of the record.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions
C.S.W. undertook the bias drift analysis and led the drafting of the manuscript. N.J.W. processed the altimeter data and worked closely on the methods development and analysis with C.S.W. and J.A.C. B.L. assisted with the generation of the altimeter data. M.A.K. undertook the VLM analysis and R.J.B. provided the earthquake threshold analysis. All authors contributed significantly to the drafting and revision of the manuscript.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to C.S.W.

Competing financial interests
The authors declare no competing financial interests.

Methods

We use hourly TG data from an expanded network of 122 TGs. Preference is given to the records commencing at, or before, the launch of T/P (August 1992). Of the initial TGs, 77% meet this threshold, 97% commenced before the switch between T/P side A and B (February, 1999) and 83% run for 20 years or longer. See Supplementary Methods for further description.

Altimeter sea surface height (SSH) is derived using 1-Hz along-track GDR altimeter data from T/P, Jason-1 and OSTM/Jason-2. For the T/P mission, we limit our analysis to TOPEX data given limited utilization of the Poseidon altimeter, and we treat TOPEX side A and side B as separate independent missions. We commence our processing using all available MGDR-B (ref. 30) and GDR-C (ref. 27) data for T/P and Jason-1 respectively, and GDR-D (ref. 28) data for OSTM/Jason-2, for the period 1993 to mid-2014. We process using the standard edits and checks as provided in the relevant product documentation[27,28,30], including corrections for the TOPEX and Jason microwave radiometers[29,31]. See Supplementary Methods for detail on the different sea-state bias models, orbit products, and corrections applied for solid Earth deformation.

Our VLM trends are an update of those of ref. 18, using an identical analysis strategy but making use of GPS sites within public archives and up to 100 km from each of the TGs. Data spanning from 1995 to mid-2013 were homogeneously analysed to derive daily time series. We estimated the linear trend simultaneously with annual and semi-annual periodic terms, offsets and appropriate treatment of time series autocorrelation (see Supplementary Methods). We assume that the linear motion is representative of the VLM over the duration of the altimeter period, despite different data durations at each site. Sites that exhibit clear nonlinear VLM (for example, due to ground water extraction or elastic rebound associated with nearby ice mass loss) are flagged for exclusion. We include sites with at least 1.5 years of data, but include only estimates of VLM that are well resolved with uncertainties less than 1 mm yr^{-1} (effectively limiting the number of sites with VLM estimated from short records).

Given that a TG may have multiple GPS sites located within 100 km, we compute a weighted mean of the GPS VLM. The weights are chosen with the aim of achieving a reasonable balance between GPS VLM uncertainty and the distance from each GPS to the TG (see Supplementary Methods). Where GPS velocities were not available (Supplementary Fig. 1), we interpolated predicted VLM due to GIA to TG locations from the ICE-5Gv1.3_2012 (VM2) model[19]. We also test the sum of the GIA VLM trend estimates from this model with those trends derived from the Earth's elastic response to present-day mass trends determined over the period 2003–2013 using data from the GRACE mission (updated from ref. 20, and linearly extrapolated over the altimeter period). We adopt a nominal uncertainty of ± 1 mm yr^{-1} for GIA VLM estimates, slightly larger than the mean GPS uncertainty. See Supplementary Methods for further detail regarding the reference frame and treatment of the time period used in the GPS analysis.

For each TG, we identify multiple altimeter passes followed by multiple offshore CPs per pass, each separated by 20 km along the nominal ground track, out to a threshold distance of 230 km from the TG. Instantaneous altimeter SSH is linearly interpolated to the CP, noting the across-track distance to the nominal ground track. For each CP, we form the altimeter minus TG difference (corrected for VLM), which contains contributions from a number of signals including the altimeter bias drift (equation (1)).

$$\Delta SL_{\mathrm{CP}}^{\mathrm{Alt}} = [\mathrm{Offset}]_{\mathrm{CP}}^{\mathrm{Alt}} + [\mathrm{Drift}]_{\mathrm{CP}}^{\mathrm{Alt}}(t - t_0^{\mathrm{Alt}}) + \cdots$$
$$\sum_{i=1}^{12} [A_i \cos(2\pi f_i t + \Phi_i)]_{CP} + [\mathrm{SSHSlope}]_{\mathrm{CP}} \cdot d + \varepsilon_{\mathrm{CP}}^{\mathrm{Alt}} \quad (1)$$

where Offset is a constant intercept term at time $t = t_0^{\mathrm{Alt}}$; Drift is the altimeter bias drift term (linear with time, t); A_i, f_i, Φ_i are amplitude, frequency and phase of the ith harmonic tidal constituents; SSHSlope accounts for the SSH slope induced by the $\sim$1 km variation in the satellite ground track location (linear with across-track distance (d)); and ε represents residual error that includes contributions from altimeter and TG noise and unmodelled sea-level variability between the CP and TG. We estimate the terms shown in equation (1) allowing for mission-specific time-correlated noise that is factored into the drift uncertainty, $\sigma \mathrm{Drift}_{\mathrm{CP}}^{\mathrm{Alt}}$, subsequently used as a weight to calculate the final ensemble average bias drift estimate for each mission. We exclude CPs from TGs that exhibit nonlinear VLM or are within an earthquake deformation threshold derived from modelling of co-seismic displacements and source data from a global earthquake catalogue. See Supplementary Methods for further detail.

To derive a GMSL curve adjusted for the effects of bias drift, we apply the bias drift and relative bias estimates to each mission in a piecewise linear fashion. Uncertainty estimates for bias drift (all 1 sigma throughout) consider the effective number of degrees of freedom derived from the number of TGs (and not CPs) included in the solution. Uncertainty estimates on our adjusted GMSL trend and acceleration incorporate uncertainties in the reference frame as well as the bias drift estimation (determined using a Monte Carlo approach with 10,000 iterations) and are in close agreement with other studies[6,7]. See Supplementary Methods for further discussion.

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