Further understanding the global mean sea level record over the satellite era

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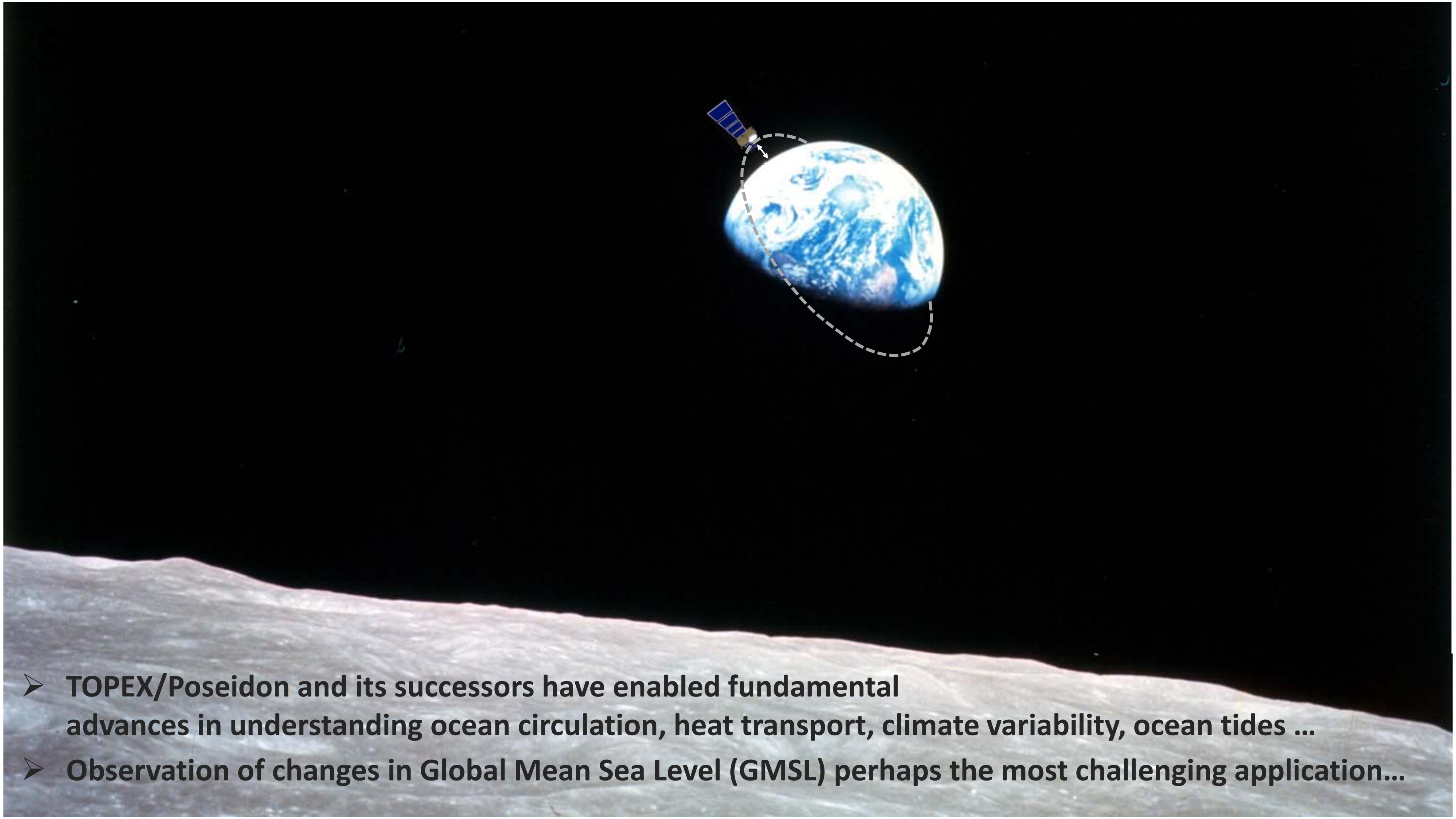
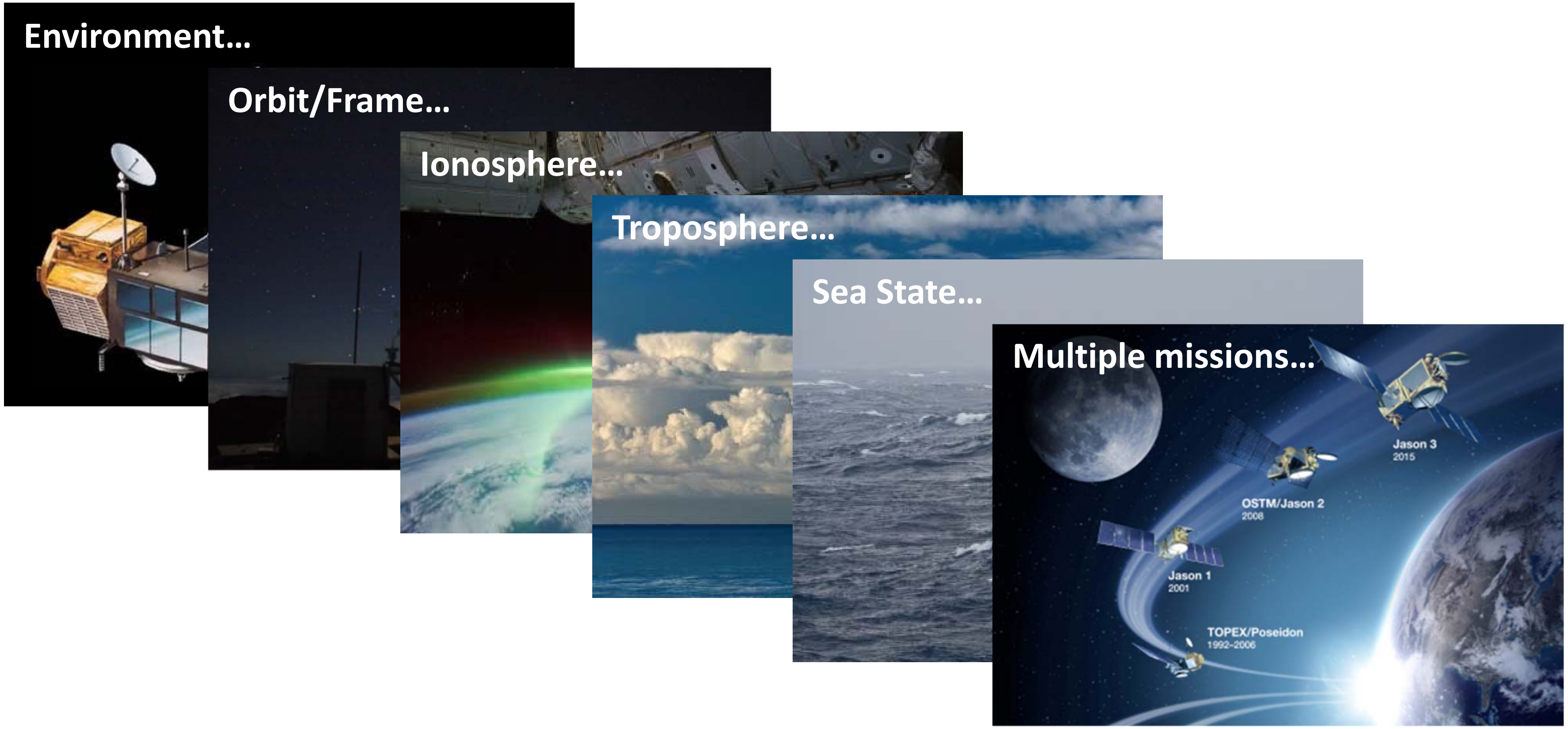


➢ TOPEX/Poseidon and its successors have enabled fundamental advances in understanding ocean circulation, heat transport, climate variability, ocean tides …
➢ Observation of changes in Global Mean Sea Level (GMSL) perhaps the most challenging application…

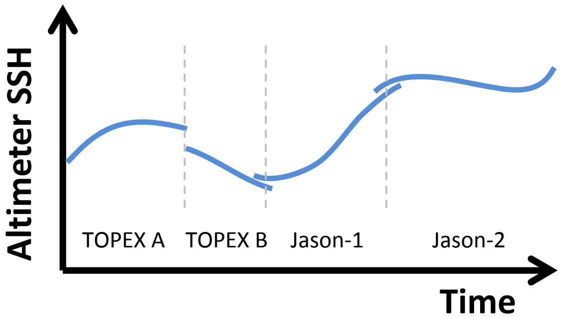
The GMSL challenge…

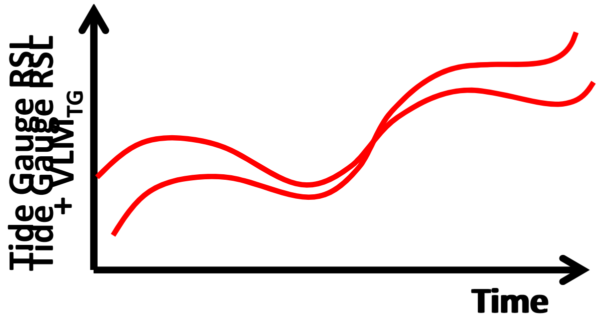


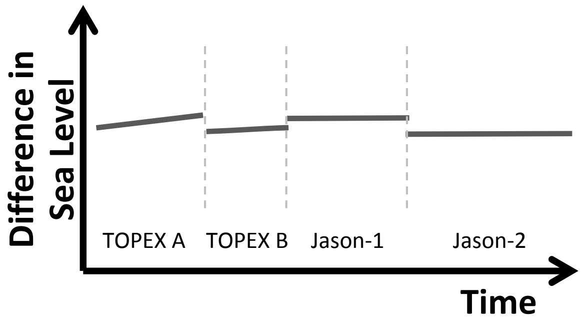
In situ SSH validation…

Sustained validation of SSH is a fundamental component of mission design:

- **'Absolute': relies on instrumented sites** (e.g. Harvest, Corsica, Bass Strait, Gavdos)
- **'Relative': relies on the global tide gauge network** (e.g. Mitchum, 2000)

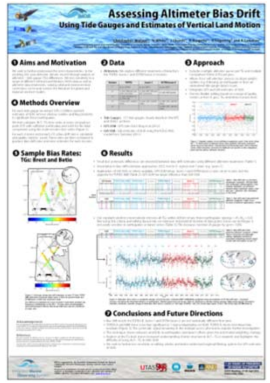




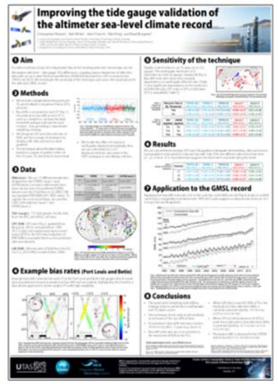


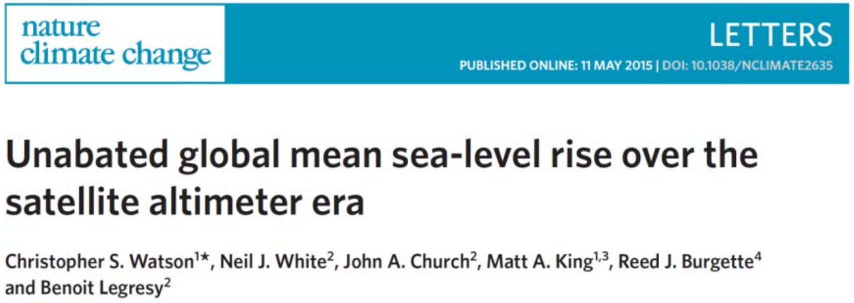
Recap of our findings…

Watson et al., 2012
(Venice OSTST)



Watson et al., 2013
(Boulder OSTST)





nature climate change

LETTERS

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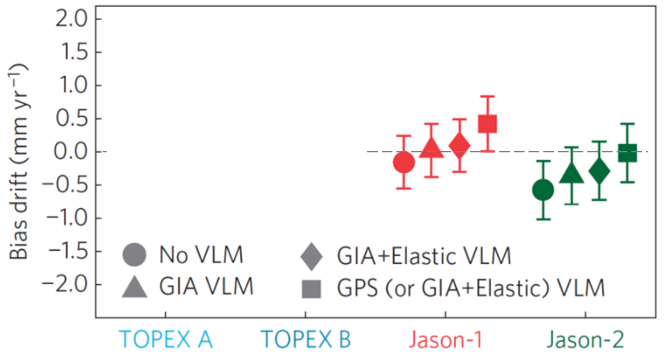
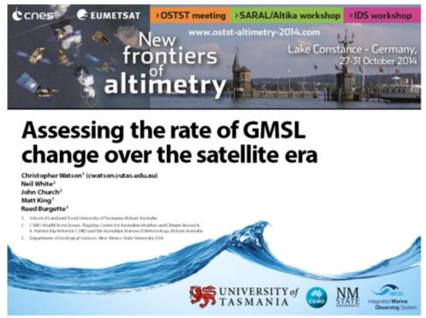
Unabated global mean sea-level rise over the satellite altimeter era

Christopher S. Watson[1*], Neil J. White[2], John A. Church[2], Matt A. King[1,3], Reed J. Burgette[4] and Benoit Legresy[2]



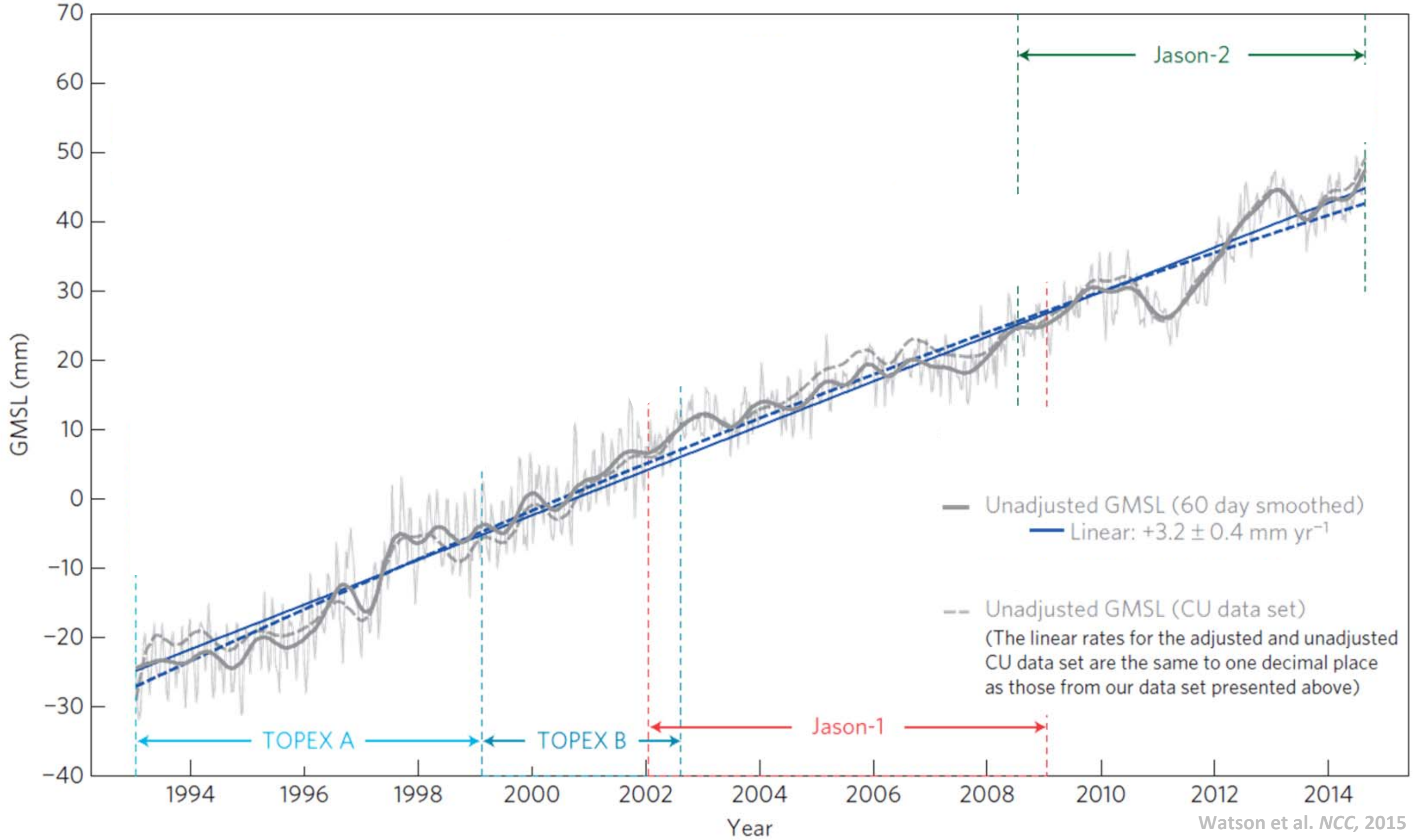
Watson et al. *NCC*, 2015

- ‘Bias drift’ results vary systematically as a function of VLM applied.
- Results suggested GMSL rate over TOPEX period is likely to be marginally high.
- Results were in contrast to other groups, and in the absence of a reprocessed record, evaluation of the impact on the GMSL record was warranted.



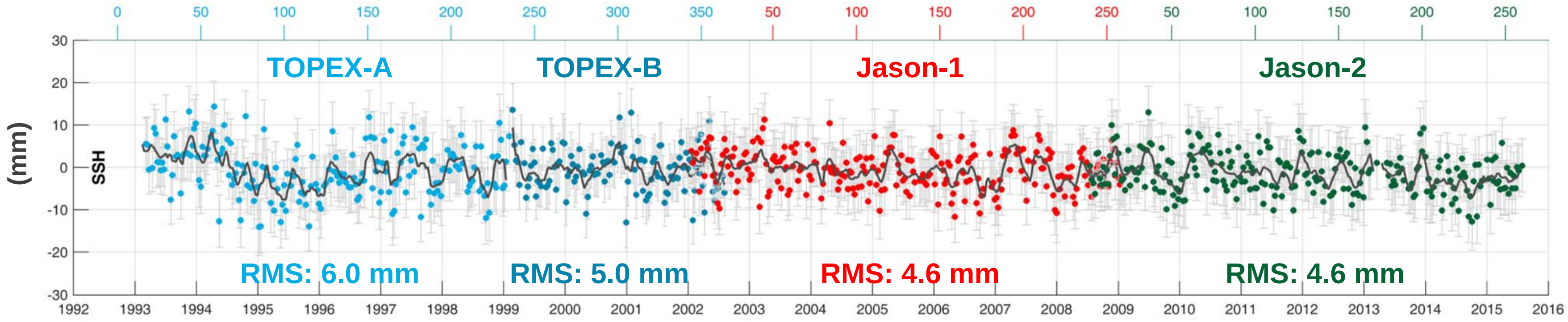
Watson et al., 2014
(Lake Constance OSTST)

Implications on the GMSL record…

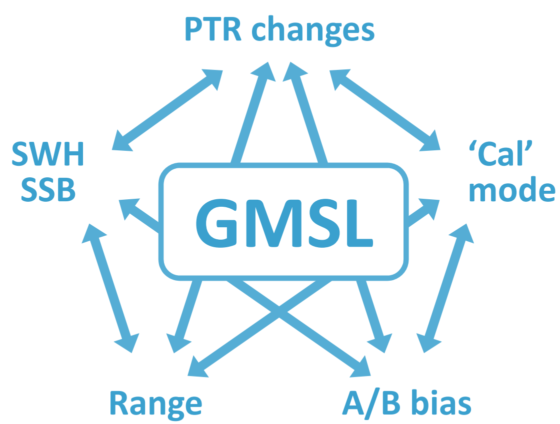


Watson et al. *NCC*, 2015

Attribution?



"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"
(Watson et al. *NCC*, 2015)



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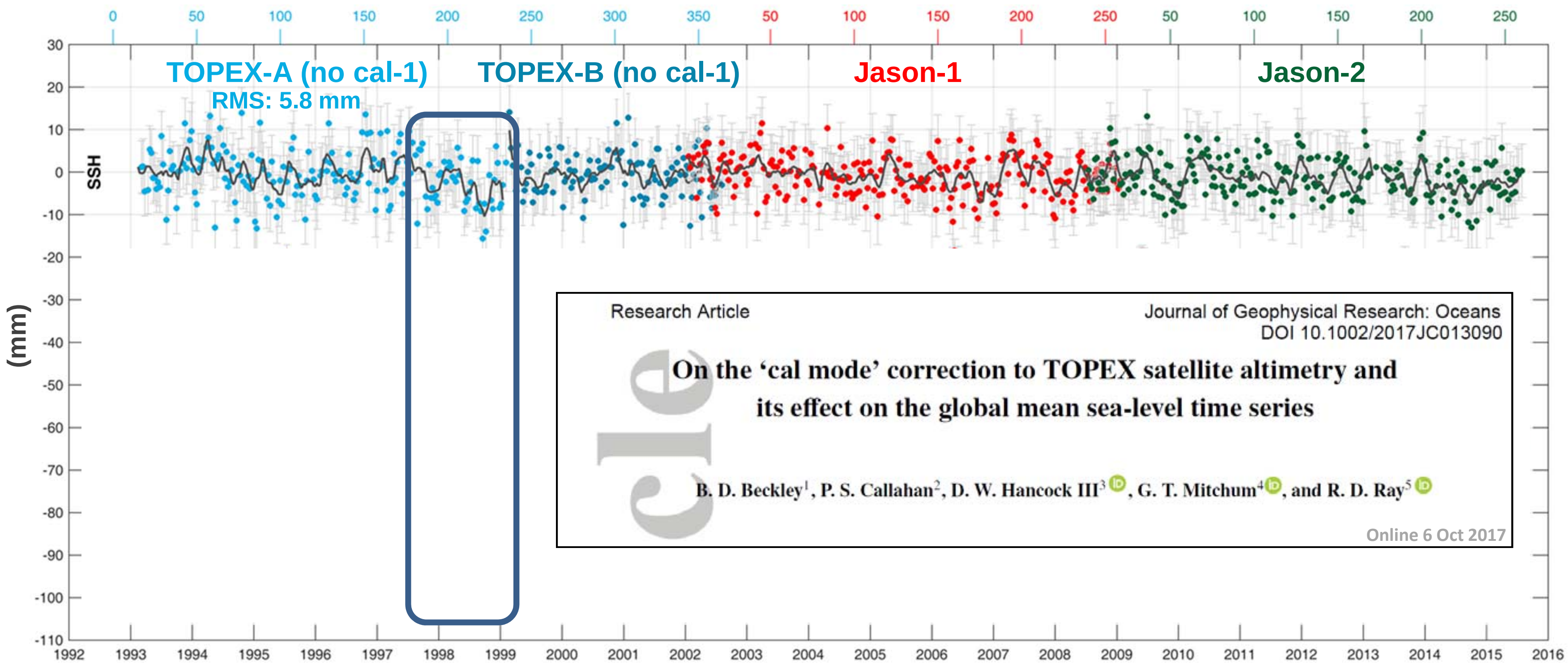
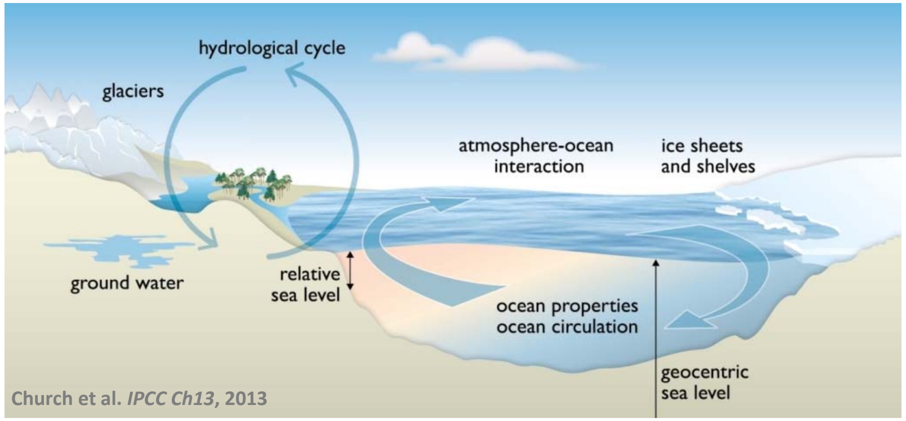


Watson et al: Physically plausible or not?

- Watson et al. advocated for a marginally lower average rate of rise (the exact amount depending on choice of VLM), but one that was increasing slightly over time, rather than decreasing slightly (both insignificant).
- **Is this result physically plausible?**



Church et al. *IPCC Ch13*, 2013

- What does the sum of the individual contributions tell us?
- This question was investigated at similar times by two groups: (Chen et al. *NCC*, 2017 & Dieng et al. *GRL*, 2017)

nature climate change
LETTERS
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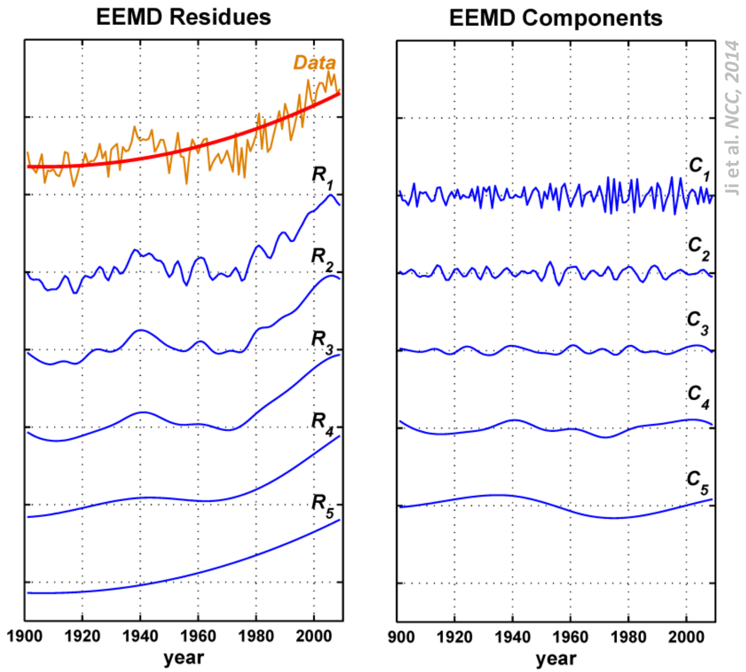
The increasing rate of global mean sea-level rise during 1993–2014

Xianyao Chen[1]*, Xuebin Zhang[2]*, John A. Church[3], Christopher S. Watson[4], Matt A. King[4], Didier Monselesan[2], Benoit Legresy[2] and Christopher Harig[5]

Chen et al: Budget Approach

- Analysis by Chen et al. (2017) is based on an ensemble empirical mode decomposition (EEMD) of each sea level component (following Wu et al. 2007, and Wu and Huang, 2009 and Chen et al. 2014).
    - Process adaptively separates a time-varying intrinsic trend from interannual variability.
    - The 'intrinsic trend' is defined as a function with a maximum of one extremum over the data span.
    - There is no reliance on a predetermined functional form.

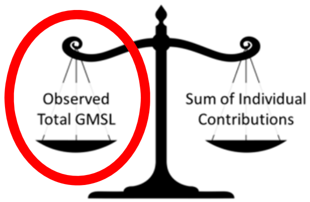
- The 'intrinsic trend' preserves potential variability on time scales longer than the length of the data series, and should be interpreted accordingly.
- The ensemble EMD approach adds white noise realizations to the input time series, and the ensemble means of the EEMD components -> overcomes some of the limitations of the EMD approach.
- The first-order time derivative of the intrinsic trend yields more useful information c.f. a fitted polynomial or sliding window linear regression.

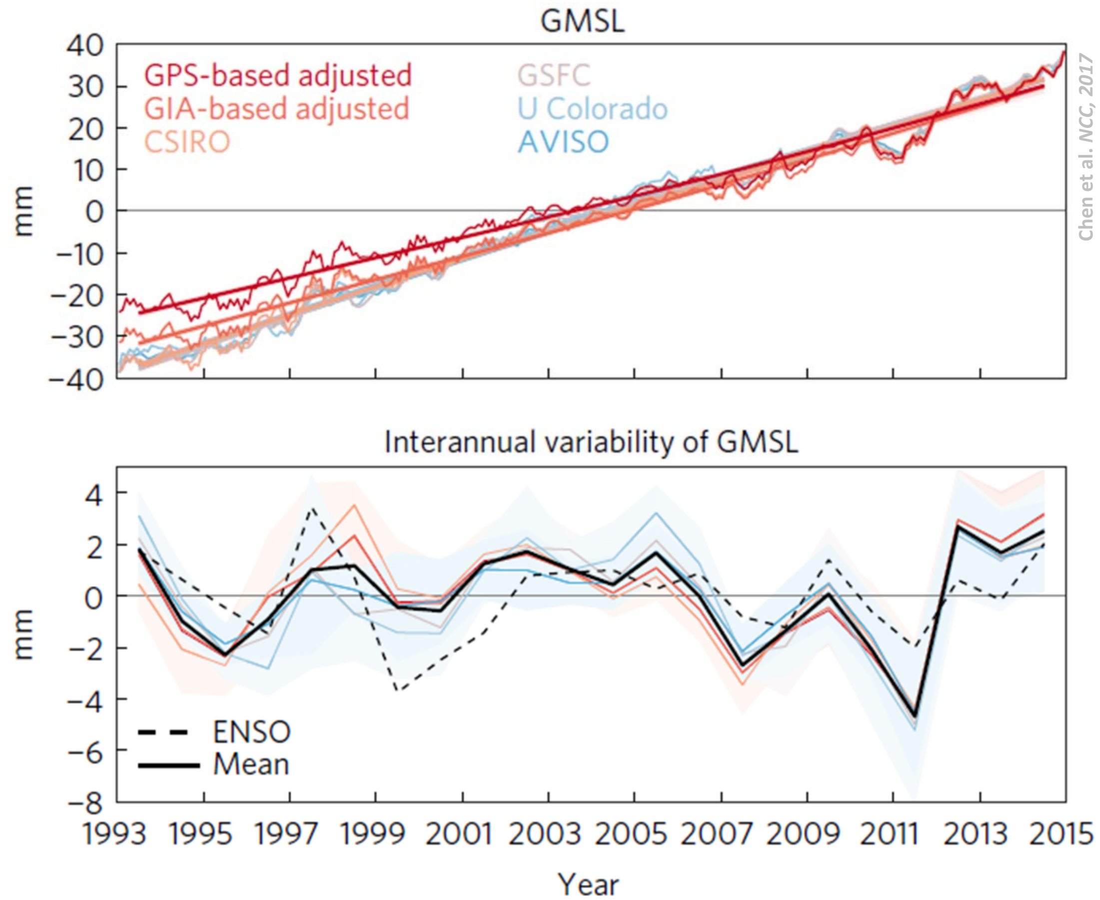


$$x(t) = \sum_{j=1}^{n} C_j(t) + R_n(t)$$

Chen et al: GMSL

- Appropriate to assess the Watson et al. (2015) results in the context of other records.
- Unsurprisingly, the Watson et al (2015) ‘GPS-based’ and ‘GIA-based’ adjusted GMSL records standout against time series from other labs.
- Also unsurprisingly, the interannual variability from the EEMD analysis agrees well between time series, and is coherent with large scale modes of climate variability.

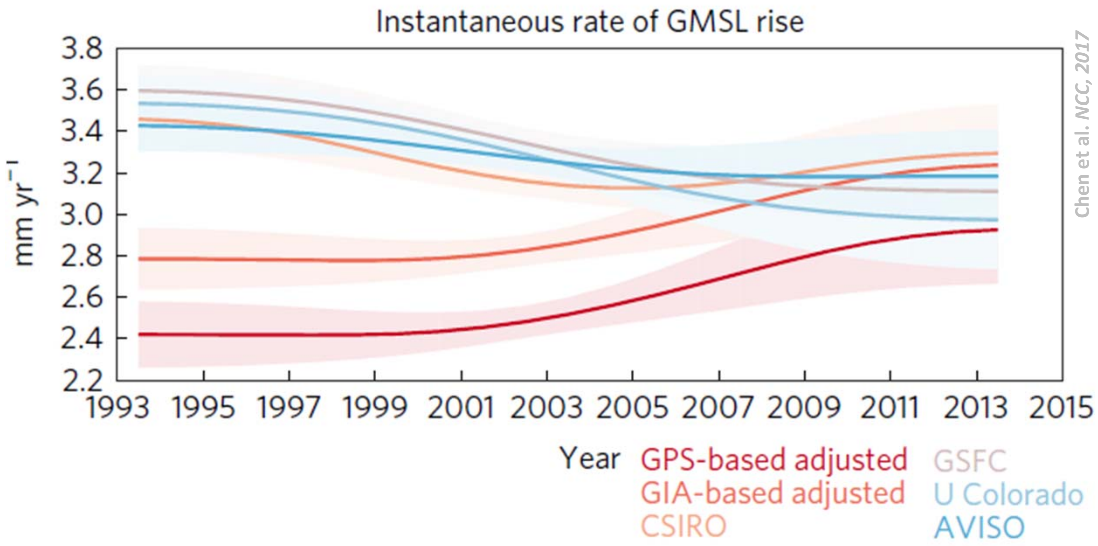




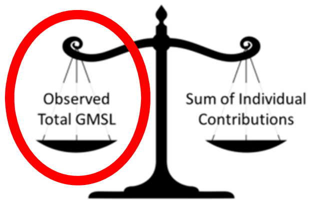
Chen et al: GMSL rates

The time variable rates from the EEMD intrinsic trend shows consistency with:

1. the previously reported deceleration in sea-level (insignificant) from the existing altimeter datasets (e.g. Cazenave et al. *NCC*, 2014).
2. the previously reported acceleration in sea-level (insignificant) (Watson et al. NCC, 2015).

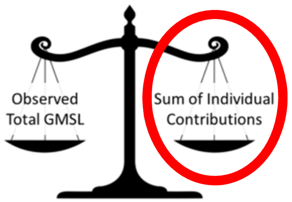


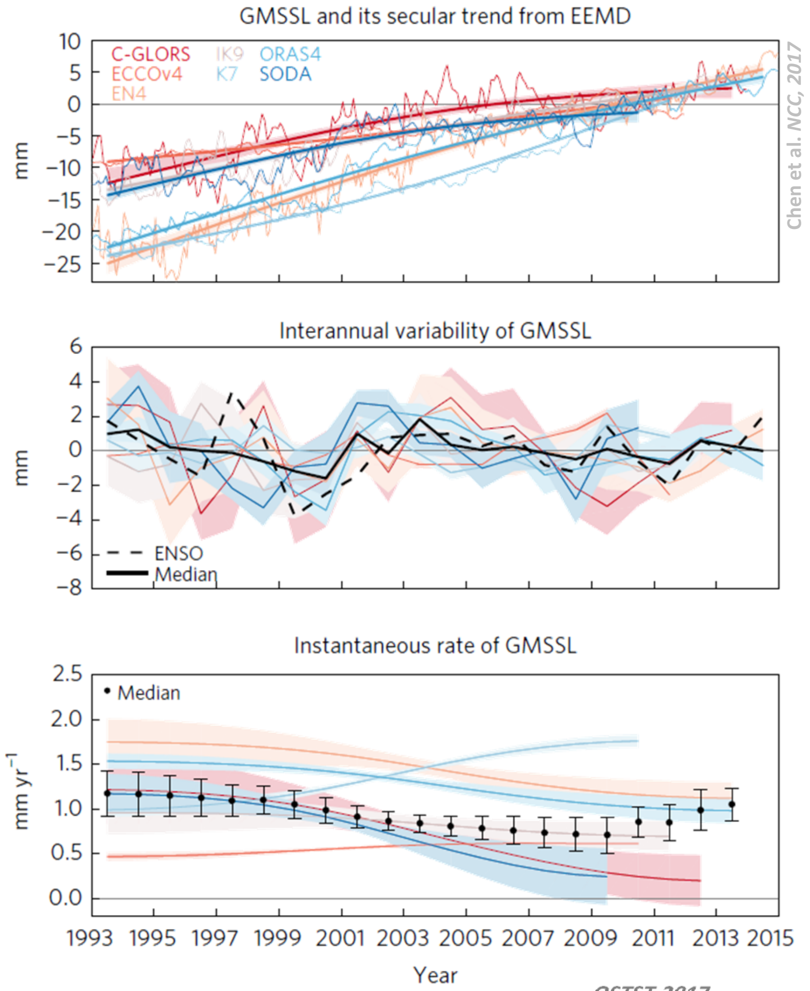
Chen et al. *NCC, 2017*



Chen et al: Steric rates

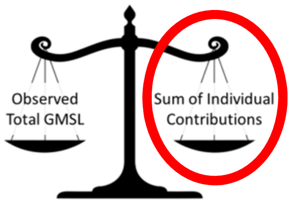
- Large variability between datasets describing the steric contribution (especially pre Argo) – characterised by inhomogeneous observations, different XBT bias corrections and QA/QC, mapping methods etc.
- We select datasets that don't have obvious discontinuities, and whose linear trend over the Argo period is within 2σ of that derived from three Argo gridded datasets. Final estimate is the median of 7 datasets.
- Steric contribution accounts for ~0.9 ± 0.2 mm yr^{-1} over the period. Insignificant change over time.

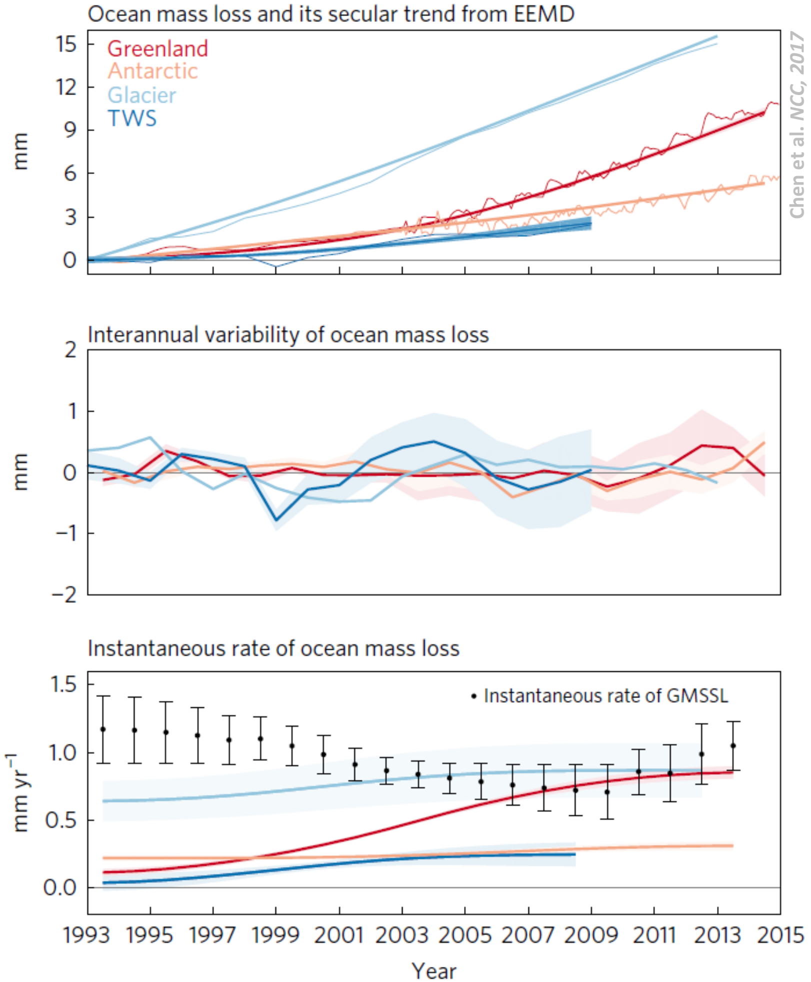




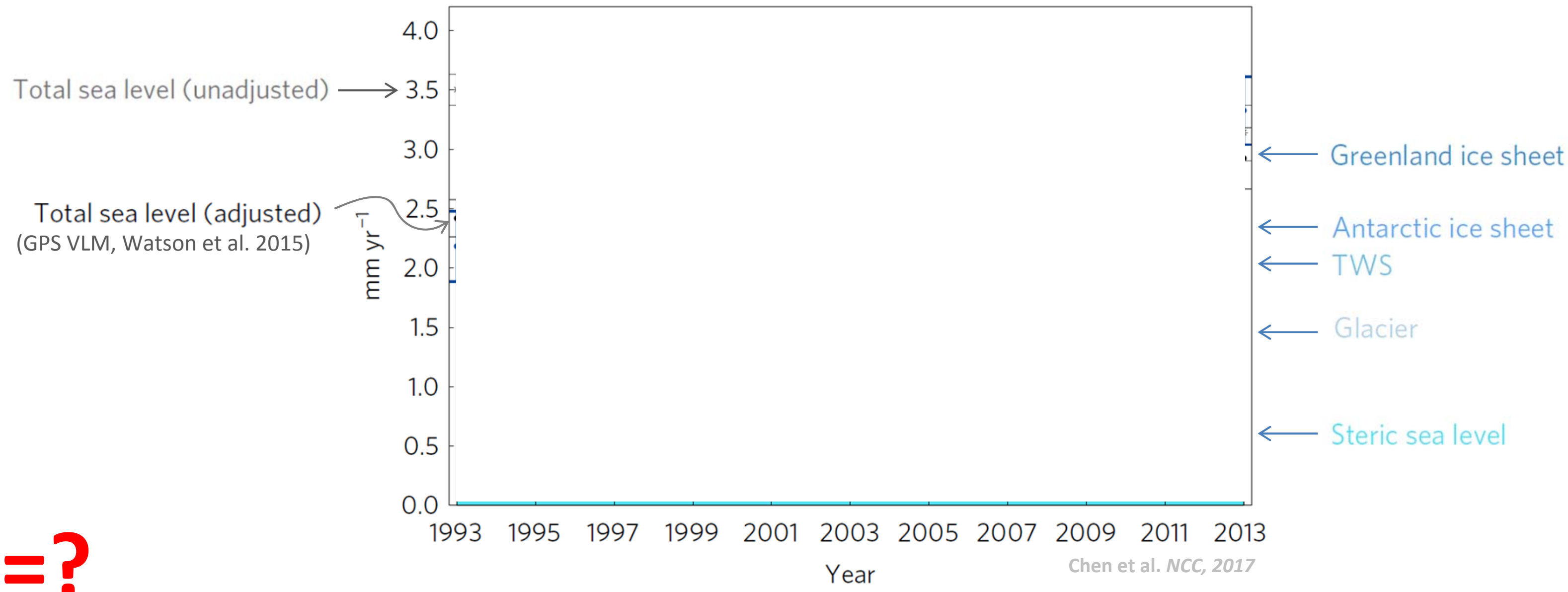
Chen et al: Mass rates

- Glacier contributions from Marzeion et al. (2014), rate is assumed unchanged from 2012-2014.
- Greenland and Antarctic ice sheet contribution from IMBIE (Shepherd et al. 2012), extended using GRACE data (adjusted to fit IMBIE over 2003-2009).
- Note the Greenland contribution is increasing notably in time (+0.11 to +0.85 mm/yr, 1993-2014).
- Terrestrial water storage from Wada et al. (2012), with their groundwater depletion replaced with estimates from Döll et al. (2014). Rate is assumed unchanged from 2009-2014.

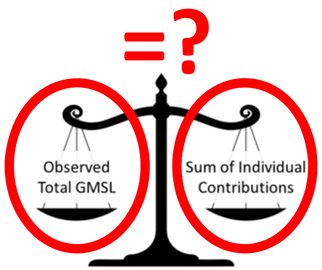




Instantaneous rate budget closure:



Chen et al. *NCC, 2017*



- The steric component contributes about ~55% of the total GMSL rate in 1993, reducing to ~30% by 2014, despite itself not changing much over the period.
- Increasing contributions come from the mass components, the largest, and statistically significant increase comes from the Greenland Ice Sheet, which is less than ~5% of the GMSL rate during 1993 but more than ~25% during 2014.

Summary and Implications (1 of 3)

1. **The findings from Watson et al (2015) remain robust:**
   - Consistent with those from other groups **(e.g. Prandi et al. & Zawadzki et al. OSTST 2016).**
   - Supported by studies of the sea level budget **(Chen et al, 2017, Dieng et al, 2017).**
   - Diversity in approaches has proved beneficial. Uncertainty remains, particularly in the treatment of land motion.

2. **What is the driver of the identified bias drift in TOPEX?**
   - Beckley et al. (2017) recently document issues associated with the TOPEX 'cal-mode', its reprocessing and subsequent effects on GMSL. This appears to explain a large percentage of the drift estimated by Watson et al.

     "The case for an 'unabated sea-level rise' [Watson et al., 2015] over the whole satellite era thus appears compelling…" **(Beckley et al. *JGR*, 2017).**

   - Some uncertainty remains, particularly in the first ~1.5 years of the record.
   - We look forward to the release of a new TOPEX dataset.

Summary and Implications (2 of 3)

3. **Validate or Calibrate?**
   - Altimeter validation remains a critical component in the cyclic chain of 'assess-diagnose-refine-rerelease-assess' altimeter processing and should remain so.
   - In the absence of a reprocessed record, assessment of the implications on GMSL has provided important insights.

"…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."
(Watson et al. NCC, 2015).

Summary and Implications (3 of 3)

4. **Incremental improvements:**
   - The magnitude of the signals discussed here are small and need to be considered in the context of the mission objectives and achievements.

5. **Geophysical implications of this work:**
   - Our work suggests the emergence of an acceleration in sea level over the altimeter era.
   - This finding is supported by an improved instantaneous closure of the sea level budget where we see the mass contributions to the GMSL rate rise from ~45% in 1993 to ~70% in 2014.
   - The record remains short and ongoing observations are required to understand the longer-term significance of this finding, and to identify the contributions of decadal and multi-decadal variations that are unresolved in ~20-year-long records.

No chaos in the satellite-data record

The use of the slang term snafu (indicating a confused or chaotic state) in your headline 'Satellite snafu masked true sea-level rise for decades' undermines the satellite record's crucial contribution to the precise measurement of indicators of Earth's changing climate (*Nature* **547**, 265–266; 2017).

The correction you report represents less than 1 centimetre of the total sea-level increase of 8 cm or more that has been observed since 1993. Removing this small correction helped to reveal that the globally averaged rise in sea levels is accelerating. We used solid analysis and detective work to refine the accuracy of the satellite-data record to within less than 1 cm — not to fix a snafu.

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John Church *University of New South Wales, Sydney, Australia.*
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Nerem, Cazenave, Church, *Nature*, 2017

Questions?

OSTST 2017
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Main Conclusions:

- Watson et al. (2015) result remains robust, confirmed by other groups, and now assessed by Beckley et al. (2017).
- Chen et al. (2017) show that the mass contributions to GMSL increase from ~45% in 1993 to ~70% in 2014.
- The largest increase comes from the contribution from the Greenland Ice Sheet: ~5% in 1993, to ~25% in 2014.

Papers:

- Watson, C.S., White, N.J., Church, J.A., King, M.A., Burgette, R.J., Legresy, B. (2015) Unabated global mean sea-level rise over the satellite altimeter era, *Nature Climate Change* 5(6), pp.565-568. DOI: 10.1038/nclimate2635.
- Chen, X., Zhang, X., Church, J.A., Watson, C.S., King, M.A., Monselesan, D., Legresy, B, Harig., C. (2017) The increasing rate of global mean sea-level rise during 1993–2014, *Nature Climate Change*, 7(1), pp.492–495. DOI: 10.1038/nclimate3325.

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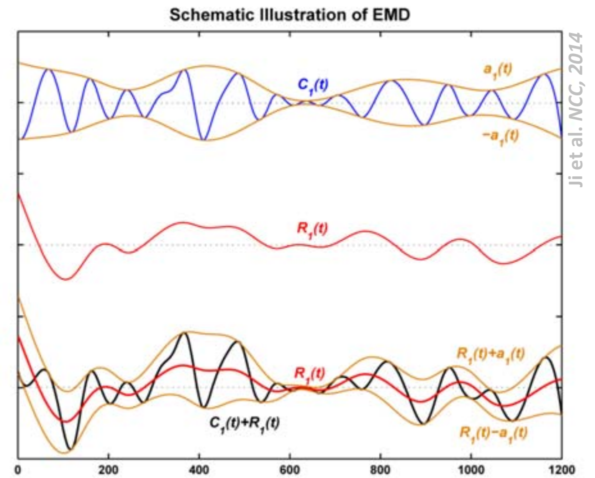
Spares

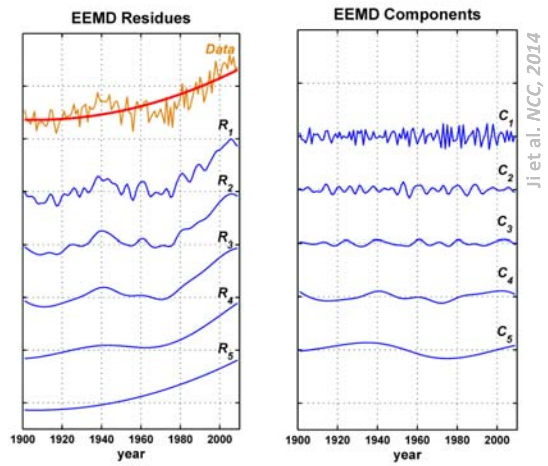
EMD Background

Steps undertaken within the EMD process:

1. Locate all maxima and minima in the input series. Connect all maxima (minima) with a cubic spline to define an upper (lower) envelope of the time series;
2. Compute the difference between the time series and the mean of the upper and lower envelopes to yield a new time series *h(t)*;
3. For series *h(t),* repeat steps 1 and 2 until the upper and lower envelopes are symmetric with respect to zero mean under the stopping criteria. The result is an IMF designated $C_j(t)$.
4. Subtract $C_j(t)$ from the original time series to yield a residual, *R(t)*.
5. Now treat *R(t)* as the original time series, repeat steps 1->4 until the residual *R(t)* becomes a monotonic function or a function with only one extremum.

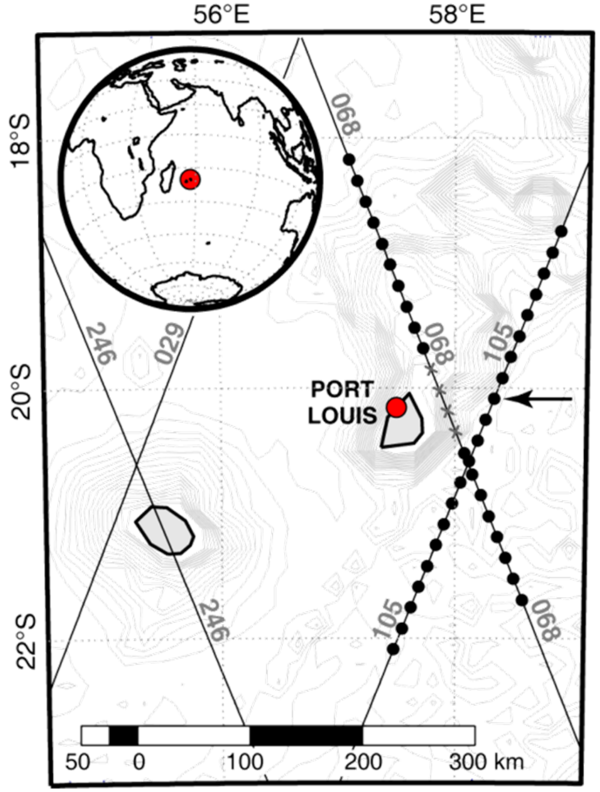
$$x(t) = \sum_{j=1}^{n} C_j(t) + R_n(t)$$





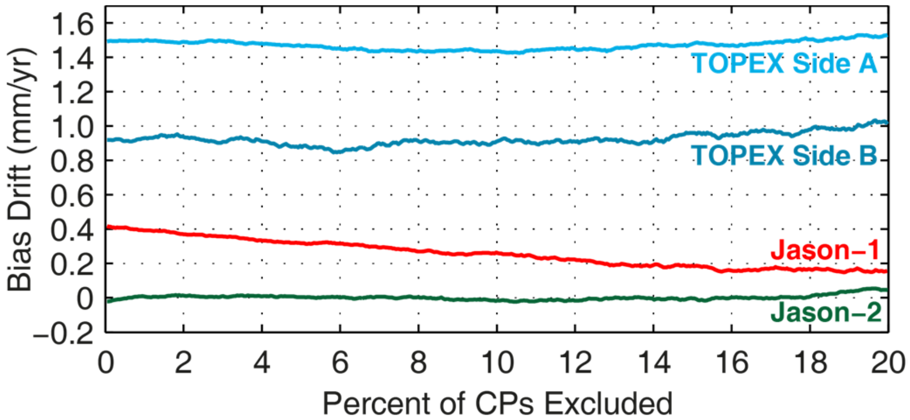
Method: Altimeter – Tide Gauge

1. **Start with 122 tide gauges, using hourly data.**
2. **Multiple passes per gauge, multiple comparison points (CPs) per gauge.**
3. **Altimeter data here are "GDR-D" standard. GSFC1204/1404 orbits. Chambers et al SSB for TOPEX.**
4. **Vertical Land Motion (VLM) at tide gauges from:**
   a) updated GPS estimates (King et al. 2012) (69% of gauges have GPS within 100 km); or:
   b) Peltier ICE-5Gv1.3_2012 (VM2) GIA + elastic effects (updated from Riva et al. 2010).
5. **For each mission, we use the variability around the trend to weight the relative contribution of each CP to a global weighted average bias drift estimate.**



How Robust Are These Findings?

- **Could a small number of TGs or CPs bias the solution?**
- **We progressively eliminate up to 20% of the CPs with highest weighting in the solution:**



Watson et al. *Nature Climate Change* 2015

How Robust Are These Findings?

- Do the inter/intra mission relative biases compare well with expected results?
- We compute these using the same weighting as per bias drift.
- Our preferred SSB model for TOPEX is from Chambers et al. 2003. Our TOPEX A/B relative bias is in close agreement with their findings.
- Note: changing the A/B bias by 1 mm introduces 0.06 mm/yr in the GMSL trend over the duration of the record

Formation Flight Relative Biases:

Jason-1 – TOPEX side B	
Our Approach	Global Mean
+86.1±2.0 mm	**+85.9**±1.2 mm

OSTM/Jason-2 – Jason-1	
Our Approach	Global Mean
-73.8±1.5 mm	**-73.2**±0.5 mm

TOPEX A / B Relative Bias:

TOPEX side B – TOPEX side A
-3.0±2.5 mm

How Robust Are These Findings?

- **Could a small portion of the TOPEX record cause the apparent drift?**
- **Recall a positive bias drift implies the altimeter data overestimates the trend in GMSL.**

TOPEX-A Data Duration	TOPEX-A Bias Drift
All TOPEX-A data (commencing cycle 11)	+1.52 ± 0.49 mm/yr
Exclude 1.5 years at end of TOPEX-A (i.e. exclude degradation of side A)	+0.93 ± 0.68 mm/yr
Exclude 1 year at start of TOPEX-A (as per Cazenave et al., 2014)	+1.95 ± 0.66 mm/yr

How Robust Are These Findings?

- **Is the linear model for bias drift appropriate?**
- **Residuals show TOPEX A bias drift is complex. A piecewise linear approach is informative.**

Parameter	Linear Model	Piecewise Linear Model
Bias Drift	+1.52 ± 0.49 mm/yr	P1: -2.91 ± 1.56 mm/yr P2: +2.84 ± 1.31 mm/yr P3: +1.04 ± 1.60 mm/yr
TOPEX A Residual RMS	6.12 mm	5.39 mm
TOPEX B-A Relative Bias	-3.0 ± 2.5 mm	+0.0 ± 5.1 mm
Calibrated GMSL Rate	+2.5 ± 0.4 mm/yr	+2.4 ± 0.5 mm/yr
Calibrated GMSL Acceleration	+0.024 ± 0.062 mm/yr^2	+0.030 ± 0.062 mm/yr^2