Assessing the rate of GMSL change over the satellite era

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UNIVERSITY of TASMANIA
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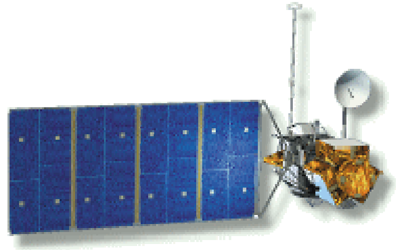
NM STATE UNIVERSITY
IMOS Integrated Marine Observing System

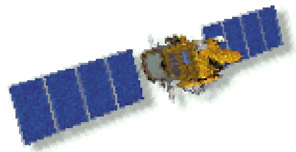
Satellite era changes in GMSL:

Consensus estimate for the rate of GMSL change using Jason-series altimetry is +3.2 ± 0.4 mm/yr (IPCC AR5, 2013)

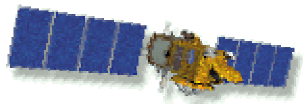
- **Useable record now approaching 22 years duration**
- **Uncertainty reflects validation approach** (e.g. Mitchum, 2000)
- **Close agreement between groups** (e.g. Masters et al, 2012)
- **Understanding of inter-annual variability in GMSL is improving** (e.g. Fasullo et al., 2013)



TOPEX / Poseidon
Aug 1992 -



Jason-1
Dec 2001 –



OSTM/Jason-2
June 2008 -

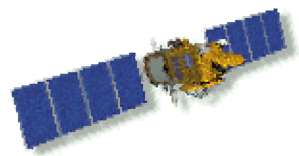
Satellite era changes in GMSL:

Some recent perspectives relating to the GMSL trend:

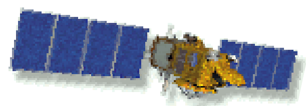
- The sum of observed contributions to GMSL over the same period is slightly smaller **+2.8±0.5 mm/yr** (IPCC AR5, 2013)
- The rate from tide gauges alone, corrected for land motion is **+2.7 ± 0.6 mm/yr** (updated from Church and White, 2011)
- ERS/Envisat GMSL time series underestimates trend w.r.t Jason-series (ESA CCI OSTST2015 talk, Meyssignac et al)
- The altimeter time series suggests a slowing in the rate despite some accelerating contributions
- Some recent evidence in the literature for questioning the early TOPEX record (e.g. Cazenave et a., 2014 excludes all 1993 data)

At what level could +3.2 ± 0.4 mm/yr be systematically biased?

TOPEX / Poseidon
Aug 1992 -



Jason-1
Dec 2001 –

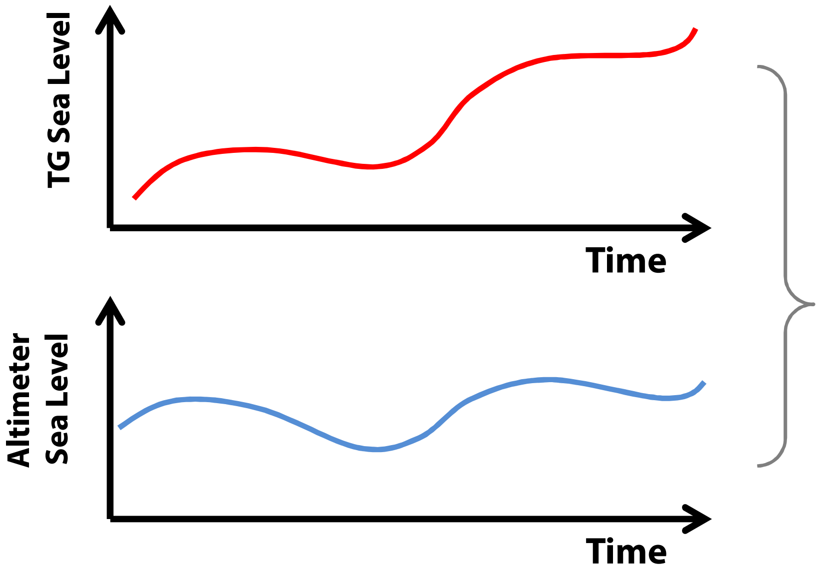


OSTM/Jason-2
June 2008 -

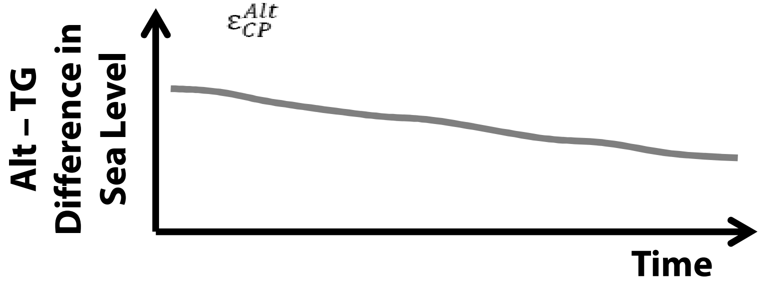
Methods Recap (1 of 2):

The difference between tide gauge (relative) sea level and altimeter (geocentric) sea level tells us about:

- **Vertical Land Motion (VLM) at the gauge**
- **Residual systematic error (“bias drift”) in the altimeter**
- **Residual tide and across-track SSH slope**
- **Residual ocean dynamics b/w the tide gauge and the offshore comparison point**



$$
\begin{aligned}
\Delta SSH^{Alt}_{CP} = {} & [Offset]^{Alt}_{CP} + \cdots \\
& [VLM]_{TG}.(t - t_0^{Alt}) + \cdots \\
& [Drift]^{Alt}_{CP}.(t - t_0^{Alt}) + \cdots \\
& \textstyle\sum_{i=1}^{N} [A_i \cos(2\pi f_i t + \Phi_i)]_{CP} + [SSHSlope]_{CP}.\mathrm{d} + \cdots \\
& \varepsilon^{Alt}_{CP}
\end{aligned}
$$

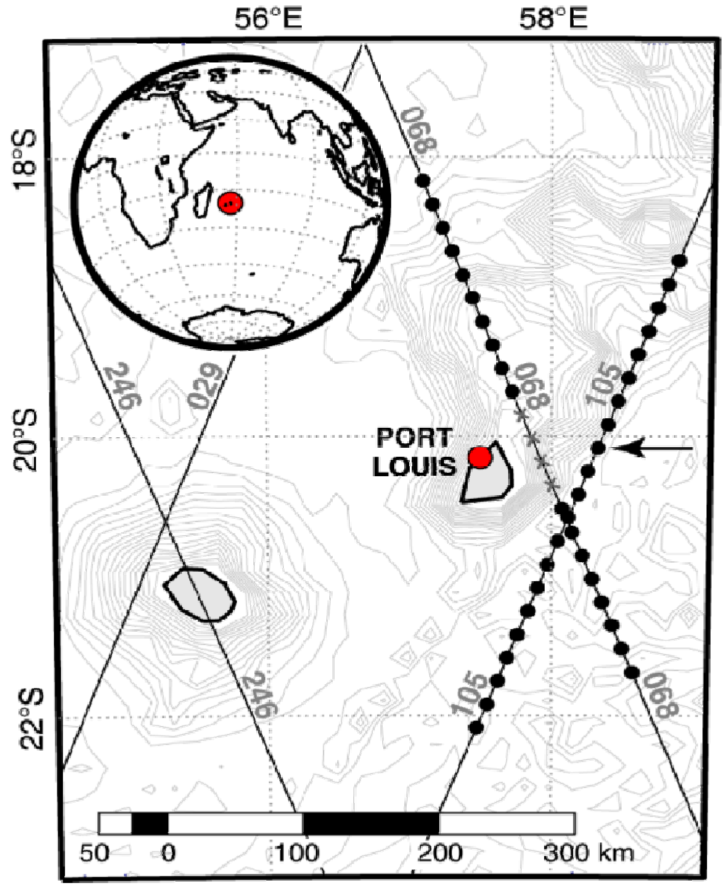


Methods Recap (2 of 2):

We take a slightly different approach to the established technique(s):

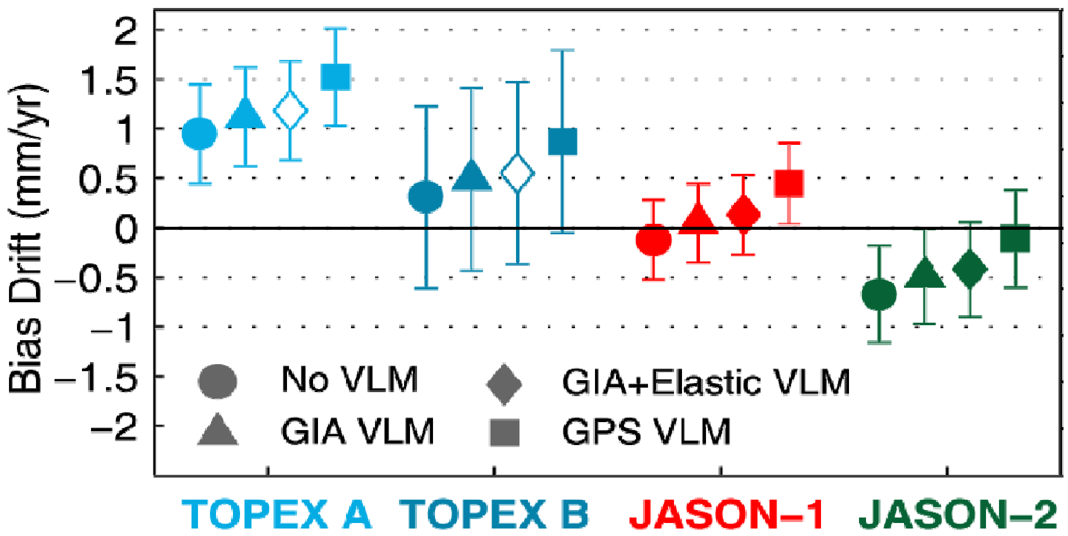
1. **Start with 122 tide gauges, using hourly data.**
2. **Multiple passes per gauge, multiple comparison points (CPs) per gauge.**
3. **We solve for residual tides and across track gradients in altimeter – tide gauge.**
4. **We use the variability around the trend to weight the relative contribution of each CP to the ensemble global average bias drift estimate.**
5. **VLM from updated GPS estimates (King et al. 2012) (69% of gauges have GPS within 100 km) else Peltier ICE-5Gv1.3_2012 (VM2) GIA + elastic effects (updated from Riva et al. 2010).**

Results here are "GDR-D" standard. GSFC1204 orbits across all missions. Chambers et al SSB for TOPEX.



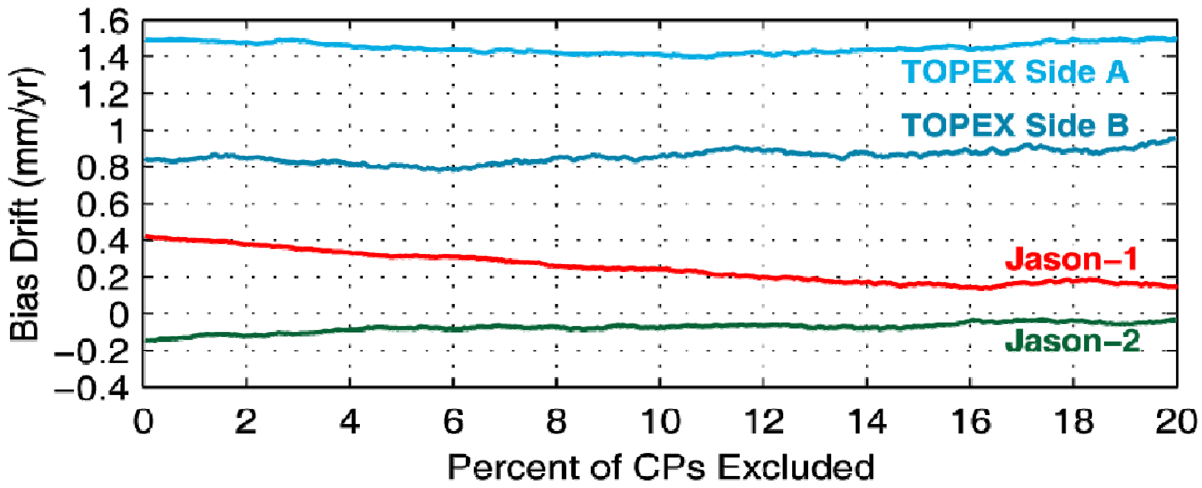
Results Recap:

- **Our bias drift results for each mission vary systematically as a function of VLM applied.**
- **Note that a positive bias drift implies the altimeter data overestimates the trend in GMSL.**
- **Should the best-estimates of systematic bias drift be used to calibrate GMSL?**



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:**



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?

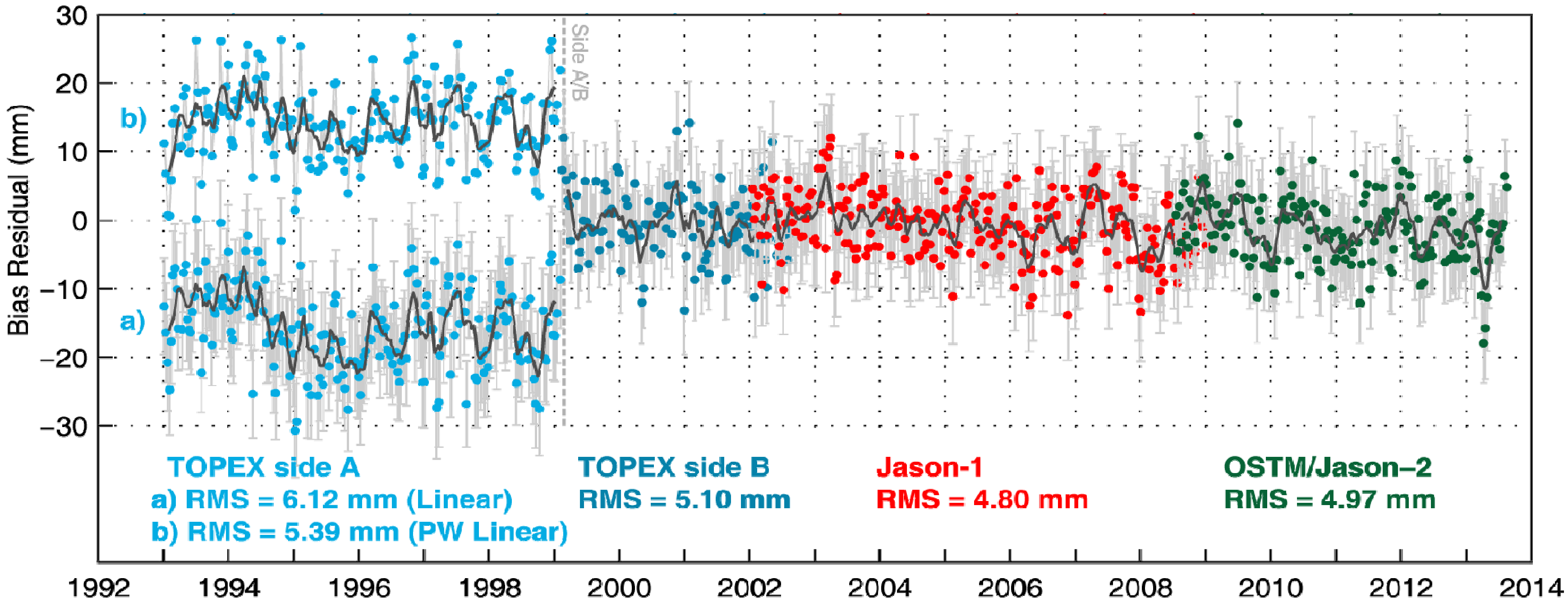
- **Could a small portion of the TOPEX record cause the apparent drift?**
- **Recall a positive bias drift implies the altimeter data overestimates the trend in GMSL.**

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

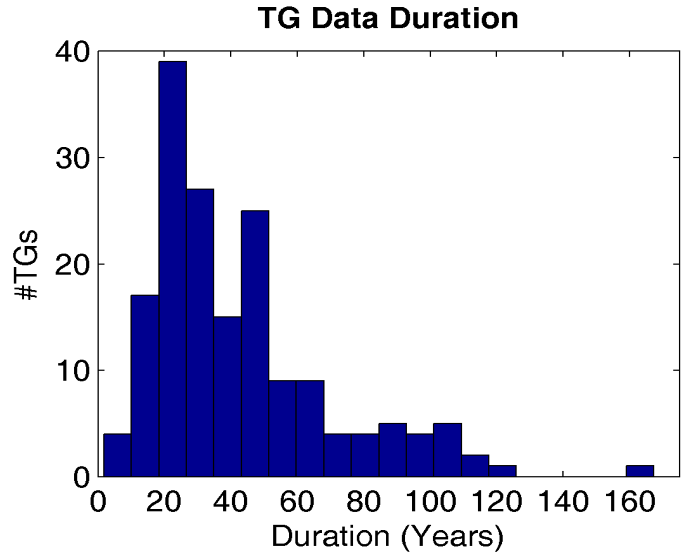


How Robust Are These Findings?

- **Is GPS or GIA + Elastic (where GPS is unavailable) the best possible vertical land motion to apply?**
- **An alternative approach is to assume that the difference between the global average rate of SLR and the "long term" rate at the TG can be attributed to VLM (Mitchum, 2000). Using this as the sole VLM (i.e. circular argument) is informative.**

Using GMSL +3.2 mm/yr to compute VLM:

	Bias Drift (mm/yr)
TOPEX A	**+0.17** ± 0.51
TOPEX B	-0.38 ± 0.93
Jason-1	-0.35 ± 0.45
Jason-2	



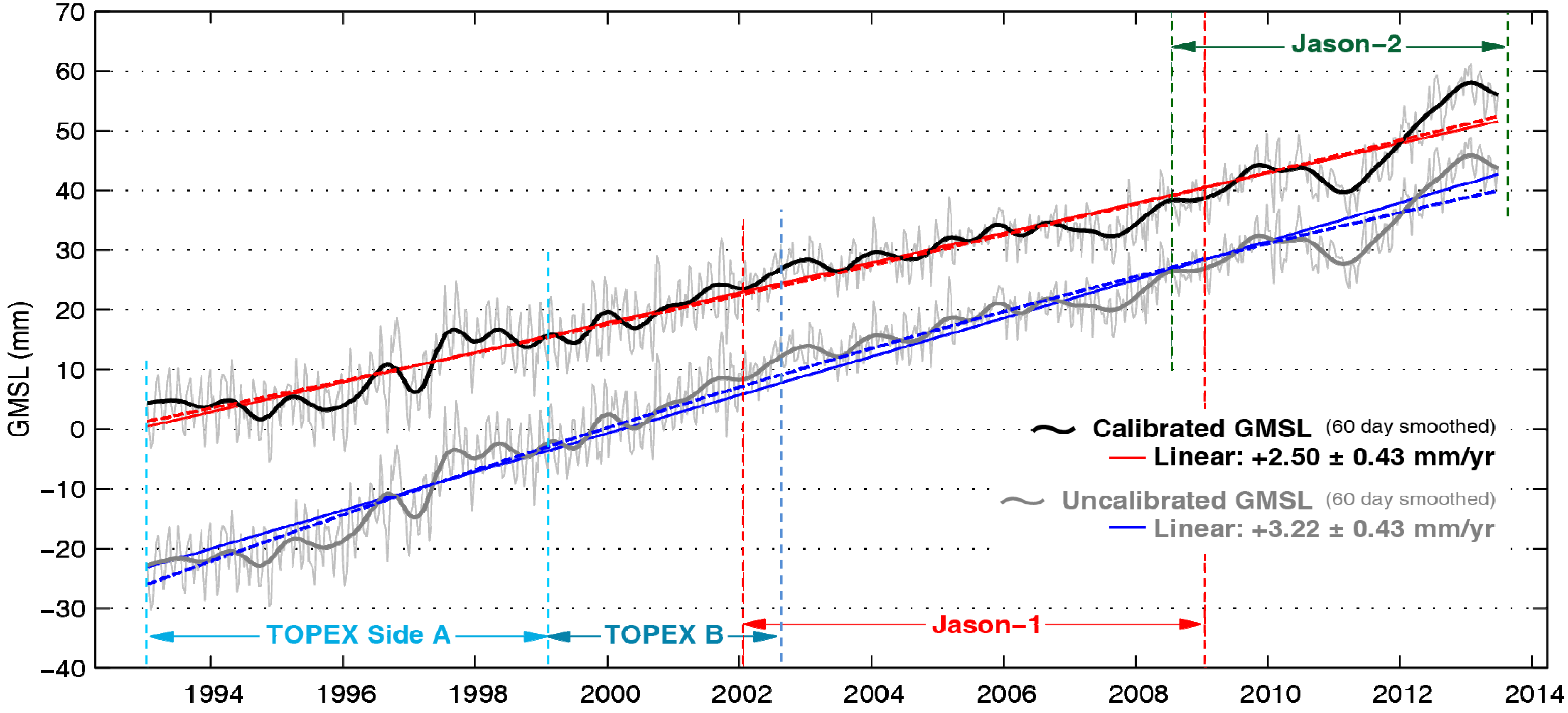
How Robust Are These Findings?

- **What does the multi-mission bias drift show?**
- **Results support previous mission-specific findings, i.e. altimeter overestimates GMSL rate if you believe GPS VLM at TGs.**

VLM Applied	Bias Drift (mm/yr)
None	+0.14 ± 0.25
GIA+Elastic	+0.45 ± 0.25
GPS (or GIA+Elastic)	+0.79 ± 0.23

- **Applying mission specific drifts, then assessing the multi-mission bias drift also provides a useful misclose test.**

What would "calibrated" GMSL reveal?



Concluding Remarks (1 of 2)

1. **Our analysis advocates a systematic reduction in the rate of GMSL rise over the satellite era:**

   From: +3.2 ± 0.4 mm/yr (consensus estimate, IPCC AR5)

   To: +2.8 ± 0.4 mm/yr (calibrated, GIA+Elastic VLM applied)

   To: +2.5 ± 0.4 mm/yr (calibrated, GPS based VLM applied)

2. **These results are supported by:**

   i. **GMSL computed from tide gauges alone (1993.0-2013.0), corrected for GPS VLM: +2.7 ± 0.6 mm/yr**

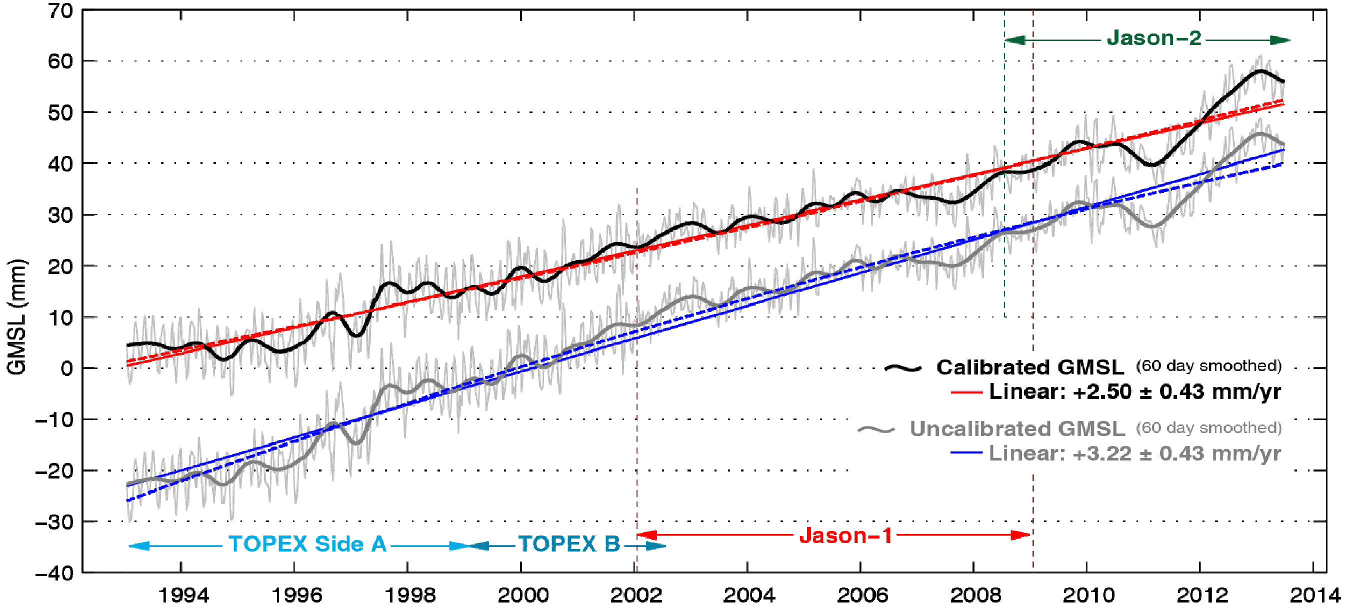
   ii. **Sum of observed contributions to GMSL (1993.0-2010.0), as per IPCC AR5: +2.8 ± 0.5 mm/yr**

Concluding Remarks (2 of 2)

3. **Our calibrated GMSL curve removes a slowing in the observed rate, leaving a small acceleration.**

4. **The dominate driver of this revision is apparent residual systematic error in TOPEX (re-tracking? TMR? Side A degradation? – note Phil Callahan's talk this Tuesday).**

5. **Improved GPS velocities at TGs remain critical.**



Questions?

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Spares: How Robust Are These Findings?

- **How does GPS + (GIA + Elastic) compare with GPS + ("Internal")?**
- **i.e. where we don't have GPS, what is the preferred strategy?**

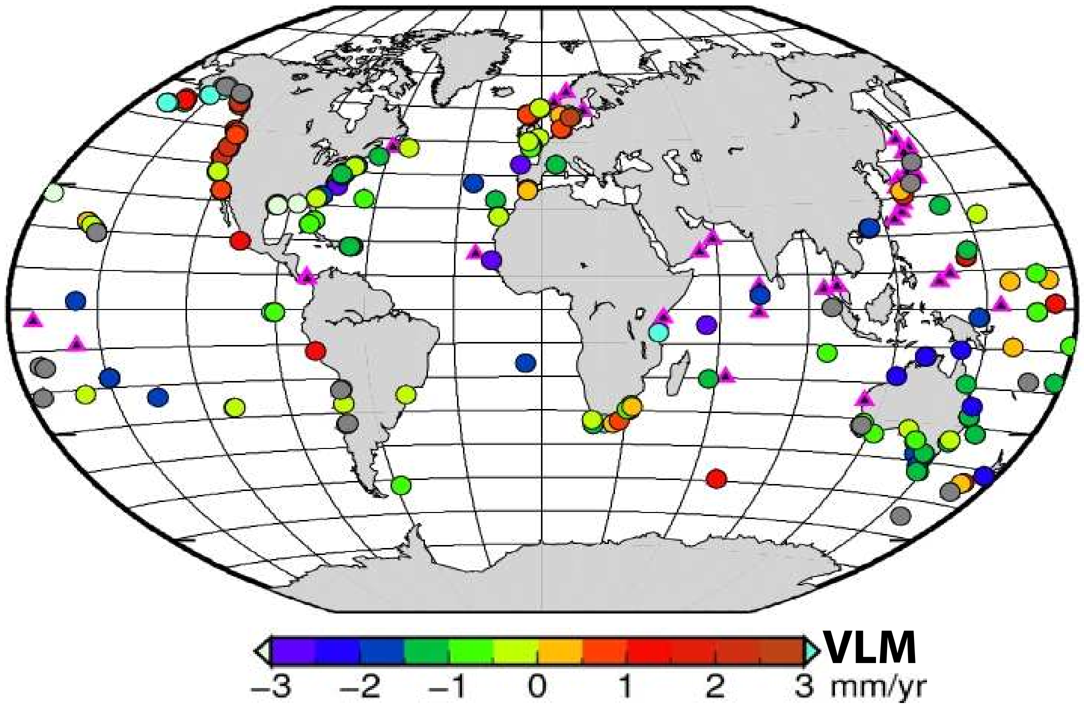
	Bias Drift (mm/yr)		
	GPS + (GIA + Elastic)	GPS + Internal (+3.2)	GPS + Internal (+2.5)
TOPEX A	+1.52 ± 0.49	+1.41 ± 0.49	+1.59 ± 0.49
TOPEX B	+0.87 ± 0.92	+0.76 ± 0.93	+0.94 ± 0.93
Jason-1	+0.45 ± 0.41	+0.50 ± 0.41	+0.66 ± 0.41
Jason-2	-0.11 ± 0.48	-0.11 ± 0.50	+0.07 ± 0.49

Note: Uses GMSL = +3.2 mm/yr when computing VLM at TGs.

Note: Uses GMSL = +2.5 mm/yr when computing VLM at TGs.

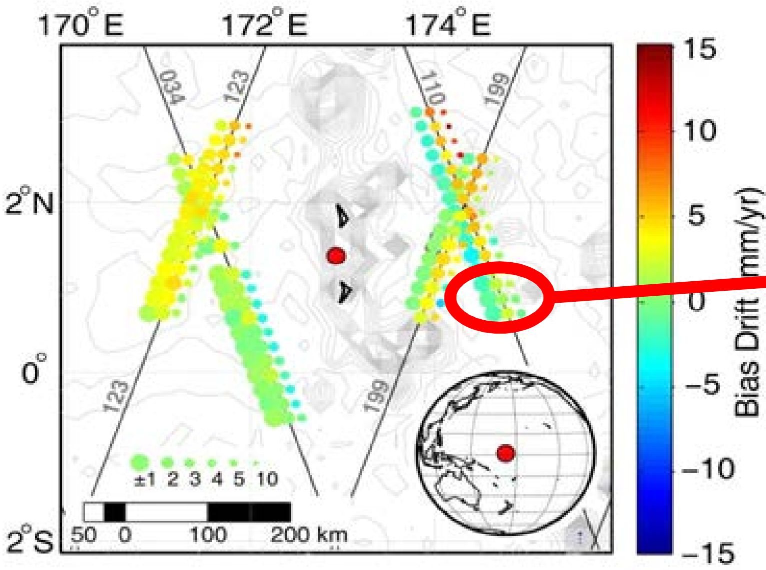
Spares – Vertical Land Motion

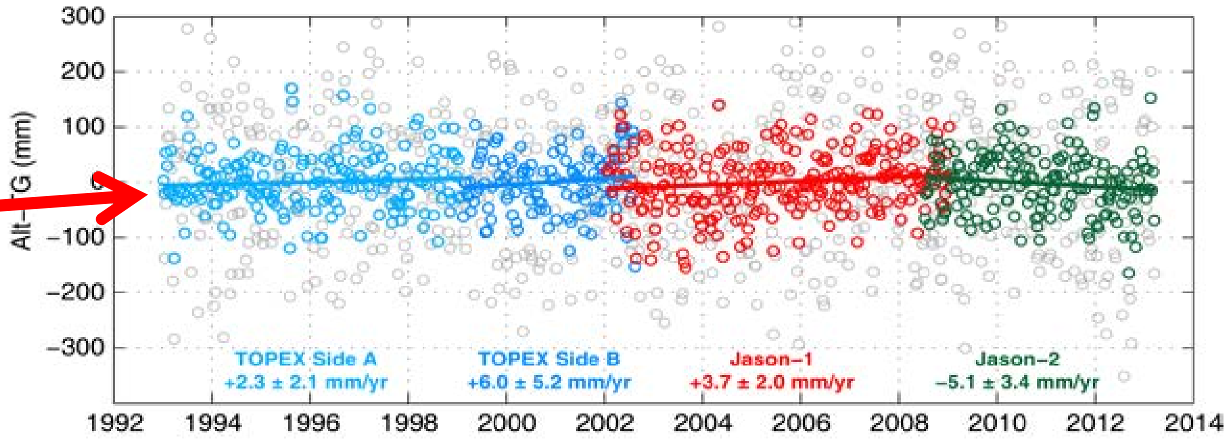
- **We use a GPS vertical land motion field (1995-2013.5, updated from King et al. 2012), else use GIA crustal rates from Peltier ICE-5Gv1.3_2012 (VM2) plus a additional term to account for elastic effects (Riva et al). We have GPS rates within 100 km at 69% of TGs.**
- **We model earthquake coseismic deformation and threshold gauges within a given criterion.**



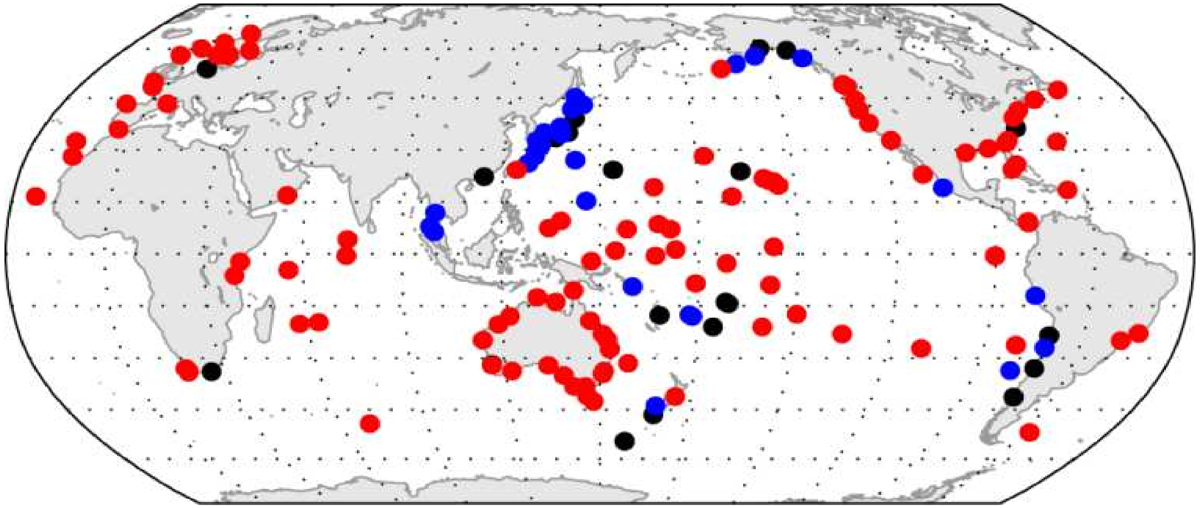
Spares – Example CP

- Grey dots are Alt - TG, before we solve for the residual tide.
- Coloured dots are mission specific Alt – TG following solution for tide and across track gradients.





Spares – Tide Gauge Network



- Initial TG outliers
- Earthquake affected TGs
- Remaining TGs