Accuracy requirements for detecting changing trends in sea level

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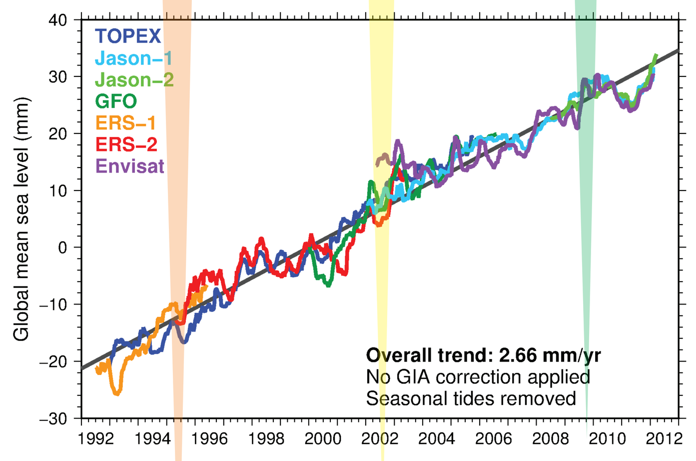
¿ Some climate models have suggested that global warming will accelerate sea level rise, which is clearly a strong motivation for maintaining a high-quality altimetric observing system. This raises the questions:

- How long is needed to detect a change?
- What is the effect of loss of continuity?

This poster explores a methodology to answer this; the author truly welcomes criticism as to the assumptions used and the numbers plucked from the literature. ?

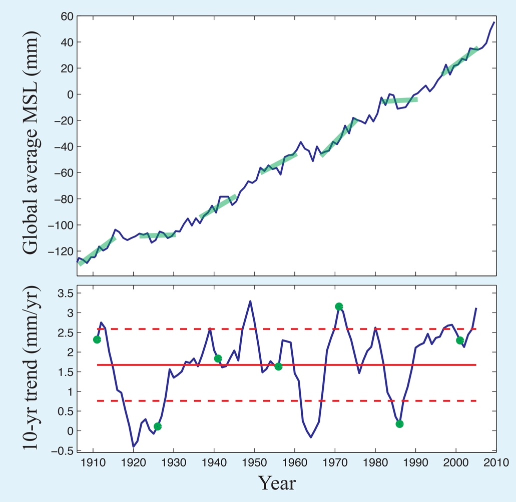


The 20-year altimetric record of global average mean sea level (MSL), based on instruments in both the TOPEX/Jason orbit and others (ERS/Envisat & GFO) has a trend of ~2.7 mm/yr, with much short-term variation (e.g. due to El Niño).

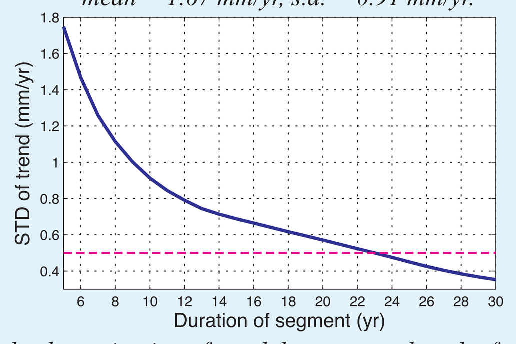
Past

What can we learn from the past?

There are clearly no century-long measurements of global mean sea level, but Church & White (2011) have developed a reconstruction based on recent altimetry plus long tide gauge records. I examine this reconstruction as a guide to the magnitude of the interannual to multi-decadal variability within the natural system.



a) Global MSL from Church & White (2011) reconstruction, with illustrative trends for 10-yr segments. b) Calculated trends for overlapping 10-yr segments: mean = 1.67 mm/yr, s.d. = 0.91 mm/yr.

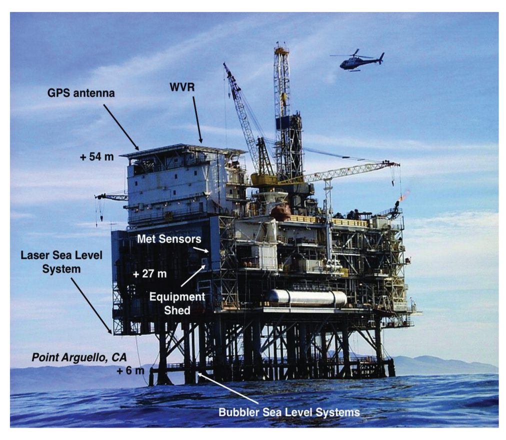


Variability in the determination of trend decreases as length of segment increases; 23 years is needed to reduce s.d. below 0.5 mm/yr

Present

What are our present capabilities?

Requirement: OSTST 2010 recommended that an altimetric observing system (altimeter plus all supporting data, field campaigns & calibration sites) should have a system drift "within 1 mm/yr". Here this is interpreted as the uncertainty should have a s.d. ≤ 0.5 mm/yr.



Harvest oil platform, equipped for altimeter calibration (from Haines et al., 2010)

Altimeter bias: Uncertainty in internal path length is of order 100 mm for a mission. Dedicated cal/val sites can reduce this to ~7 mm in the first 6 months and to ~4 mm given many years (Haines et al., 2003; Bonnefond et al., 2003; Watson et al. 2004). Using global data from the tandem phase, uncertainty may be reduced to 1-2 mm (Leuliette et al., 2004; Dettmering & Bosch, 2010).

Temporal variation: Long-term validation reveals slow drifts in the observing system, with uncertainty of order 0.4-1.0 mm/yr (Leuliette et al., 2004). Individual altimeters have also had step changes of 0.5 mm (Leuliette & Miller, 2009), which are best estimated through comparison with independent altimeter systems

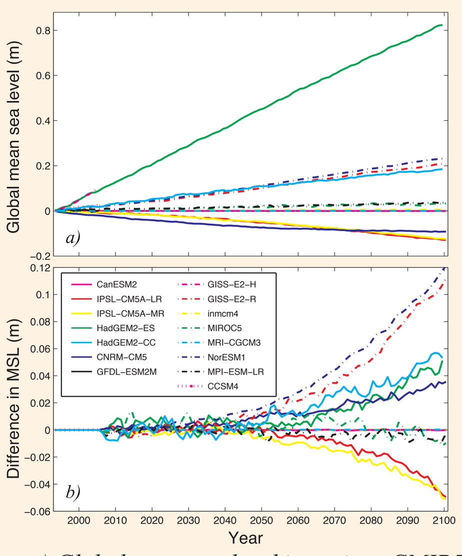
Lack of continuity: If there is no overlap (explosion on launch / telemetry or stabilization failed prematurely / lack of international funding!), then altimetric datasets would be stitched together via their separate calibration phases (assuming that we don't have complementary altimetric missions on alternative orbits.) This would be ~10 mm (root sum of squares of individual calibrations).

Future

What do we know of the future?

I obtained global average MSL from 15 different CMIP5 models (Taylor et a;., 2009), considering output for historical, RCP45 & RCP85 runs (latter 2 are warming scenarios for the 21st century).

Model name	Seas. Amp (mm)	Trend (mm/yr) 1993-2005 (hist)	2091-2100 (r45)	2091-2100 (r85)
CanESM2	0	0.0	0.0	0.0
IPSL-LR	1	-0.6	-1.3	-3.5
IPSL-MR	1	-0.5	-1.6	-3.2
HadGEM2-ES	2	8.3	7.6	8.6
HadGEN2-CC	2	1.3	1.6	2.9
CNRM-CM5	1	-1.3	-0.3	0.7
GFDL-ESM2M	1	-0.6	—	—
GISS-E2-H	3*	9.0	—	—
GISS-E2-R	3	1.9	2.3	4.7
inmcm4	0	0.1	0.1	0.1
MIROC5	2	1.3	1.1	-0.5
MRI	0	0	0.0	0.0
NorESM1	0.5*	1.5	2.0	5.0
MPI-ESM-LR	1	0.2	0.4	-0.1
CCSM4	0.5*	1.8	—	4.3



a) Global mean sea level in various CMIP5 models for end of "historical" period and for 21st century of RCP45 run. b) Increase in global mean sea level for RCP85 conditions instead of RCP45.

All the CMIP5 models analysed lack interannual variability in their rate of MSL rise. Some show no change with seasons or with 100 years of warming — presumably model specification does not permit it. Even more surprisingly there is not a full consensus on the basics:

Seasonal cycle: 9 peak in Sept-Oct; 3 in March-April

Current MSL rise: 9 positive (range 0.1-9.0 mm/yr); 4 negative

Change in MSL rise: 5 increase in rate (or less negative); 4 decrease in rate (or more negative)

Effect of greater warming: 5 have enhanced sea level rise; 4 have diminished rates.

These models can give us only minimal insight into the expected rates of changes.

Illustration of Monte Carlo technique. The grey line indicates the real MSL time series; the coloured segments are individual 5-year missions based on "truth", but with small random drift and inter-satellite biases

Monte Carlo Simulations

I investigate the confidence of the trend estimated from a sequence of altimeters, noting the duration required to reduce uncertainty below 0.5 mm/yr. Consider a set of altimeters, each running for 5 years in a near-global reference orbit, with each launch timed for 6-month overlap with predecessor. Each will measure the true MSL signal, but have uncertainty in the instrumental trend, t_i, and in relative to predecessor, b_i (see schematic above). Typically with n such missions, the uncertainty in the overall estimated trend will be, σ_T, is given by

$$\sigma_T^2 = \sigma_t^2 / n + (\sigma_b / 4.5\ \mathrm{yr})^2 / (n-1)$$

Series of 200 simulations were run for each case to note the duration needed for σ_T to be less than 0.5 mm/yr.

	0 mm/yr	0.25 mm/yr	0.5 mm/yr	0.75 mm/yr	1 mm/yr
0 mm	10	10	10	11	22
1 mm	10	10	10	13	24
2 mm	10	10	10	17	27
3 mm	10	10	15	22	31
4 mm	15	17	22	29	41
5 mm	24	26	31	42	52
6 mm	42	44	49	57	66

Years required to reduce total uncertainty below 0.5 mm/yr. In this evaluation, durations were considered after a minimum of 10 years (i.e. a year after the third mission began).

Combining Error Sources

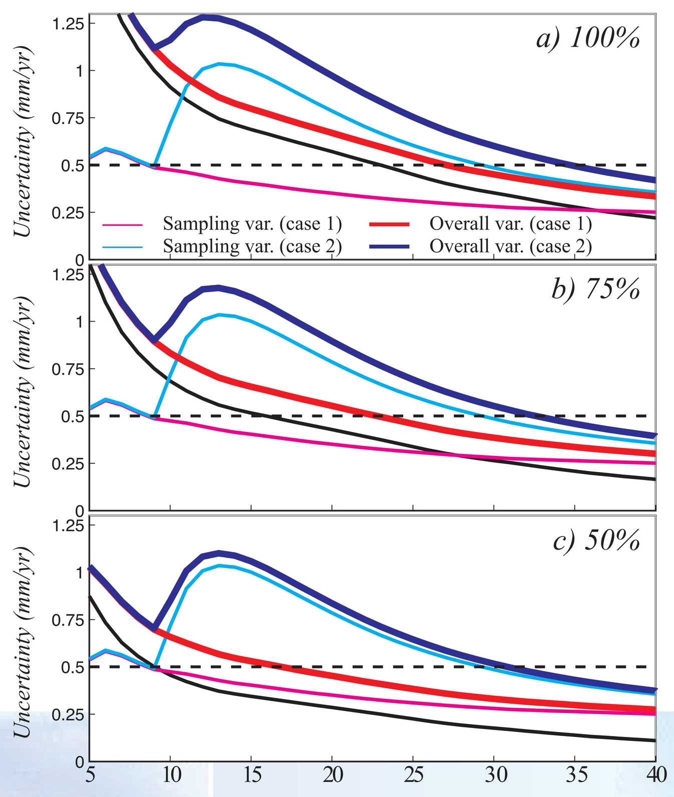
Finally, I consider the challenge of determining the long-term trend when there are both real interannual variability in MSL and uncertainties in the observing system.

Two versions of the observing system are evaluated, along with 3 grades of interannual variability, since the values I derived from the Church & White reconstruction may be larger than for a true global altimeter system. Thus simulations are performed with a) 100%, b) 75%, c) 50% of the variability calculated from their dataset (note different scaling of black line in figure).

Case 1 has all high-quality ("reference class") altimeters, with a r.m.s. uncertainty in instrument drift of 0.5 mm/yr, and the mismatch between successive missions having a r.m.s. of 2 mm. Case 2 is the same except there is no overlap (tandem phase) at the start of the third mission so the r.m.s. uncertainty in the bias between missions 2 and 3 is 10 mm.

- Black and red curves shows that a complete "reference class" altimetric observing system only adds a few years to the requirement set by natural variability
.
- Light blue curves show that a single break in the observing system interrupts the otherwise monotonic curves.
- Light and dark blue curves show that with a discontinuity, overall error is almost completely set by the quality of the observing system.

Some improvement would be possible if there were other altimeters contemporaneous with both missions 2 and 3 that could improve the co-registrations of those datasets. This has not been quantified here.



Uncertainty in trend as a function of duration (black lines represent different assumed levels of natural interannual variability)

Conclusions

- Simplistically, errors in mean trend will always come down if one waits long enough, but with poor instrument design or cal/val it could take more than half a century to see whether sea level acceleration is a concern (see picture below)!
- Reduction in inter-instrument bias due to tandem phase is critical.
- Dedicated cal/val is essential for measuring uncertainty in instrument drift.
- Independent altimeter observing systems (e.g. ERS/Envisat) have been ignored in this study. Through global analyses these will greatly assist in the detection of step changes in altimeter bias and also reduce the impact if there is loss of continuity.

Acknowledgements

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Photo courtesy of Istituzione Centro Previsioni e Segnalazioni Maree (ICPSM), Comune di Venezia