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Altimeter accuracy requirements for detecting changes in sea level rise

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ABSTRACT

All nations with a maritime border are concerned about changes in sea level, with an increase in sea level leading to flooding of coastal areas, damage to property, salinification of fresh water aquifers and destruction of valuable agricultural land. Around the change of the millenium global sea level rise was estimated to be 2.7 mm/yr, but various climate models have suggested the rate of rise will increase markedly necessitating governments to take action more swiftly. This report looks briefly at the accuracy requirements and time series duration needed to be able to detect reliably a significant change in the rate of sea level rise. One constraint on detecting an increased trend is the natural interannual variability of the climate system, which implies that a minimum duration of around 10-20 years is required in order to detect a trend with confidence to within 1 mm/yr. Added to this will be the effect of efficiencies in the observing system.

This is investigated through a series of simulations, mimicking the sampling of a long-time series by altimeters with random bias and drift terms. Whilst not directly addressing issues relating to the choice of orbit configuration, this preliminary work prototypes a methodology for assessing the design of a long-term altimetry observing system. Naturally the maintenance of multiple altimeter systems plus a representative global network of tide gauges provides the best basis for such monitoring. However, considering only a single system, one notes that the required dataset duration can be between 10 and 60 years depending upon the quality of the altimeter missions. Due to the difficulty of tying separate missions to a common datum, a single short interruption to precise monitoring may add more than a decade to the time required to detect an increased rate of sea level rise.

KEYWORDS:
Altimetry observing system, CMIP5 model analysis, Detectability of change, Future climate, Global mean sea level (MSL), Jason altimeters

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Executive Summary

Satellite-based radar altimetry has become an integral part of many aspects of oceanography. Altimetric observing systems, in which I include the instrumented spacecraft, the orbit determination, the accurate measurement or estimation of various correction terms and the dedicated sites for calibration and validation of the data, produce products that are used both in real-time applications and in long-term climate studies. They can provide contextual information for multi-disciplinary regional investigations or be applied as assimilation input or validation data for complex numerical models. The key products are near-global coverage of sea surface height, wind speed and wave height, which can be incorporated in forecast models to aid tourism and ship safety, as well as to improve our scientific understanding of the complex dynamics of the ocean circulation.

Although there are many strong drivers for the maintenance of a high-quality altimetric observing system (or preferably more than one in order to give a much improved spatial coverage and redundancy in the event of one system failing), this report focusses on the need to maintain at least one such system to address the issue of monitoring mean sea level with sufficient accuracy to be able to infer the likely trajectory of sea level rise with a degree of confidence. Clearly an observing system does not, *per se*, give predictions concerning future sea level, so the issue is one of using the altimetric record to distinguish between the forecasts of various climate models.

Consequently this report first analyses the sea surface height record from 15 coupled models that have been made available as part of the 5th Coupled Model Intercomparison Project (CMIP5) in preparation for the IPCC's 5th Assessment Report (AR5). Four of the models show no appreciable change in sea level during the 21st century, and three have sea level to be decreasing. In those showing a rise, the predicted sea level by the end of the 21st century could be between 20 and 80 cm above that at its beginning. This does vary with the warming scenario considered, but inter-model differences are the dominant factor. What is striking about these models is that none of them shows a pronounced change in the rate of sea level rise during the period, whereas many models considered during AR4 had shown some acceleration.

To understand the challenges in determining the long-term trend in sea level this report makes use of a century-long reconstruction of mean sea level based on tide gauges plus altimetry. Whilst the rate of sea level rise was on average 1.6 mm/yr for most of the 20th century, the trend that would be determined for individual decades varies between -0.4 and 3.7 mm/yr due to various phenomena with time scales from interannual to decadal. If this represented the variability in mean sea level during the altimetric era, then a period of 23 years of perfect measurement would be required to determine the trend with confidence to within ±1 mm/yr. However, if the short-term variability in an altimetrically-measured dataset is much less than in this reconstruction the requisite period is reduced significantly.

A potentially more important aspect is how errors in the observing system will affect our ability to determine the long-term trend with accuracy. Random errors within the altimetric observing system are inconsequential when calculating global averages; however biases in the measurements will persist. Given that multiple consecutive spacecraft will be required, the concerns are two-fold: a calibration offset between different missions and a gradual drift in performance during the lifetime of any instrument. Significant biases (of order 10 cm) have been noted in the calibrations of similar instruments, and drifts of several mm/yr have been noted related to the degradation of the space hardware. However, biases and drifts of this magnitude can be estimated through careful calibration campaigns and monitoring; that which is pivotal to the accurate determination of trends by the altimetric observing system is the uncertainty in these estimates.

Based on cited values in the refereed literature, this report looks at the effect of random intercalibration offsets and instrument drifts on the ability to derive the trend to the required accuracy. Simulations are performed assuming that all the missions will occupy the same orbit, allowing for accurate recovery of the bias via the tandem phase (when the new satellite follows its predecessor in the same orbit only a minute or so apart) thus permitting both to overfly dedicated validation sites without the atmospheric or oceanic conditions changing perceptibly. The natural choice for this is the orbit already used for 20 years by the TOPEX and Jason altimeters. Its long occupation means that the gravity anomalies associated with that orbit are well known, and the relevant tidal aliasing fully understood. Although a switch to some other orbit has been mooted in order to increase the latitudinal coverage, the interruption to the time series caused by such a change would significantly affect the ability to look at changes in the rate of sea level rise. The analysis in this report simulated the effect of a short interruption to the continuity of monitoring, which will impact the accuracy of the intercalibration between successive missions; however the shift of precision altimetry to a different orbit was not modelled because there are too many unknowns concerning the aliasing of tides and other geographically-correlated errors in addition to the effect of poor intercalibration.

The report brings together the errors associated with both the observing system and with estimating a long-term trend in sea level with variability on scales from interannual to decadal. Depending upon the assumptions made, either term may dominate. Although the uncertainties of each tend to zero for long dataset durations, the period needed to achieve a required accuracy can be decades long, with the two effects combining non-linearly. Although more complicated statistical techniques could address some of the problems with interrupted data series, it is clear that maintaining a continuous high-precision altiimetric observing system would be the most reliable way to be able to derive trends in mean sea level and judge whether rates are accelerating. A short interruption, such as a failure to fund Jason-CS in time to overlap with Jason-3, could add more than a decade to the amount of time needed to record sea level rise reliably to within ±1 mm/yr.

This work has been a first look at the problem, and developed a methodology for assessing the impact of various mission scenarios. There are many demands for multiple simultaneous altimeter missions to aid in ocean forecasting and provide better statistics on mesoscale variability. However, we should not ignore the impact of these other missions on the ability to produce long-term highly consistent mean sea level time series. Although various errors have regional biases affecting different observing systems differently, it has been through the comparison with these independent datasets that many of the drift and bias errors in the TOPEX-Jason altimeter series have been identified and rectified.

The issue of regional mean sea level does not seem as important in the recommendations for maintaining the continuity of high-precision altimetry observations. Although changes in regional waters will be of more concern to particular governments and aid agencies, and their changes in CMIP5 models show greater variability than for the global average sea level, the recovery of regional trends relative to global is not affected by the errors in intercalibration between different instruments.

Contents

1. Introduction

Changes in sea level are of great concern for many nations, especially low-lying lands with no flood protection. Of particular note are the Maldives, where 80% of land is within 1 m of sea level (Environment Agency, 2012) and Bangladesh, where 6-8 million people would be displaced by a 1 m rise of sea level (MoEF, 2008). Western developed nations do have protection in place to prevent/minimise the loss of life, famously the dykes of the Netherlands and the Thames Barrier in London, but there is great expense involved in maintaining and strengthening them. Thus governments are keen to know the likely scenario of sea level rise, which motivates regional studies e.g. UKCP09 (Lowe et al., 2009).

Over the last 20 years the recorded rate of sea level rise is 2.7 mm/yr (see Fig. 1) from a combination of altimetry, ground-truthing by tide gauges and corrections for local land movement (global isostatic adjustment). There are many factors contributing to this, which are the subject of active research (Church et al., 2010). A continuation of that rate will lead to sea level 27 cm higher in 2100 than in 2000. However, a number of climate models have suggested that climate feedbacks will lead to a gradual acceleration of sea level rise, with sea level at the end of the century possibly being considerably higher than in 2000. The predictions generated by some semi-empirical models, which relate global mean sea level to other model diagnostics, can be much more than a metre (e.g. Rahmstorf, 2007).

Complex coupled climate models clearly give us an idea of the range of possible values, but to determine which pathway the climate system is actually on requires a long time series of accurate measurements. The stated accuracy for the global sea level trend during the altimetry era is ±0.4 mm/yr (Leuliette et al., 2004; Nicholls and Cazenave, 2010), which is principally due to the effects of interannual variations, the uncertainty in the drift of individual altimeters and the errors in establishing the offset between different altimeters. This report addresses the issue of analysing how different accuracy requirements for the whole altimetric observing system affect the international community's ability to distinguish between different scenarios of climate change.

Section 2 of this report looks at rates of sea level rise in various state-of-the-art coupled models, considering both the absolute values they suggest for the current era, and how much they are likely to change during the 21st century. Section 3 provides a brief reprise of the century-long record of mean sea level (MSL) available in a reconstruction based on tide gauge and altimetry data, showing how the inherent variability in the climate system precludes accurate detection of trends with only short extents of data. Section 4 then considers the systematic errors in the altimetric measurement system, principally concentrating on the uncertainty in instrument drift and the challenge in accurately co-aligning data from successive missions to help build up a long climate data record. Section 5 describes the simulations used to determine the accuracy of retrievals of MSL trend, given certain constraints on instrument performance, with overall conclusions and discussion of regional interest being provided in section 6.

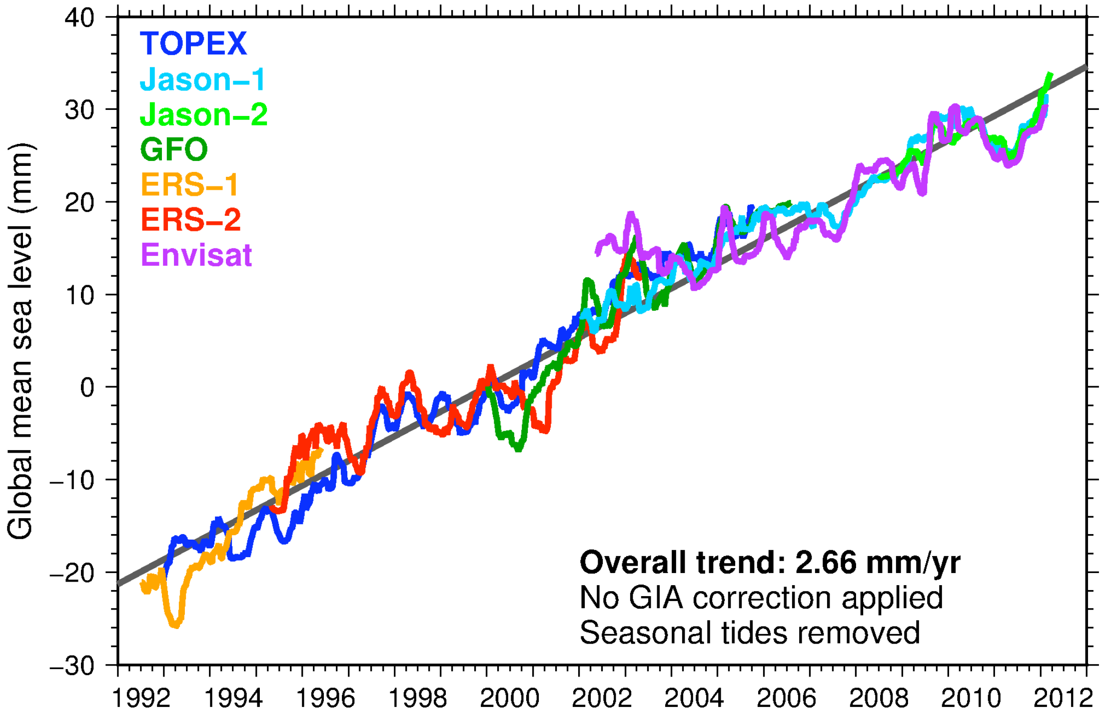

Fig. 1 : Series of global mean sea level from altimeter datasets spanning the last 20 years (courtesy of Remko Scharroo) No correction for Global Isostatic Adjustment (GIA) applied.

2. Future scenarios of sea level rise

a) Introduction to CMIP5 models

As part of the precursor to the 5th Assessment Report (AR5), the IPCC has instigated a new round of the Coupled Model Intercomparison Project (CMIP5), in which model output from a wide variety of models are shared throughout the international community. These models were run for a large number of specified scenarios (distant past, recent historical and possible future conditions), with the main diagnostic fields being readily available as NetCDF files on a few dedicated websites. The runs considered here have been the "historical" run, which covers the period 1850 to 2005 with various forcing parameters (solar flux, CO_2 concentration and aerosol content) matching closely to what is known for the period (including, in some cases, specific volcanic eruptions adding particulates to the stratosphere). However, all the atmospheric and oceanic fields are freely determined by the models, with no assimilation of real world observations, and thus the model output will not match individual El Niño events *per se*. Rather it is expected that modes of variability will occur naturally within these coupled systems. Here only data from 1993 onwards are considered, reflecting the period when regular monitoring of mean sea level was available on the "reference" track occupied by the TOPEX/Jason series of altimeters.

The coupled models provide output corresponding to various future scenarios, two of which (RCP45 & RCP85) are amongst the core set of simulations intended to be performed by all of the models to be evaluated (Taylor et al., 2009). Representative Concentration Pathways (RCPs) specify a change in net radiative forcing over the ensuing 95 years, reaching (for the two specified) peaks of 4.5 or 8.5 Wm^{-2} respectively in 2100 without ever exceeding those values. RCP45 corresponds to a "moderate" amount of global warming, consistent with governments taking significant concerted action to reduce CO_2 emissions, whilst RCP85 indicates more likely conditions if governments fail to achieve a consensus and action is piecemeal and not co-ordinated.

The various different models have different oceanic and atmospheric modelling components (with some having ice and active biological components that feedback into CO_2 absorption and albedo), and their output fields are provided on their own native grids (which are not always regular longitude-latitude grids).

b) Model selection and caveats

To encompass the wide range of sea level rise scenarios expected, data from fifteen different CMIP5 models were downloaded from the UK, US and German servers. These models include HadGEM2-ES and HadGEM2-CC, but HadCM3 could not be used for this investigation because there is no sea surface height field for that model. The other models considered came from various institutes and meteorological agencies in the US, Canada, Russia, Norway, France, Germany and Japan (see Table 1). For this investigation, fields were downloaded at monthly resolution, although for most of the ensuing analysis the regular seasonal cycle is suppressed by the use of 12-month averages. The key fields required were those beginning "zos_" which contained "sea surface height above geoid" and ones commencing "zosga_' which were "global average sea level change". (For some models different fields exist showing, for example, the thermosteric contribution to sea level change; these by themselves were not useful without knowing the overall sea level change.) The data within the "zosga" files would be expected to correspond to an area-weighted average of that in the "zos" files; however for a number of models these showed different behaviour. Given the lack of clarity as to what these output files actually represent, these models are treated with caution. I continue here with the files starting with "zos_" as these have monthly maps of the sea level height (which is useful for regional comparisons, see section 6), and compute the global average of these fields.

Model	**Organizations responsible**
CanESM2	Canadian Centre for Climate Modelling and Analysis
IPSL-LR	Institute Pierre-Simon Laplace
IPSL-MR	Institute Pierre-Simon Laplace
HadGEM2-ES	Met Office Hadley Centre
HadGEM2-CC	Met Office Hadley Centre
CNRM-CM5	Centre National de Recherches Meteorologiques / Centre European de Recherche et Formation Avances en Calcul Scientifique (CNRM/CERFACS)
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory
GISS-E2-H	NASA Goddard Institute for Space Studies
GISS-E2-R	NASA Goddard Institute for Space Studies
inmcm4	Institute for Numerical Mathematics
MIROC5	Atmosphere and Ocean Research Institute, University of Tokyo, National Institute for Environmental Studies & Japanese Agency for Marine-Earth Science and Technology
MRI-CGCM3	Meteorological Research Institute
NorESM1	Norwegian Climate Centre (NCC)
MPI-ESM-LR	Max Planck Institute for Meteorology
CCSM4	NCAR Community Climate System Model CCSM version 4

Table 1 : List of the 15 models analysed, giving all the research groups responsible for their development

A simple consideration of the amplitude of the seasonal cycle near the end of historical run (Table 2) reveals 3 models to have no appreciable seasonal cycle (these are later shown to have no significant trend or acceleration either). A further two models have a weak seasonal variation, but with peak in mean sea level (MSL) during March-April, 6 months different from that seen in observations and in the majority of models).

In some of these climate runs, the sea level record will not include a component relating to melting of land ice; this may have to be explicitly determined and added later (A. Pardaens, pers. comm. 2012). Finally, it should be noted that all models may show a problem of drift. For these future emissions scenarios, the models are supposed to be initialised from the end of the "historical" run, which will already have at least 155 years of spin-up. However if the formulation of some terms is not fully correct, the models may continue to lose mass, for instance. Thus some models show an apparent lowering of sea level (see section 2c). This decrease is consistent with the behaviour they had shown in the "historical" run; thus it may be valid to consider whether the future forcing scenarios engender any appreciable change in the rate of change of sea level.

Can-ESM2	—	CNRM-CM5	1	MIROC5	2
IPSL-LR	1	GFDL-ESM2M	1	MRI	—
IPSL-MR	1	GISS-E2-H	3*	NorESM1	0.5*
HadGEM2-ES	2	GISS-E2-R	3	MPI-ESM-LR	1
HadGEM2-CC	2	inmcm4	—	CCSM4	0.5*

Table 2 : Approximate amplitude (half peak-to-peak) of seasonal cycle (mm). Data are from 1993-2002 (historical run) and peak is around September-October, except for those asterisked which show a peak in March-April. Note 3 models have no seasonal signal.

c) Trends and acceleration in mean sea level

In subsequent analysis, I use data from the end of "historical" plus "rcp45" or "rcp85" to produce two time series for possible warming scenarios, covering the period of the potential satellite altimetry climate data record (1993 onwards). Figure 2 shows the resultant time series for these two scenarios and their difference. The complex forcing scenarios used for RCP45 and RCP85 do not have a simple linear ramp up of radiative forcing over the whole century, but a more complicated pathway, following almost the same trajectory for the first 40 years, with the "moderate" scenario then reaching a plateau, whilst the more extreme case continues to increase the radiative excess before reaching a peak near the end of the century. However, at first glance, most of the models show a nearly linear rise in sea level over the first 100 years (Fig. 2a,b). Three models (IPSL-LR, IPSL-MR and CNRM-CM5) indicate sea level to be decreasing, although this is consistent with the end of their historical run. As noted before, this is likely to be due to uncorrected model drift. For CNRM-CM5 the rate of decrease diminishes, but for the two IPSL models, the mean sea level drops faster as time progresses.

Examining the difference between the two scenarios (Fig. 2c), one notes that both IPSL models show greater decreases in sea level for the more extreme conditions, whereas five of the models (HadGEM2-ES, HadGEM2-CC, CNRM-CM5, GISS-E2-R and NorESM1) show the greater warming scenario to have the greater acceleration in sea level as would be expected from basic principles. However the difference between the two scenarios has no more than a 12 cm difference over the 95 years. Four of the models show negligible difference between the two scenarios. The calculated trends for the models at the start of the altimetry era, middle of the 21st century and at its end are given in Table 3. The trends are calculated by applying a 12-month running mean (to remove the annual signal) and then fitting a linear function of time. These show that the typical change in trend over 50 years is of order 1 mm/yr for RCP45 and roughly twice as large for RCP85. Table 4 shows the results for explicitly calculating the acceleration term for the difference between RCP45 and RCP85 over the 95 years.

A very different result is obtained by Rahmstorf (2007) who develops a semi-empirical link between mean air temperature and the rate of increase in mean sea level to infer that the projected temperature changes by the end of the century, according to AR4, could result in a raising of sea level by between 50 cm and 1.4 m. Holgate et al. (2007) argue that observations from the past century do not support the assumption of a linear relationship between temperature and rate of rise, and thus that Rahmstorf's predictions are somewhat

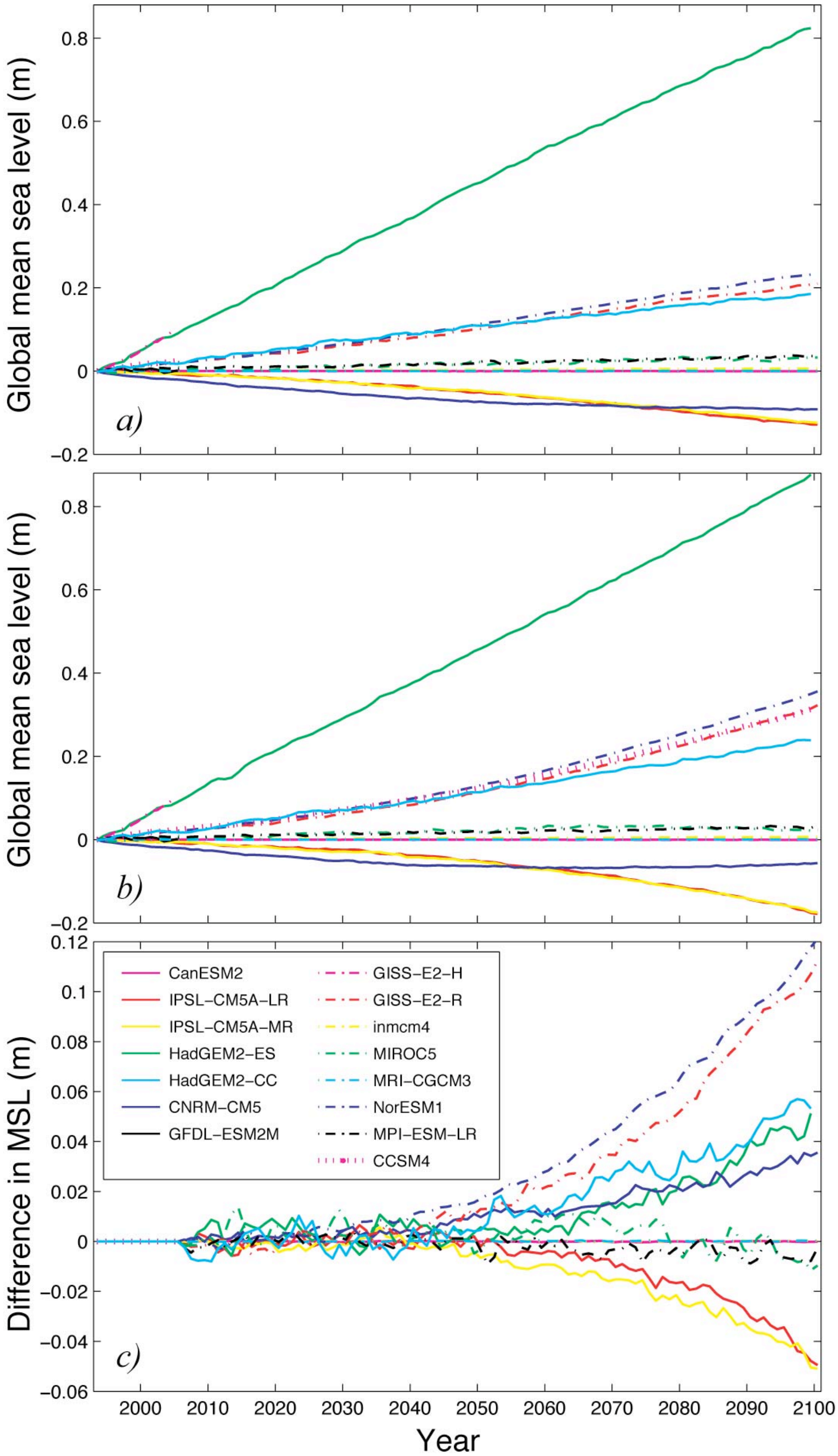

Fig. 2 : Evolution of global mean sea level in various coupled models. a) With RCP45 conditions for 2006-2100, b) with RCP85 simulation, c) Difference.

Model	1993-2005 (historical)	2046-2055 (RCP45)	2091-2100 (RCP45)	2046-2055 (RCP85)	2091-2100 (RCP85)
CanESM2	0.0	0.0	0.0	0.0	0.0
IPSL-LR	-0.6	-1.1	-1.3	-1.7	-3.5
IPSL-MR	-0.5	-1.3	-1.6	-2.0	-3.2
HadGEM2-ES	8.3	7.7	7.6	8.2	8.6
HadGEN2-CC	1.3	1.3	1.6	2.6	2.9
CNRM-CM5	-1.3	-0.8	-0.3	-0.3	0.7
GFDL-ESM2M	-0.6	—	—	—	—
GISS-E2-H	9.0	—	—	—	—
GISS-E2-R	1.9	2.4	2.3	3.2	4.7
inmcm4	0.1	0.1	0.1	0.1	0.1
MIROC5	1.3	0.8	1.1	0.7	-0.5
MRI	0.0	0.0	0.0	0.0	0.0
NorESM1	1.5	2.5	2.0	3.6	5.0
MPI-ESM-LR	0.2	0.2	0.4	0.0	-0.1
CCSM4	1.8	—	—	3.0	4.3

Table 3 : Rates of sea level rise (mm/yr) for three different decades according to a number of readily available CMIP5 models. Not all of the selected models had sea level fields available for all 3 scenarios. [For explanation of terms 'historical'; 'RCP45' and 'RCP85' see main text.].

Can-ESM2	0.0	CNRM-CM5	0.4	MIROC5	-0.4
IPSL-LR	-1.0	GFDL-ESM2M	—**	MRI	0.0
IPSL-MR	-0.8	GISS-E2-H	—**	NorESM1	1.8
HadGEM2-ES	1.0	GISS-E2-R	1.8	MPI-ESM-LR	-0.1
HadGEM2-CC	0.8	inmcm4	0.0	CCSM4	—*

*Table 4 : Difference in acceleration between RCP45 and RCP85 runs (mm/yr per century). A positive number indicates that sea level rises faster under RCP85 conditions than under RCP45. * - No data for RCP45 run ** - No data for either RCP45 or RCP85.*

alarmist. Lowe and Gregory (2010) also note that some of more extreme predictions coming from such statistical inferences are implausible without there being significant melt of land ice from Greenland and Antarctica. However, given the rather smooth projections from CMIP5, with their unrealistically low temporal variability (see section 2d) it is worth noting that a wide range of forecasts do exist in the scientific literature.

d) Lack of variability in models

A generic problem with models is their inability to include all the scales of temporal variability noted in the real world, thus encouraging people to underestimate the uncertainties in our knowledge of the climate system (Valdes, 2011). The majority of the models do show a seasonal cycle in mean sea level (Table 2), but once annual averages are considered, sea level rise is almost linear, with no apparent modulation by El Niño or other short-term climate variations whereas the altimeter record is marked by variations on all time scales (Fig. 1). Gregory et al (2006) had noted this lack of variability in HadCM3 too. With such a lack of interannual variation, or any perceived measurement error, it would be possible to estimate a very weak acceleration reliably from only a short span of data. Instead to ascertain the detectability of trends with an altimetry observing system we need to consider time records with realistic interannual signals, and also uncertainty within the measuring system.

Rather than focus on estimating an acceleration term, which may be very weak, the problem is re-expressed as one of determining some true long-term trend to confidently within 1 mm/yr. Assuming the statistics will ultimately conform to a normal distribution, a 95% confidence of being within 1 mm/yr translates to finding conditions (environmental and observing system) such that the standard deviation in the estimates of the trend is no more than 0.5 mm/yr.

3. Church and White's reconstruction of MSL

There are no fully authenticated reliable measures of globally-averaged mean sea level spanning a century or more. Instead I consider a reconstruction developed by John Church and Neil White of CSIRO, utilizing 18 years of continuous altimetry and the long tide gauge data records available from a number of stations. [The longest duration tide gauge series are not uniformly distributed throughout the ocean; in their methodology, Church and White (2011) allow for their irregular distribution and spatial correlation.]

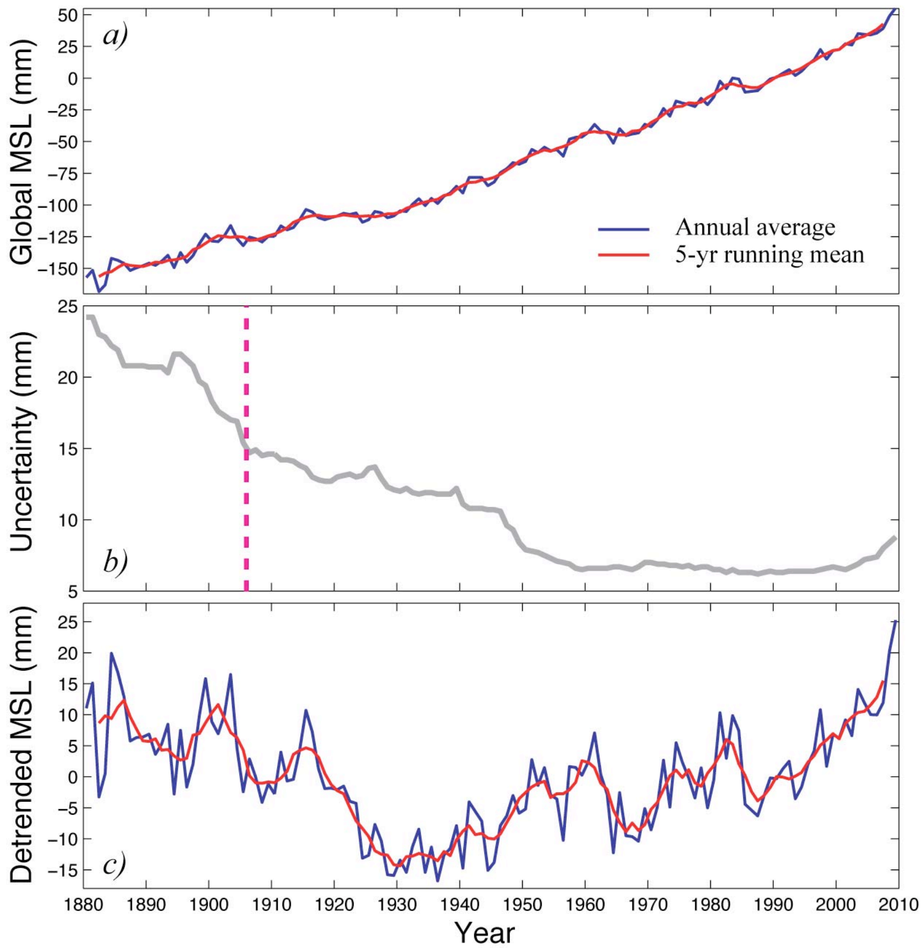

Fig. 3 : a) Time series of global mean sea level from Church and White reconstruction, b) Uncertainty in estimate, c) Global MSL with trend of 1.54 mm/yr (average over 1880-2010) removed. For further analysis data before 1906 are excluded, since the uncertainty is greater in the first period.

Figure 3a shows the result of their reconstruction, which although seemingly close to linear does contain significant variability on scales from years to decades (Fig. 3c). To assess the variability in this record, I consider all data from 1906 onwards, as the uncertainty in the reconstructed MSL (Fig. 3b) is much greater for earlier periods. Figure 4 shows the trends derived treating overlapping 10-year periods separately. The mean value (1.67 mm/yr) is close to that found by treating the series as a whole, but for individual decades the trend can vary between -0.40mm/yr and 3.29 mm/yr, with a standard deviation of 0.91 mm/yr.

Performing such an analysis for segment lengths varying between 5 and 30 years shows the uncertainty in the estimate of the trend to fall off as the data record increases (Fig. 5).

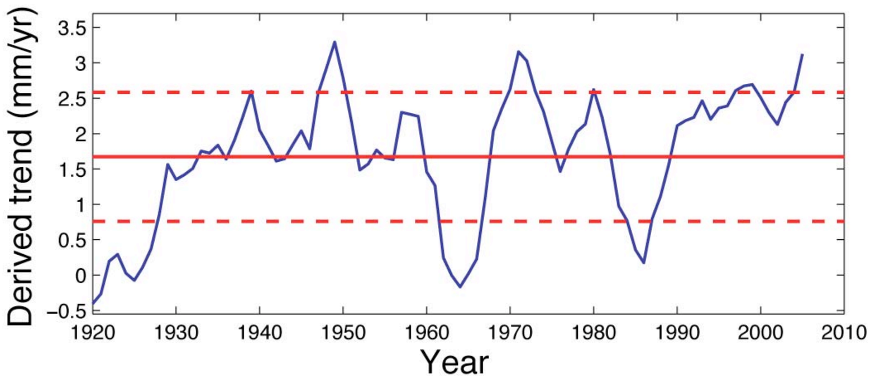

Fig. 4 : Trend calculated from overlapping 10-yr segments of the Church and White reconstruction.. Red lines indicate mean (1.67) and +/- 1 s.d. (0.91).

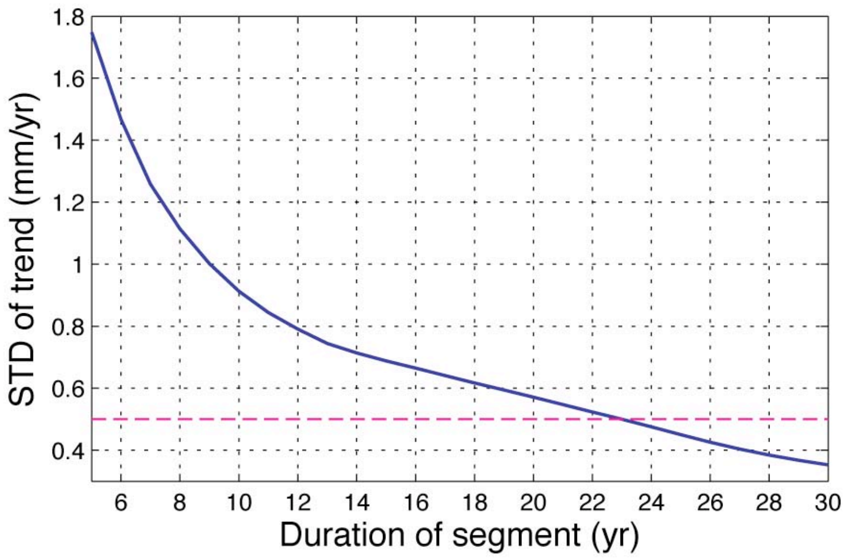

Fig. 5 : Standard deviation of trend derived from Church and White reconstruction, for different length segments.

If we conjecture that global climate change has increased the rise of sea level by 1 mm/yr, then a sampling period of 23 years is required to be able to detect it with a 95% probability (2 s.d.). Such a conclusion assumes that the altimetry observing system has perfect consistency (no measurement bias between different satellite missions and no drift in the instruments' performance) and that the short-term variability in the mean sea level will be similar to that portrayed in Fig. 5. As the analysis of Fig. 5 was based on a reconstructed series from a limited set of tide gauges, it will have more variability than one computed from the global coverage of an altimetric observing system. However, it is also possible that conditions of climate change will also enhance the short-term variability in the system. Without a 100-year record of global MSL from altimetry and also fully credible models of projected MSL change under warming scenarios, it is difficult to be clear whether the estimate from this analysis is biased high or low. However, it is an appropriate tool to investigate the effect of changes in the quality of the observing system.

4. Intercalibration errors within the altimetric observing system

Altimetric measurements of sea level require precise knowledge of orbits, measurements of range and calculation of corrections. To produce a global average of mean sea level simply requires a weighted average of all these measurements, albeit with some allowance for those regions not measured (outside latitudinal range of system, affected by sea-ice or too near to land). In such a calculation using millions of points, the random errors will average out; however biases in the system will remain. These could be errors in the knowledge of microwave path lengths in the instrument, the position of its centre-of-gravity or errors in various corrections (wet troposphere, ionosphere or tracker bias). Thus all altimeter missions require significant calibration effort to minimise uncertainty in the bias of the overall altimetric measurement.

This discussion will concentrate principally on altimeters in the so-called "reference" orbit occupied by TOPEX/Poseidon, Jason-1 and Jason-2 to-date, with frequent overflights (every 10 days) above dedicated calibration sites and inter-mission calibration achieved by tandem missions with successive altimeters making the same measurements only about a minute apart. These three satellites have made continuous observations for ~20 years, whereas the ERS-1, ERS-2 and Envisat satellites have not fully maintained observations in their multi-disciplinary 35-day orbit, and that time series is interrupted now following the recent demise of Envisat. Combining estimates of mean sea level between the two sets of altimeters is difficult to achieve at the millimetric scale, because of their different sampling of the diurnal cycle (one set being in a sun-synchronous orbit and the other not) and also the large differences in their maps of sea level, which are associated with geographically-correlated errors.

During an initial 6-month calibration phase, an instrument in the reference orbit will pass 18 times over a dedicated reference site. Unexplained height errors of order 10 cm are found between different satellites (Haines et al. 2010; Woodworth et al., 2004; Watson et al., 2004; Bonnefond et al., 2010), with standard errors for the comparisons at reference sites of about 0.8 cm. A more precise intercalibration may be obtained through using all the near-simultaneous observations during the tandem overlap mission. Thus without any intercomparison, a switch between data from different altimeters may have a change in bias of ~10 cm; whereas if they have been compared via a long period of simultaneous measurements, the step in bias will be at least a factor of ten less. However if the two altimeters do not overlap in time or overfly the reference sites on different days, the ability to determine their relative offset is worsened because of the changing oceanic and atmospheric conditions. The estimate of the relative bias will be confounded by the uncertainty in the correction terms, which could previously have been dismissed as unchanging. The situation is even more complicated if the two altimeters to be aligned are not on the same ground track, and thus use different ground stations to achieve their long-term calibration.

Secondly the performance of the altimetric observing system may be affected by gradual drifts in the altimeters or in the correction terms that are to be applied. Leuliette et al (2004) found a drift in Topex-A measurements of -0.37 mm/yr , and in Topex-B of 1.56 mm/yr. Their estimate for Jason-1, based on a short period early on in the mission was -5.7 mm/yr, but now that a change in behaviour of one of the radiometer channels has been identified (Brown et al., 2004) and a correction implemented, this effect has been removed. Two occasions of 0.5 mm jumps in Envisat's range bias have also been identified (Leuliette and Miller, 2009). The ability to elucidate these documented changes is dependent upon the maintenance of an extensive set of ground observations, and greatly helped by the existence of totally independent altimeter systems. One of the stated aims for the forthcoming Jason missions (jason-3 and Jason-CS) is that the end-to-end calibration should not have a drift of more than 1 mm/yr. Leuliette and Miller (2009) found that the global trend using just the Jason-1 mission to have an r.m.s. error of 1.1 mm/yr, whilst that from Envisat for the same time was 1.5 mm/yr.

To consider the feasibility of the altimetric system to detect an increase in sea level rise to 1 mm / yr above what had previously been expected, I simulate offsets and drifts for successive altimetric missions intended to construct a climate data record.

5. Simulation studies

a) Simulation set-up

The methodology is illustrated in Fig. 6. The top panel shows a sea level rise scenario in grey, indicating the measurements that would be recorded by an ideal system. The specific scenario has a rate of MSL rise of 1.8 mm/yr in 2014, with an acceleration of 1 mm/yr per century, and a seasonal cycle of amplitude 2.5 mm peaking in September-October. However the specific scenario is not important, as rather than record how long is needed for an increase of 1 mm/yr to be reliably determined, I have restructured the question as how long a duration is required to be certain that the trend has been estimated to within 1 mm/yr of true. In this form, the results are not dependent upon which model and which future warming scenario is being considered.

Individual coloured segments show the possible record from a series of different satellite altimeters, with Jason-3 scheduled for April 2014 and Jason-CS for 2018. For simplicity of the simulation, all subsequent missions are timed for launch every 4.5 years and to last 5.0 years in the reference orbit, allowing for a 6-month overlap with their successor. For this illustration the top panel shows each altimeter's height record to have a random bias and drift, with these numbers being drawn from normal distributions of standard deviation 100 mm and 0.8 mm/yr respectively. The middle panel shows the combined time series if the relative bias between successive altimeters is estimated via the tandem phase to within an r.m.s. accuracy of 4 mm. The exception is that a greater error is assigned to the match-up between the fourth and fifth missions, which is what would be expected if the fourth mission failed to last long enough to overlap with its successor.

The trend in sea level rise is then determined for various durations starting in 2014 (Jason-3), and the error in the trend calculated by comparing to the ideal case of no measurement error (grey line in Fig. 6a). Two hundred simulations were performed for each specification of the uncertainties in the measuring system, and thus the associated error determined for the recovered trend. When this uncertainty reduced below 0.5 mm/yr, the record duration was deemed suitable for reliable detection of sea level rise to within 1 mm/yr.

Provided there are always sufficient overlaps between succeeding altimeters the expected O(100 mm) difference in bias between instruments is not important; what matters is the accuracy of the estimate of this bias and the size of the uncertainty in drift. To improve clarity of the depiction in Fig. 6b, the magnitudes of the biases and drifts are some of the larger ones used in the simulations performed.

b) Simulation results

Simulations were performed for a wide range of altimeter performances and intercalibration, with the r.m.s. uncertainty in the bias between missions varying between 0 and 6 mm and the r.m.s. uncertainty in the drift between 0 and 1 mm / yr. All the simulations were performed for a series of 5-year missions with 6-month overlaps unless stated otherwise, and with 200 random realizations of each set of conditions. For each set of conditions I noted the minimum duration required for error in derived trend to fall below 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
2 mm	10	10	10	17	27
4 mm	15	17	22	29	41
6 mm	42	44	49	57	66

Table 5 : Duration of time series (in years) required to determine trend of MSL to within an uncertainty of 0.5 mm / yr, given as a function of uncertainty in offsets of contiguous missions and in the drifts during missions. (10 years was the minimum length considered and so a value of 10 implies that that combination of bias and trend errors has minimal effect on the ability to recover the trend to the required accuracy.)

Unsurprisingly, scenarios with little (if any) error enable the accurate determination of drift as early as a perfect observing system, and increases in σ_h (r.m.s. height bias) and σ_d (r.m.s. drift) can lead to much longer datasets being needed. Even the scenarios with large intercalibration biases and/or drifts will eventually converge to the simulated trend once enough successive altimeters have been flown (independent realizations of individual bias and drift leading to the mean values tending towards zero). When the number of missions (n) is large, the overall uncertainty in the derived trend, σ_T, will be expected to follow:

$$\sigma_T^2 = \sigma_d^2 / n + (\sigma_h / 4.5 \text{ yr})^2 / (n-1) \qquad (1)$$

A slightly nonsensical consequence of this simplistic formulation is that significantly better convergence to the true trend would be obtained if new high-performance well-intercalibrated altimeters were launched every 12 months, as this would quickly reduce the mean bias and drift in the overall observing system, although at great cost! The simulation results in Table 5 roughly match this formula, although it is more complicated when the period is short and the required duration does not correspond to an integral number of missions. This simulation also enables us to investigate more complicated scenarios involving programmatic changes to the altimetric system.

c) Interrupted and degraded monitoring systems

The recent loss of Envisat before Sentinel-3 was in place, and the launch failures for OCO and the initial Cryosat remind us that continuity of an observing system cannot be assumed. Here I assess the effect that a gap in the data series has on the ability to register that the trend has changed. If the two altimeters either side of a hiatus are of similar heritage, then an initial error in offset of the two may be or order 100 mm (based on the experience of Jason-1 and Jason-2, which were similar but not identical spacecraft), with the uncertainty likely to be much greater for a change in hardware. Such an erroneous offset would have a pronounced and noticeable effect on the quality of the time series. However, if each altimeter is separately calibrated to dedicated well-monitored reference sites (such as Harvest, Senetosa or Bass Strait) then the error in alignment over that gap could be kept to ~6 mm. The results in Table 6 show the effect of a very short gap in the mission coverage, such that there is no overlap between the second and third missions to enable an accurate intercalibration.

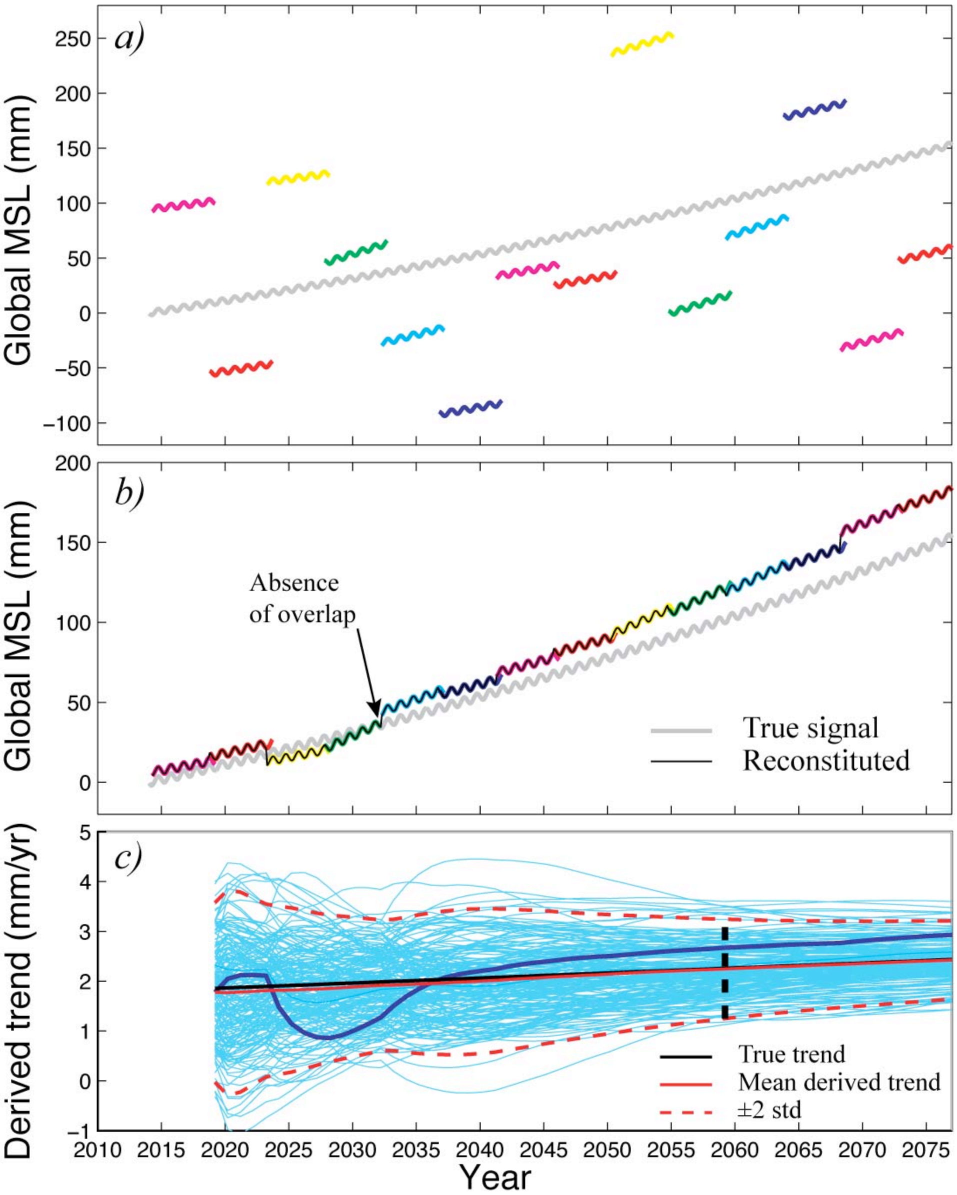

Fig. 6 : Schematic to illustrate simulation (note figure uses relatively large offsets in second panel to make methodology clear). a) Idealised time series (in grey) showing gradually accelerating sea level rise, with unadjusted samples (coloured lines) from independent 5-yr altimetry missions (std. dev. of offset = 100 mm; std. dev. of instrument drift = 0.8 mm/yr). b) Result of realigning independent altimetric series based on a good intercalibration during tandem missions (std. dev. of mismatch on alignment = 4 mm, except for match between 4th and 5th which has a r.m.s. of 10 mm). c) Determined trend as a function of end of period (time series starts in 2014). Blue line shows worked example; light blue lines show the other 199 simulations and red lines giving mean and ±2 std. dev. indicate the breadth of the envelope. In this (somewhat extreme) case, the std dev reduces below 0.5 mm / yr after 45 years (indicated by vertical dashed black line).

	0 mm / yr	0.25 mm/yr	0.5 mm / yr	0.75 mm/yr	1 mm / yr
0 mm	10	10	10	23	29
2 mm	10	10	22	25	31
4 mm	23	24	27	32	43
6 mm	42	44	49	57	66

Table 6 : Same as Table 5, but with second altimeter mission only lasting 4.5 years causing a data gap and hence greater uncertainty (r.m.s. of 6 mm) for alignment of third mission.

Finally, a similar exercise can be performed to show the effect if one of the altimeters is replaced by one with a greater drift (Table 7), possibly representing a short-term programmatic solution to a potential data gap. The issue of a switch to a different orbit has not been addressed here. Maps of the difference in MSL recorded simultaneously by Jason and Envisat show large regional biases (Ollivier et al, 2011) that are still poorly understood, although the relative accuracy of ephemerids predictions on different orbits plays a part. Determining the offset between two altimeters in different orbits is challenging and much less accurate than between two missions having a tandem overlap phase. Indeed MSL from missions in different orbits shows marked temporal variation (Fig. 1).

	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
2 mm	10	10	10	21	27
4 mm	24	25	27	31	41
6 mm	45	47	51	58	66

Table 7 : Like Table 5 but with greater drift (1mm/yr) for the third mission.

The results presented in Tables 5-7 show the data duration required for the r.m.s. uncertainty in the derived trend to be no more than 0.5 mm/yr, with 10 years being the minimum period considered. For altimeter mission scenarios with low uncertainty 10 years (corresponding to 1 year into the third mission) is sufficient. Thus the more complicated scenarios involving a greater bias between 2nd and 3rd missions (Table 6) or a greater drift during the 3rd mission (Table 7) have little impact on the duration required. However, this apparent lack of effect is thrown into great contrast when the uncertainty as a function of time is seen in full, rather than just noting a single threshold being crossed. In the following section incorporating the errors due to the natural climate variability into the assessment (Fig. 7) leads to very different results for such cases.

On the other hand, scenarios where the uncertainties in bias and drift are already quite large are only slightly affected by increasing one of the bias or drift terms. The effect of the extra uncertainty is most pronounced in this analysis when the other sources of uncertainty are of a moderate level, leading to a required duration of 3-5 missions (i.e. 14-23 years for missions of length 4.5 years). For example, the scenario with 4 mm calibration bias but no drift error requires 15 years (see Table 5) but if the drift for just the third mission has an uncertainty of 1 mm/yr, the required duration is now 24 years (Table 7).

d) Combining uncertainties

In order to provide an estimate of the dataset duration required to detect trends reliably given errors in the measurement system and inherent temporal variability of the observable, the uncertainties due to each aspect must be combined. As climate system and altimetric system are independent, it is appropriate simply to add the variances of the two separate terms. This will, of course, have a highly non-linear effect on when the uncertainty falls below the chosen threshold of 0.5 mm/yr.

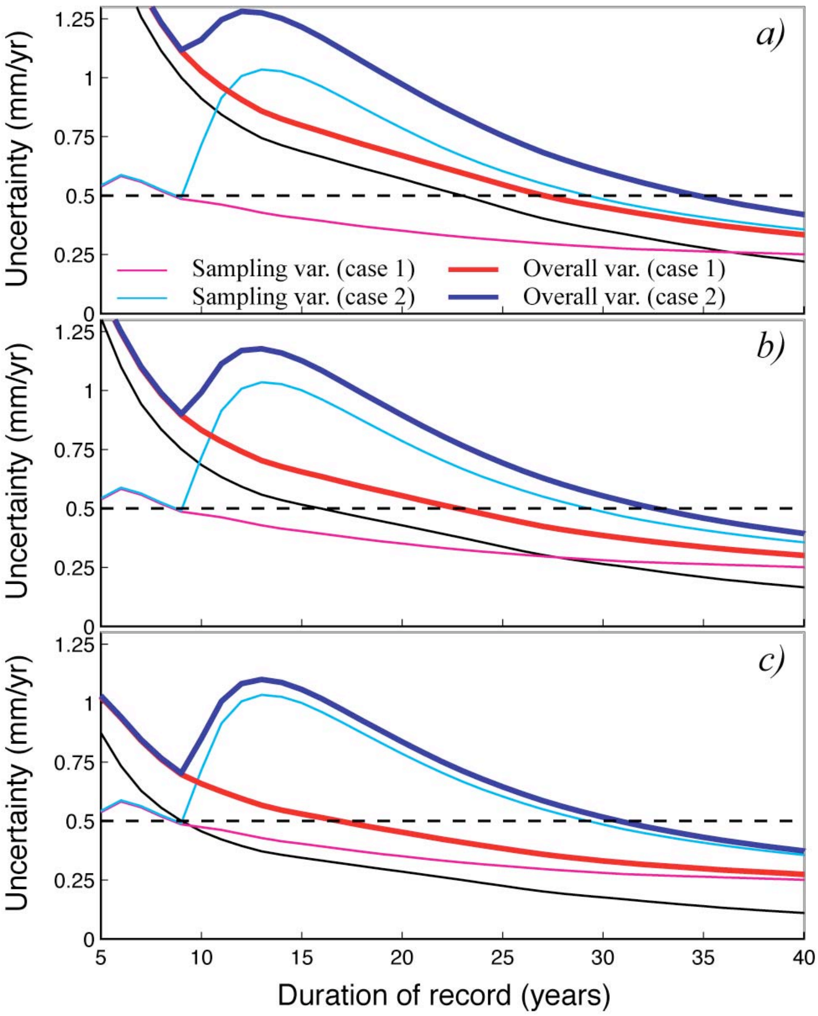

Fig. 7 : Illustration of the uncertainty and required dataset duration for cases involving interannual variability in the observable plus bias and drift errors in the altimetric sampling. In all three panels, case 1 corresponds to mismatch bias between successive missions with s.d. = 2 mm and drift uncertainty with s.d. = 0.5 mm/yr, and case 2 is the same except with increased mismatch (s.d. = 10 mm) between missions 2 and 3, simulating the lack of a tandem mission for good intercalibration. The full black line indicates the uncertainty in the trend due to inherent variability of the actual climate system, with values derived from Church and White reconstruction (see Fig. 4) multiplied by a) 100%, b) 75%, c) 50%. [Overall uncertainty simply estimated by summing variances of the two terms.]

Such calculations could be performed for all altimeter mission scenarios previously considered, plus many different spectral descriptions of the variability in the climate system. Figure 7 provides an illustration of the process, using 2 altimeter scenarios (continual high-quality altimeters, and same but with an interruption between missions 2 and 3) and 3 representations of the variability in the true signal (scaled versions of the analysis of Church and White's reconstruction dataset).

If the natural variability in MSL is as derived as in section 3, then 23 years is required to determine the trend to within 0.5 mm/yr given a perfect observing system. The uncertainty curve for case 1 (consistent high-quality sampling) is then far below the inherent MSL variability, and thus the combined curve (bold red line) crosses the 0.5 mm/yr threshold only a few years later (27 years total). The uncertainty curve for case 2 (simulating a single interruption to the continuity of the observing system at 9 years) is above that for the true MSL variability, and thus the combined error for this case only crosses the threshold at 35 years.

It seems likely that the uncertainty curve derived from the Church and White reconstruction will be an overestimate. Figures 7b & 7c show the effect of reducing the uncertainty curve for the inherent variability of the climate system by 25% and 50%. In the latter case a perfect altimetric observing system would require 9 years (black curve), the uninterrupted high-performance one would need 17 years (red curve) and that with an interrupted record 31 years (dark blue curve). In this last example, with the relatively large uncertainty between the second and third missions, the trend will be more precisely determined by discarding the first 9 years. (Admittedly more advanced statistical techniques treating the two segments separately could make some use of the earlier data.) This may appear extreme but does reflect the major impact of unresolved biases in the measurement system.

6. Conclusions

There is great societal need to be able to determine the likely development of sea level rise, with model predictions spanning a wide range of scenarios. To distinguish between these will require an accurate well-monitored integrated altimetric observing system. This report has examined the ability of a continuation of the current high-performance altimeters, on a well-known orbit with overflights of reference sites, to detect whether sea level rise has increased by 1 mm/yr. Secondly I show the increase in the duration of the data record required to make a reliable detection of such a change if the missions are generally expected to have a greater internal drift or greater uncertainty in the alignment of sea level records from successive missions. In the final section, this report details the degradation in performance that is likely to occur if there is an interruption to the continuity of service or a lower-specified mission with greater internal drift is used to reduce costs.

However, to be able to put realistic bounds on the international community's ability to estimate the long-term rate of sea level rise, one needs to understand first how much uncertainty is engendered by short-term interannual variability in the observable itself. Simply using Church and White's (2011) reconstruction of mean sea level gives an indication that, if the desire is to be confidently within 1 mm/yr of the true trend, 23 years would be required with a perfect observing system. Incorporating observation errors commensurate with a high-performance altimetric observing system only extends this duration to 27 years, whereas if there is an interruption in the continuity of the record, requiring more complicated and less accurate fixes to align the data, the needed duration will be 35 years.

Church and White's MSL reconstruction is, of necessity, dependent upon a limited set of tide gauges with long records, and may thus have greater uncertainty than would be noted from a long-term near-global set of altimetry observations. If one supposes the magnitude of the true MSL variability in only half of that in their dataset, the necessary data duration for a r.m.s. trend uncertainty of 0.5 mm/yr is 9 years for a perfect observing system, 17 for the high quality continuous record and 31 years if interrupted. In this case, if the community does not have a high confidence in the co-alignment between the non-overlapping 2nd and 3rd missions, a better trend estimate is actually achieved by discarding the first 9 years of data (2 missions). Many of the published papers on MSL rise fail to give uncertainty estimates for their trends, but a value of 0.4 mm/yr is given by Leuliette et al. (2004) and Nicholls and Cazenave (2010) for when the dataset duration is of order 15 years. This lies approximately on the thin pink curve in Fig. 9c suggesting that my simulations have in general overestimated the dataset duration needed. This could be either because inherent variability in the global MSL is negligible (unlikely given the short term variability shown in Fig. 1) or that the altimeter variability specification in case 1 is a little larger than that associated with the TOPEX and Jason altimeters. However it should be remembered that even trends based nominally on TOPEX and Jason data have in fact benefitted from the other contemporaneous missions, which have helped highlight peculiarities in trends and geographically correlated errors that have then been addressed by many research groups.

Individual governments may have a much stronger interest in the ability to detail changes in the regional mean sea level pertinent to their particular country. A regional sea level is not just affected by the melt of land-ice (increasing the total mass of the ocean) and total heat content (increasing sea surface height by thermosteric effect), but also regional differences in sea level pressure, atmosphere-ocean heat flux and changes in the circulation e.g. reduction in gyral circulation. Consequently on short time scales (<30 years) regional

MSL varies much more markedly than global MSL. The illustrations for UK and North Atlantic waters (Fig. 8) show the regional change in the first 100 years relative to each model's global signal, with more short-term variability, and even less consistency than is seen for the global averages (Fig. 2). Such variety in the short-term spectrum of variability is very much borne out by altimetric analysis (Hughes and Williams, 2010).

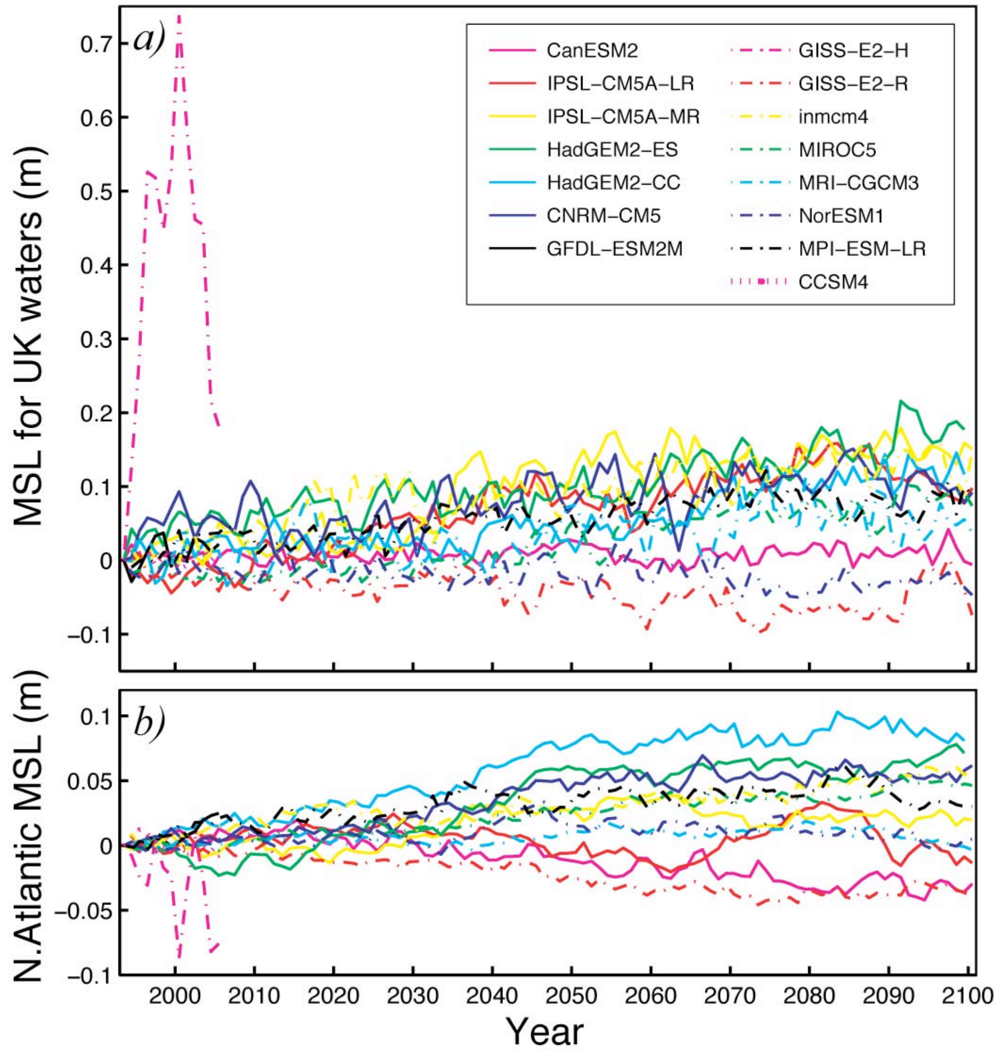

Fig. 8 : Time series of regional MSL relative to the global average as portrayed in CMIP5 models for the historical and RCP45 runs. a) UK waters (12˚W-3˚E, 49˚-58˚N), b) North Atlantic (20˚-66˚N).

However, the detectability of changes in the rate of MSL rise in a region relative to global average is not such a problem for altimeters. Any long-term uncertainties in mission alignment or drift will not contribute to errors in the determination of relative regional MSL. On a regional scale, issues may arise due to problems in radiometer corrections or sea state (tracker) bias, which are terms whose mean varies regionally. However, the more critical issue is likely to be the inherent variability in the regional MSL, which will necessitate much longer time series to ascertain estimates of trend reliably.

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