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A new assessment of the error budget of global mean sea level rate estimated by satellite altimetry over 1993–2008

M. Ablain[1], **A. Cazenave**[2], **G. Valladeau**[1], **and S. Guinehut**[1]

[1]CLS, Ramonville Saint-Agne, France
[2]LEGOS, OMP, Toulouse, France

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Abstract. A new error budget assessment of the global Mean Sea Level (MSL) determined by TOPEX/Poseidon and Jason-1 altimeter satellites between January 1993 and June 2008 is presented using last altimeter standards. We discuss all potential errors affecting the calculation of the global MSL rate. We also compare altimetry-based sea level with tide gauge measurements over the altimetric period. Applying a statistical approach, this allows us to provide a realistic error budget of the MSL rise measured by satellite altimetry. These new calculations highlight a reduction in the rate of sea level rise since 2005, by ∼2 mm/yr. This represents a 60% reduction compared to the 3.3 mm/yr sea level rise (glacial isostatic adjustment correction applied) measured between 1993 and 2005. Since November 2005, MSL is accurately measured by a single satellite, Jason-1. However the error analysis performed here indicates that the recent reduction in MSL rate is real.

1 Introduction

One of the most important indicators of global warming is the global Mean Sea Level (MSL) which integrates the response of many components of the climate system. Precise monitoring of MSL variations with global coverage is a major objective, not only for climate research but also for socio-economic purposes. Tide gauge records have shown that during the 20th century, global MSL has risen at an average rate of about 1.7 mm/yr (Church and White, 2006, Jevrejeva et al., 2008). Since 1993, altimeter measurements from TOPEX/Poseidon (T/P) and Jason-1 satellites provide precise MSL measurements with global coverage (e.g., Nerem and Mitchum, 2001; Cazenave and Nerem, 2004; Leuliette et al., 2004; Nerem et al., 2006). The most recently published study using altimeter data reports a global MSL rate of 3.3±0.4 mm/yr over the 1993-2006 time span (Beckley et al., 2007). If the Global Isostatic Adjustment (GIA) correction (of about −0.3 mm/yr; (Peltier, 2004)) is accounted, this rate increases to 3.6 mm/yr. However differences in estimated MSL rates from different authors up to 0.7 mm/yr are commonly reported. It is likely that such a scatter mostly results from differences in data processing and in applied geophysical corrections. One purpose of the present study is precisely to provide an updated assessment of the errors affecting altimetry-based MSL rate. Earlier studies, e.g., Nerem et al. (2001a, b), Fernandes at al. (2006), had similar objective but reprocessed GDRs and updated geophysical corrections are now available, which justifies a new assessment. Another main issue of the paper is to provide the error of the global MSL trend with a confidence interval thanks to a statistical approach based on an inverse formulism (Bretherton et al., 1976).

In the first part of this study, we propose a new calculation of the global MSL from January 1993 to June 2008 using new standards for the processing of the T/P and Jason-1 data. This new calculation highlights a reduction in the rate of sea level rise since 2005, by ∼2 mm/yr.

In the second part, we check if this reduced rate of rise is real or results from anomalies of the Jason-1 altimeter system. This question is legitimate as any calibration between Jason-1 and T/P data is not possible any more, the T/P mission having ended in November 2005. Note that because of abnormal trends detected on the global MSL deduced from Envisat and Geosat Follow-on altimeter systems, we cannot use these missions for the calibration of Jason-1 with a good confidence. For this purpose, we investigate all sources of errors which might affect altimetry-derived MSL over the whole altimetric period since 1993. The statistical approach to estimate the error of the global MSL trend is then described in detail. Finally, an external calibration of

Correspondence to: M. Ablain
(michael.ablain@cls.fr)

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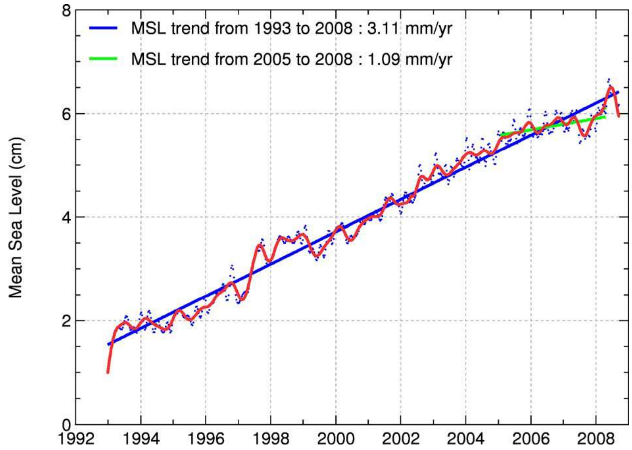

Fig. 1. Altimeter MSL from Jason-1 and T/P over the 1993–2007 period without GIA correction applied. Annual and semi annual signals have been adjusted and a 60-day low-pass filter has been applied. Red curve is smoothed over a semi-annual period.

the MSL is carried out through a comparison of tide gauge-based and altimeter MSL. This approach also allows detection of anomalies in MSL rise.

2 Altimeter MSL calculation over 1993–2008 period

Measuring MSL by satellite altimetry requires extreme stability of the system, in terms of orbit, instrumental and geophysical corrections. For that purpose, we need to use homogenous time series of T/P and Jason-1 SSH data.

The Jason-1 data used in this study are the Version B reprocessed Geophysical Data Records (GDRs) from cycles 1 to 232. SSHs are derived using the corrections summarized in Table 1, except for dry troposphere and inverse barometer corrections which have been updated. For the latter, we use rectangular surface pressure grids from the European Centre for Medium-range Weather Forecast (ECMWF) instead of the Gaussian grids provided in the standard GDRs. In theory, this modification should have no impact on the correction itself but in practice, jumps have been detected in the Gaussian pressure fields with significant effects on the MSL trend. A bias of 75.5 mm is then removed from Jason-1 SSHs to have Jason-1 and T/P SSH in a common datum. Thanks to the Jason-1 verification phase where both satellites were on the same orbit spaced out by 72 seconds, the SSH bias can be precisely determined, associated uncertainty being lower than 1 mm.

Concerning T/P, data have been reprocessed from the merged Geophysical Data Records (MGDRs) to be consistent with Jason-1 data (see Table 1). Some geophysical corrections have been updated: the GOT2000 model (Ray and Egbert, 2004) is used for ocean and loading tides and dry troposphere correction. The combined atmospheric corrections (sum of high frequencies of MOG2D model (Carrere and Lyard, 2003) and low frequencies of inverse barometer correction) is applied instead of the usual inverse barometer correction in order to improved the cycle by cycle SSH variability. The wet troposphere correction is based on the TOPEX radiometer measurements, after removing a long-term drift (Scharroo et al., 2004) and correcting for the time dependent yaw state (Aviso T/P yearly report 2005). A non-parametric model is used for the sea state bias correction (SSB) with two distinct solutions for TOPEX A and TOPEX B (Gaspar, 2002). Subsequent SSH bias between TOPEX A and TOPEX B is then 1.17 cm, instead of 0.5 cm when using the 4-parameters SSB proposed with the merged GDRs. Finally, the standard orbit has been replaced by a new orbit generated by the Goddard Space Flight Centre (GSFC). The new orbit is based on the GRACE gravity field model, GGM02C (Tapley et al., 2004) and is expressed in the ITRF2000 (Altamimi et al., 2002) reference frame throughout the period.

Using these new T/P and Jason-1 data (spurious measurements removed), global SSH grids are then computed for each cycle. To account for the heterogeneous data distribution with latitude and for data gaps, a $2^\circ \times 2^\circ$ boxes averaging is performed. The global MSL curve is further computed by geographically averaging data of each cycle (using a cosine latitude weighting function).

3 MSL evolution analysis

Figure 1 shows the global MSL curve between 1993 and 2008 after removing the annual and semi-annual cycles. A 60-day filtering is applied to the raw data (blue dots). A 6-month smoothing is further performed (red curve). The mean rate of sea level rise estimated over 1993–2008 amounts to 3.11 mm/yr. Applying the GIA correction (−0.3 mm/yr) (Peltier, 2004) leads to a rate of rise of 3.4 mm/yr over the past 15 years. Although the global MSL evolves rather linearly (adjustment formal error is 0.02 mm/yr), inter-annual variations can nevertheless be observed, in particular during the 1997–1998 ENSO (El Niño Southern Oscillation) event. At the end of the time span (since 2005), the MSL curve appears relatively flat with a marked negative anomaly in mid-2007.

We have computed MSL rates using moving windows of 3-year and 5-year. These are shown in Fig. 2. Estimated MSL rates display two maxima, in 1997 and 2002. Corresponding rates are in the range of 4–6 mm/yr when using the 3-year window. It is very likely that these two maxima reflect the influence of ENSO events on the MSL. The signature of the 1997–1998 ENSO is clearly visible on the MSL curve, as shown by Ngo-Duc et al. (2005) due to an excess of precipitation in tropical river basins. Another weaker ENSO event occurred in 2002–2004. It is likely that the secondary peak seen in Fig.2 also reflects the sea level response to this ENSO event. Past decades sea level rates based on tide gauge

Table 1. Corrections applied for the Jason-1 and T/P MSL calculation.

Corrections & models	Jason-1	TOPEX/Poseidon
Orbit	Cnes POE (GDR B)	GSFC, ITRF2000+ Grace (Altamimi 2002; Tapley et al., 2004)
Dry troposphere	ECMWF model computed from rectangular grids (new S1 and S2 atmospheric tides are applied)	
Wet troposphere	JMR	TMR with drift correction (Scharroo et al., 2004) and empirical correction of yaw maneuvers [T/P 2005 annual validation report]
Ionosphere	Dual-frequency altimeter range measurements	Dual-frequency altimeter range measurements (for TOPEX) and Doris (for Poseidon)
Sea State Bias	Non parametric SSB (Gaspar et al., 2002)	Non parametric SSB (for TOPEX), BM4 formula (for Poseidon).
Ocean tide and loading tide	GOT2000 (S1 parameter is included)	
Combined atmospheric correction	Mog2D (Carrère and Lyard, 2003) + inverse barometer computed from ECMWF model (rectangular grids)	
Solid Earth tide	Elastic response to tidal potential , (Cartwright and Tayler, 1971)	(Cartwright and Edden, 1973)
Pole tide	(Wahr, 1985)	
Specific corrections	Jason-1/T/P SSH bias	Doris/Altimeter ionospheric bias, TOPEX-A/TOPEX-B bias and TOPEX/ Poseidon bias [TOPEX/Poseidon 2005 annual validation report]

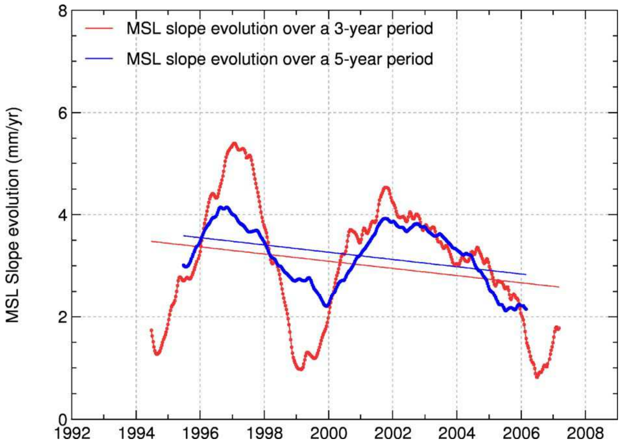

Fig. 2. Evolution of the altimeter MSL slope using a 3-year (blue curve) and a 5-year window (red curve) sliding over all the TOPEX/Jason-1 period.

records also show systematic high values during ENSO years (Landerer, 2008).

As expected, smaller variations of rates are reported when using the 5-year window since inter-annual variations are partly smoothed. Quite low rates are observed during La Nina events (1999) and (2007), although no quantitative explanation has been given yet. Nevertheless, the recent reduction observed in sea level rate is likely real as it coincides with an exceptionally strong La Nina event (Kennedy, 2007). To check the robustness of the estimated smaller rate of sea level rise over the past few years, we next investigate whether it could be related to drifts or jumps in the Jason-1 altimetry system.

4 Uncertainties on altimeter measurements

In this section we discuss the main source of errors affecting Jason-1 and T/P SSH measurements.

4.1 Wet troposphere correction

One major source of error affecting the MSL estimate is the wet troposphere correction derived from microwave radiometers on-board altimetric satellites. Indeed, this correction is potentially contaminated by long-term instrumental drifts. Such drifts may result from internal temperature changes induced by yaw maneuvers or when the instrument is turned off. Calibrations with external measurements are periodically performed to detect drifts on the T/P radiometer (TMR) (Scharroo et al., 2004) and Jason-1 radiometer (JMR) (Desai et al., 2004; Jason-1 GDR-B release). Though meteorological models do not represent necessarily the truth in term of stability, they provide a good estimate of the radiometer drift error through altimetry missions and model cross-calibration. Here we use outputs from three meteorological models: the ECMWF operational model from 2002 onwards, the ERA40 reanalysis (Uppala et al., 2005) from 1992 to 2002, and the NCEP reanalysis (Kalnay, 1997) over the same period. Operational model data regularly show jumps, thus are inadequate for long-term comparison with TMR data, at least before 2002. Fortunately, more coherent ERA40 and NCEP reanalyses allow us to assess the reliability of TMR correction. In addition, the Envisat radiometer (MWR) and model cross-calibration provide a complementary comparison to study the long-term JMR stability. Figure 3 shows the wet troposphere correction daily differences for four couples of data: (1) TMR minus ERA40, (2) TMR minus NCEP, (3) JMR minus ECMWF and (4) MWR minus ECMWF. TMR

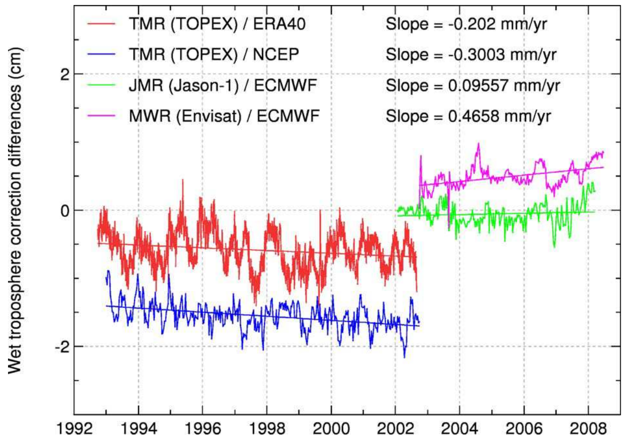

Fig. 3. Daily wet troposphere correction differences: (1) TMR minus NCEP reanalysis, (2) TMR minus ERA40 reanalysis, (3) JMR minus ECMWF model and (4) MWR minus ECMWF model.

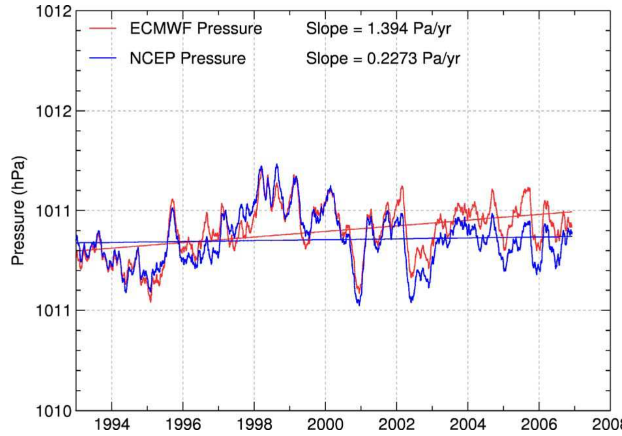

Fig. 4. Global trend of pressure over ocean derived from ECMWF (blue curve) and NCEP reanalysis (red curve) models smoothed over a semi-annual period.

and model cross-calibrations (cases 1 and 2) highlight a negative slope between 0.2 and 0.3 mm/yr from 1992 to 2002. The trend obtained with NCEP reanalysis is more accurate than with ERA40 reanalysis, since significant inter-annual signals are observed with this last one. Concerning case 3 using JMR and ECMWF model from 2002 to 2008, the global trend is very small, on the order of 0.1 mm/yr. However, the end of the curve beyond 2006 displays a significant increase close to 1 mm/yr. In the meantime, Envisat and ECMWF comparison (case 4) highlights a similar slope from 2006 onwards, whereas between 2002 and 2005 both radiometers do not show a very good agreement. The cross-calibration of both radiometer corrections, independently calibrated, is here useful to detect a drift in the ECMWF model probably related to several model changes. These evolutions (February and September 2006, June and November 2007, March 2008) can generate small jumps close to 1 mm signing as a drift over a period of 2 or 3 years.

In addition, the physical content evolution of the wet troposphere correction appears to be a supplementary source of uncertainty to estimate its potential drift. The correction is firstly strongly correlated with ENSO oscillations, and in the meantime, the long term evolution of the correction is affected by climate warming, e.g. the increase of atmospheric water vapor content around 0.041 kg/m^2/yr since 1988 (DOE/Lawrence Livermore National Laboratory, 2007). The MSL rate error associated with the absolute wet troposphere correction is on the order of +0.2 mm/yr. These variations, of physical origin, represent a limiting factor for an accurate calibration of radiometer or model corrections.

To summarize the above discussion, from this analysis, we estimate that the uncertainty of the MSL trend calculation due to the wet troposphere correction ranges between 0.2 and 0.3 mm/yr over the whole altimeter period.

4.2 Dry troposphere and inverse barometer corrections

Another source of error is linked to the use of operational ECMWF atmospheric pressure fields provided in the Jason-1 and T/P products. Indeed, the dry troposphere and inverse barometer corrections are directly derived from these fields used to compute the (time variable) surface pressure averaged over the oceanic domain. Although their good quality has already been demonstrated (Ponte et Dorandeu, 2003; Salstein, 2008), surface pressure grids may not be appropriate for long-term sea level estimates. We compared the Gaussian ECMWF surface pressure grids (as given in the Jason-1 GDRs) with NCEP reanalyses grids. Two jumps, in 2004 and 2006, of about 20 hPa have then been detected, one in the instantaneous ECMWF surface pressure grids, the other in the mean surface pressure grids. Corresponding effects on SSH and MSL trend (over 2002–2008) amount respectively to 2.5 mm and 0.2 mm/yr. Rectangular pressure grids (as given with the T/P M-GDRs) do not show such discontinuities and are thus preferred for the MSL calculation. We also compared time series of mean surface pressure averaged over the oceanic domain, from two sources: ECWMF rectangular grids and NCEP grids (see Fig. 4). Trends in time series are respectively 1.39 Pa/yr and 0.23 Pa/yr. Considering the uncertainty induced by the potential heterogeneity between the different local pressure and mean pressure fields as well as the error in the global pressure trend, we estimate the error on the MSL rate on the order of 0.05 to 0.1 mm/yr.

4.3 Orbit calculation

To be consistent with Jason-1 orbit, NASA/GSFC recently recomputed new T/P orbits (see first section) that significantly reduced the geographically correlated SSH biases (Ablain et al., 2007). As far as the long term stability is

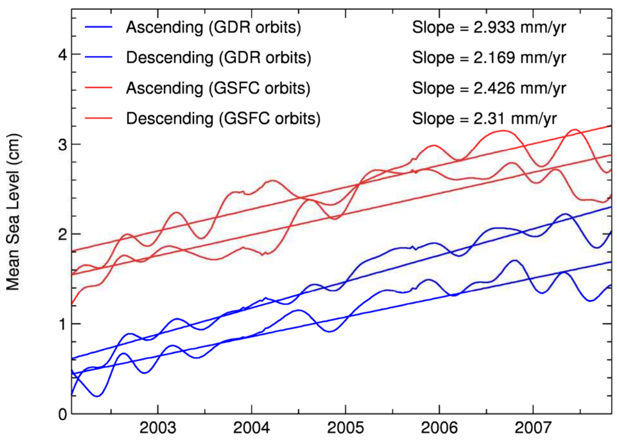

Fig. 5. Global Jason-1 MSL separating ascending and descending passes using Jason-1 GDR's orbit (blue curve) and ITRF2005 GSFC orbit (red curve).

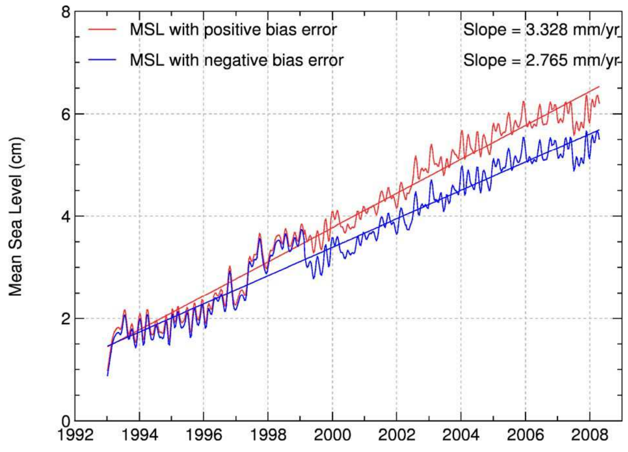

Fig. 6. Impact of the SSH bias uncertainty on the global MSL trend considering extreme SSH bias errors between TOPEX A and TOPEX B, and between TOPEX and Jason-1.

concerned, the impact on the global MSL trend is weak (about +0.1 mm/yr over the T/P period) but much larger on regional slopes, with opposite hemispheric differences close to 2 mm/yr. Despite this improvement, global trend discrepancies remain between both hemispheres since MSL trend is about 2.5 mm/yr in the North and 3.5 mm/yr in the South. This 1 mm/yr trend differences can be explained by physical processes (the long-term changes in the ocean heating and circulation is different from one hemisphere to another). But, they can also be considered as an uncertainty due to the orbit calculation. Indeed, the use of a recent orbit solution for Jason-1 and T/P (GSFC orbit computed with a new ITRF2005 reference frame (Altamimi et al., 2007)) allows to remove the heterogeneity between global hemispheric MSL trends. As the ocean surface is not the same for both hemispheres, this hemispheric trend error impacts the global MSL on the order of 0.1 mm/yr over the whole altimeter period.

In addition, other sources of trend discrepancies are observed between ascending and descending passes using GDR's orbit over the Jason-1 period (2002–2008). MSL rates computed with ascending alone on one hand and descending tracks alone on the other hand are respectively 2.9 mm/yr and 2.1 mm/yr as plotted in Fig. 5. These unexpected differences are reduced applying the ITRF2005 GSFC orbit close to 2.4 mm/yr and 2.3 mm/yr. However, some residual incoherent signals are still observed (see Fig. 5), since ascending and descending MSL curves are worse correlated than using GDR's orbit. In any case, improved orbit calculation is essential to explain and resolve these discrepancies. Assuming it is only a problem of orbit centring, this error is probably weak after averaging ascending and descending passes. Finally, a realistic error budget ranging from 0.1 to 0.15 mm/yr on the global MSL trend can be allocated to the orbit calculation.

4.4 Others potential errors

Other factors can also affect global MSL rate estimate as for instance the SSH bias applied to link together MSL time series from different altimeters: TOPEX A and TOPEX B (March 1999), TOPEX-B and Jason-1 (April 2003). The SSH bias values mainly depend on the SSB solution applied on each subset, impacting directly the global MSL trend estimation (Chambers et al., 2003). The objective here is precisely to estimate this SSH bias uncertainty using noparametric SSB solutions (see Sect. 2). In this case, SSH bias between TOPEX A and TOPEX B is 11.7 mm, and 75 mm between TOPEX B and Jason-1. A realistic error between 1 and 2 mm for TOPEX A/TOPEX B bias is estimated taking into account the uncertainty to estimate the SSH bias without overlapping between both datasets and a strong decrease of the MSL evolution in relationship with "La Ninã" 1999. The error is reduced between 0.5 and 1 mm for TOPEX/Jason-1 thanks to the Jason-1 verification phase allowing an accurate cross-calibration between both missions. The uncertainty associated to each bias is large enough to significantly affect the global MSL trend. Considering extreme bias errors, we find an MSL trend ranging from 2.8 to 3.3 mm/yr (see Fig. 6) and highlighting an error of ±0.25 mm/yr on the global MSL trend in the worse case. Notice that the impact of the SSH bias uncertainty is depending on the period and thus reduced with a longer period.

Another source of potential errors concerns altimeter instrumental ageing. Altimeter parameters are precisely monitored over all the mission life-time to detect instrumental anomalies. However, after analyzing altimeter parameters that directly affect the MSL calculation, potential drifts in the altimeter wind speed (derived from Sigma0 parameter) have been detected. Comparisons between different source of meteorological data (NCEP reanalysis and ECMWF model)

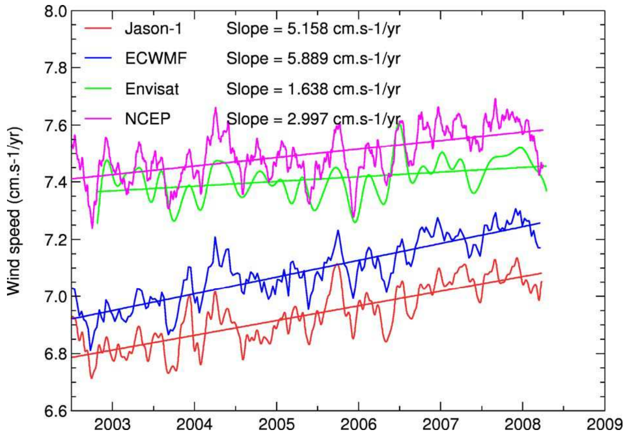

Fig. 7. Monitoring of the wind speed derived from Jason-1, Envisat, NCEP and ECMWF over the Jason-1 period.

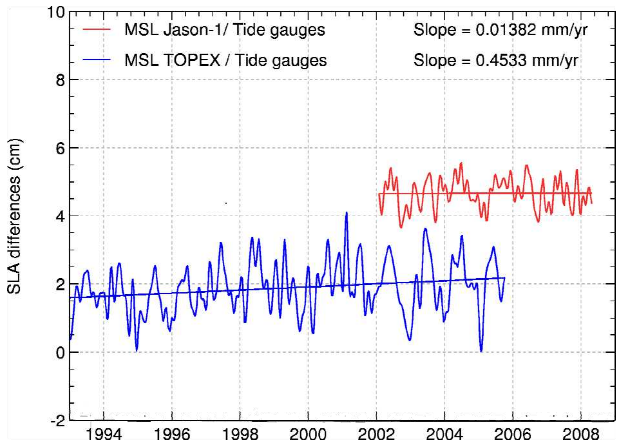

Fig. 8. Altimeter and tide gauges MSL comparisons for Jason-1 and T/P.

and cross-calibration between altimeter missions allow us to quantify this drift (see Fig. 7). Over the Jason-1 period, the Jason-1 and ECMWF altimeter wind speeds show a significant trend of 5.2 and 5.9 cm.s^{-}1/yr, respectively. In the meantime, the Envisat altimeter mission provides a wind speed trend weaker of about 1.6 cm.s^{-}1/yr, which is relatively close to the NCEP reanalysis (3 cm.s^{-}1/yr). Considering now the T/P period (not plotted here), the wind speed trend deduced from T/P measurements is around 1 cm/s^{-}1/yr and 2.5 cm.s^{-}1/yr for the NCEP reanalysis. As the real evolution of wind speed is unknown, this analysis just highlights the long-term trend discrepancies between each wind speed derived from altimeters and models. An uncertainty varying between 2 and 4 cm.s^{-}1/yr appears as a realistic value. Through the sea state bias correction applied to SSH measurements induces an error of 0.05–0.10 mm/yr in the MSL rate over the entire altimetric period.

4.5 Total error budget

Considering independently all the potential errors of altimeter data described previously and reported in Table 2, the global MSL trend is then majorized by an upper bound limit error of 0.9 mm/yr considering highest errors. This total error is a pessimistic point of view since we assume errors are additional and can not be negatively correlated. From a classic way, the quadratic sum of each error leads to a lower value close to 0.45 mm/yr. But, this basic method doesn't take into account the potential correlation between each error and the no-linearity of the MSL evolution. In addition, the confidence interval of the total error is unknown. Then, an important issue of this paper is to apply an inverse method (Bretherton et al., 1976) to estimate a more realistic error from a statistical approach:

$$x_{\text{est}} = R_{xx} H^T (H R_{xx} H^T + R_{vv})^{-1} z,$$

(Bretherton et al., 1976)

In this formula, x_{est} is the estimated unknown vector (estimated trend here), z is the observation vector and H the observation operator, R_{vv} the covariance matrix of observation errors and R_{xx} the unknown covariance matrix. Thanks to this appropriate mathematic formalism, we are able to take into account each error after filling the covariance matrix of observation errors (R_{vv}). This allows us to describe them differently according to the time period (TOPEX and Jason-1 can be separated) or their nature (jump or drift for instance). The formal error can then directly be estimated from the following formalism from the diagonal term in C_{xx}(estimated unknown covariance matrix) corresponding to the slope:

$$C_{xx} = R_{xx} - R_{xx} H^T (H R_{xx} H^T + R_{vv})^{-1} H R_{\text{xx}},$$

(Bretherton et al., 1976)

A realistic error is then calculated after multiplying this formal error by the coefficient given by the student law for a dedicated confidence interval. Finally, assuming the maxima uncertainties (described in Table 2), we obtained a statistical error of 0.6 mm/yr with a confidence interval of 90%.

If we focus on the 2005–2008 period, the error related to pressure fields and the wet troposphere correction mainly affects the MSL over this period. Other errors have a very homogenous behavior over the whole altimetric period (orbit, wind speed), or do not impact the end of the period (TOPEX/TOPEX B and TOPEX/Jason-1 subsets for instance). Thus this can not explain a change in the MSL trend. We have already shown that the inconsistency between mean pressure and local pressure fields has a weak impact. Over a short 3-year period, it is limited to 0.2 mm/yr. The uncertainty on the wet troposphere correction has been described above (∼0.5 mm/yr difference is observed between ECMWF and radiometer correction). But, in the meantime, both radiometer corrections (AMR for Envisat and JMR for Jason-1) show a very good consistency and a similar trend over this

Table 2. MSL trend uncertainties from 1993 to 2008 for each correction or model impacting the MSL calculation.

Source of error for the MSL calculation		MSL trend uncertainties from 1993 to 2008	
		Minima	Maxima
Orbit:Cnes POE (GDR B) for Jason-1 and GSFC (ITRF2000) for T/P.		0.10 mm/yr	0.15 mm/yr
Radiometer Wet troposphere correction: JMR and TMR (with drift correction).		0.20 mm/yr	0.30 mm/yr
Dynamical atmospheric and dry troposphere corrections using ECMWF pressure fields.		0.05 mm/yr	0.10 mm/yr
Sigma0 drift impacting altimeter wind speed and sea state bias correction		0.05 mm/yr	0.10 mm/yr
Bias uncertainty to link TOPEX A and TOPEX B, and TOPEX and Jason-1.		0.10 mm/yr	0.25 mm/yr
Total error budget	absolute sum	0.50 mm/yr	0.90 mm/yr
	quadratic sum	0.32 mm/yr	0.44 mm/yr
	inverse formalism	0.6 mm/yr in a confidence interval of 90%	

period. Finally, on no account, altimetric errors can explain the slowing down MSL evolution at the end of the period.

5 Comparison with tide gauge network

5.1 Estimation of altimeter MSL drift

The analysis of potential drifts in altimeter measurements points out uncertainties, in particular for the wet troposphere correction. A relevant way of checking the reliability of the global MSL over the whole period and especially the 3 last years is to compare altimeter data with independent in-situ datasets such as tide gauge measurements. Several studies have been already performed (Mitchum 1998 and 2002; Chambers, 1998) showing the good consistency between altimeter and tide gauge measurements. More recent results (Beckley and al., 2007), based on a 64-site high quality tide gauges, provide an estimation of the drift derived from in-situ and altimeter measurements, of 0.04 mm/year for T/P between 1993 and 2002 and 0.69 mm/year for Jason-1 from 2002 through 2006 included. We present here a new assessment of these long-term comparisons until 2008 in agreement with our MSL calculation based on a larger number of tide gauges.

134 tide gauges have been selected from the University of Hawai Sea Level Centre (UHSLC) after a careful analysis of records quality (no jump or abnormal strong drifts). Some of them do not cover the whole altimeter period, but they are calibrated together in order to be used. Thanks to this higher number of tide gauges, the coastal sampling is improved (especially along African coasts), allowing to better take into account the regional MSL trend variability. In addition, the consistency between altimeter and in-situ measurements is increased, improving the capacity to detect a change between altimeter and in-situ data as described further.

Vertical land movements (post-glacial rebound, plate tectonics, water land storage. . .) at tide gauges have also been corrected for. For that purpose we used GPS-based vertical motions estimated by the University of La Rochelle (ULR) analysis centre consortium (Wöppelmann et al., 2007). After selecting the closest GPS stations from the given tide gauges, a global mean correction of about 0.3 mm/yr has been computed. Applying it to the *altimetry minus tide gauge SLA differences*, the altimeter drift estimation is now very weak close to +0.01 mm/yr for Jason-1 and +0.45 mm/yr for TOPEX (see Fig. 8). Merging both altimeter missions over the whole period, the drift becomes close to +0.3 mm/yr.

5.2 Accuracy of the method

These comparisons do not show any anomaly on altimeter measurements, especially at the end of the period since no difference is observed from the Jason-1 and tide-gauge comparisons. This result seems to prove the reliability of the Jason-1 altimeter data between 2005 and 2007. However the accuracy of the method (especially due to land motion) is a limiting factor to detect altimeter drift or jump. The relatively strong adjustment formal error, 0.27 mm/yr for Jason-1 and 0.11 mm/yr for T/P, points out the sensitivity of the drift calculation, though it has been reduced (by 0.15 mm/yr) thanks to the higher number of tide gauges. It mainly ensues from the consistency between altimeter and in-situ measurements (the standard deviation of differences is in average close to 7 cm for one tide gauge). It takes into account the error of in-situ and altimeter MSL, but also the colocation error which depends on the distance between the tide gauge and the closest altimeter measurements. Statistic monitoring computed through this method may work on the assumption that the use of long data time series reduces the impact of this uncertainty on the trend estimation. In addition, the vertical land movements correction directly impacts the long-term drift estimation.

The uncertainty of this correction remains relatively significant since the colocation between tide gauges and GPS stations is possible only for about 60 sites. The accuracy close to 0.2 mm/yr could be refined with an extended GPS station network. Finally, an important limitation of the method is the capability to detect an altimeter change in open ocean because of the coastal sampling of tide gauges. This is in particular true for the wet troposphere correction whose regional trends are strong and variables in wet tropical areas but not well displayed at tide gauge sites. On average, the method is able to assess the long term drift of the global altimeter MSL. Taking into account the error related to the adjustment formal error and the uncertainty of the vertical land movement correction, the accuracy of the method is close to 0.5 mm/yr over all the altimetric period. Finally, the altimeter drift estimation derived from Jason-1 and T/P data is around 0.3 ± 0.5 mm/yr.

6 Conclusions

On the one hand, thanks to the analysis of each error budget, we show that the global MSL trend is 3.11 ± 0.6 mm/yr over the whole altimetric period (1993-2008) with a confidence interval of 90%. On the other hand, the altimeter MSL drift derived from altimeter and tide gauge comparisons is on the same order close to $+0.3\pm0.5$ mm/yr. The good consistency of these both independent approaches demonstrates the reliability of T/P and Jason-1 altimeter data to compute the global MSL trend from 1993 to 2008. The capability to observe inter-annual variations related to ENSO oscillations is possible thanks to the good accuracy of altimeter MSL. Indeed, we have demonstrated that the weak MSL trend observed for the 3 last years (1 mm/yr) cannot result from the altimeter MSL drift error. Besides, preliminary MSL analyses (not described here) using Jason-1 data since June 2008, indicate an acceleration of the MSL trend likely in relationship with the end of the 2007–2008 “La Niña” event.

Though the MSL trend error is already in agreement with scientific objectives, it could probably be significantly reduced applying homogenous SSH calculation for T/P and Jason-1, and very soon Jason-2. The use of similar orbits or similar retracking algorithms for T/P and Jason-1 data would reduce the correlated geophysical biases. The accuracy of TOPEX A/ TOPEX B and TOPEX/Jason-1 SSH biases could be then improved. In addition, the use of pressure fields derived from models with a stable configuration (without jump) would reduce or even remove the drift uncertainty linked to the dry troposphere and dynamical atmosphere corrections. Along the same idea, a more stable wet troposphere correction derived from operational models will be useful to better calibrate corrections derived from radiometer.

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