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Satellite Altimetry-Based Sea Level at Global and Regional Scales

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Abstract Since the beginning of the 1990s, sea level is routinely measured using high-precision satellite altimetry. Over the past ~25 years, several groups worldwide involved in processing the satellite altimetry data regularly provide updates of sea level time series at global and regional scales. Here we present an ongoing effort supported by the European Space Agency (ESA) Climate Change Initiative Programme for improving the altimetry-based sea level products. Two main objectives characterize this enterprise: (1) to make use of ESA missions (ERS-1 and 2 and Envisat) in addition to the so-called 'reference' missions like TOPEX/Poseidon and the Jason series in the computation of the sea level time series, and (2) to improve all processing steps in order to meet the Global Climate Observing System (GCOS) accuracy requirements defined for a set of 50 Essential Climate Variables, sea level being one of them. We show that improved geophysical corrections, dedicated processing algorithms, reduction of instrumental bias and drifts, and careful linkage between missions led to improved sea level products. Regarding the long-term trend, the new global mean sea level record accuracy now approaches the GCOS requirements (of ~0.3 mm/year). Regional trend uncertainty has been reduced by a factor of ~2, but orbital and wet tropospheric corrections errors still prevent fully reaching the GCOS accuracy requirement.

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Similarly at the interannual time scale, the global mean sea level still displays 2–4 mm errors that are not yet fully understood. The recent launch of new altimetry missions (Sentinel-3, Jason-3) and the inclusion of data from currently flying missions (e.g., CryoSat, SARAL/AltiKa) may provide further improvements to this important climate record.

Keywords Satellite altimetry · Sea level · Climate Change Initiative

1 Introduction

Sea level is one of the key indicators of climate change because it integrates changes of several components of the climate system in response to anthropogenic forcing as well as natural forcing factors related to natural sources and internal climate variability. Since the beginning of the twentieth century, the global mean sea level (GMSL) has been rising at a mean rate of 1.7 ± 0.3 mm/year as recorded by in situ tide gauges (e.g., Church et al. 2011, 2013; Woppelmann et al. 2009; Jevrejeva et al. 2008). However, values in the range 1.2 to 1.9 mm/year have also been proposed (Hay et al. 2015; Jevrejeva et al. 2014). Since the early 1990s, sea level variations are routinely measured by high-precision satellite altimetry. In terms of global mean, sea level rise over 1993–2014 amounts to 3.4 ± 0.4 mm/year (e.g., Nerem et al. 2010; Cazenave et al. 2014; Ablain et al. 2015). This value is two times larger than that of the previous decades, suggesting an acceleration of the GMSL rise. Present-day GMSL rise primarily reflects ocean warming (through thermal expansion of sea water) and land ice melting, two processes which result from anthropogenic global warming (Church et al. 2013). The Earth is currently in a state of thermal imbalance because of concentrations of anthropogenic greenhouse gases (GHG) in the atmosphere (Von Schukmann et al. 2016). Most of this heat excess is accumulated in the ocean (93 %); the remaining 7 % being used to warm the atmosphere and continents, and melt sea and land ice. GMSL rise is a direct consequence of these processes. Over the course of its five assessments, the Intergovernmental Panel on Climate Change (IPCC) has reported a significant improvement in our understanding of the sources and impacts of GMSL rise. Over the altimetry era, observed sea level rise and sum of contributions (ocean thermal expansion, land ice melt, land water storage change) concur, allowing the closure of the sea level budget for this period within estimated uncertainties (Church et al. 2013). Confidence in projections of future sea level rise has increased, thanks to improved physical understanding and closer agreement between model hinscasts and observations. However, significant problems still remain. The IPCC 5th assessment report—AR5—(Church et al. 2013) reported a 0.4 mm/year difference between the observed GMSL rate and the sum of contributions over the 1993–2010 time span. Yet uncertainties of components of the sea level budget equation (including sea level) are still large, in the order of 1 mm/year (2-sigma) (Church et al. 2013). The challenge is thus to reduce the components' errors, in order to check the statistical significance of the difference between observed sea level and sum of contributions. The satellite altimetry-based sea level record is affected by errors due to the imperfect altimeter corrections applied to the data (with the orbit solution and the wet tropospheric correction displaying the largest uncertainties), geographical averaging process and imperfect linkage between successive altimetry missions. In terms of long-term (decadal) trends, such factors contribute to the 0.4 mm/year difference quoted above (Ablain et al. 2009, 2015). At the interannual time scale, errors in the GMSL record are also significant and amount to 2–4 mm (Ablain et al. 2009; Dieng et al. 2015a, b). Secondly, as far as the contributions are concerned, current estimates of ice sheet and glacier mass balances also display significant uncertainty (Church et al. 2013; Clark et al. 2015). Another issue concerns the land water contribution due to human activities (e.g., ground water depletion and dam building), its quantification being very difficult due to lack of global data (Church et al. 2013; Dieng et al. 2015c). Finally, although the steric contribution (effects of ocean thermal expansion and salinity) was considerably improved since the advent of the Argo project in the early 2000s. But the contribution of the deep ocean (below 2000 m) remains unknown, and prior to Argo, the steric component is quite uncertain due to the poor and heterogeneous distribution of historical hydrographic observations.

A precise estimation of the influence of these factors is crucial to understand processes at work under current climate change and to validate the climate models used for future projections. Over the last decade, the Global Climate Observing System (GCOS), in support of the United Nations Framework Convention on Climate Change (UNFCCC), has put together a set of requirements for satellite data to meet the needs of the climate change community (see GCOS 2011, for the satellite supplement). These requirements are broken down into key parameters of the Earth system, called Essential Climate Variables (ECVs). The goal is to provide accurate and stable values on the long-term, satellite-based ECV data products for researchers. Among the 50 ECVs identified so far by GCOS, 26 are observable from space. Sea level is one of these.

To respond to this need for climate-quality satellite data, the European Space Agency (ESA) has set up a programme, known as the ESA Climate Change Initiative (CCI). The aim of the programme is to realize the full potential of the long-term global Earth Observation archives from satellites as a significant and timely contribution to the ECV databases required by the UNFCCC. The ECVs are derived from multiple satellite data sets via international collaboration and include specific information on the possible biases and uncertainties of the data set. The CCI provides a unique opportunity to set up dialogue and cooperation between Earth observation and climate research communities.

In this overview article, we focus on the sea level record computed in the context of the ESA CCI project. Contributions and sea level budget issues are discussed in other papers in this Special Issue. Section 2 summarizes the high-precision satellite altimetry missions and their characteristics. Section 3 briefly presents the CCI sea level (SL_cci) project. In Sects. 4 and 5, we discuss how multi-mission altimetry-based sea level products are built and what the current level of uncertainties of the global and regional products are. Validation procedures are discussed in Sect. 6. Section 7 provides a summary of the main accomplishments. Conclusions are presented in Sect. 8.

2 Brief History of Satellite Altimetry Missions

Satellite altimetry has revolutionized the research in ocean dynamics by providing high-precision, high-resolution measurements of the ocean surface topography with global coverage and a revisit time of a few days or weeks. The concept of (nadir) satellite altimetry measurement is rather straightforward. The onboard radar altimeter transmits a short pulse of microwave radiation with known power towards the nadir. Part of the incident radiation reflects back to the altimeter. Measurement of the round-trip travel time provides the height of the satellite above the instantaneous sea surface (called altimeter range R). The quantity of interest in oceanography is the height of the instantaneous sea surface above a fixed reference surface (typically a conventional reference ellipsoid). This quantity (called SSH) is simply the difference between the height H of the satellite above the reference ellipsoid and the altimeter range R: SSH = H-R. H is computed through precise orbit determination, a long-tested approach in space geodesy, which combines accurate modelling of the dynamics of the satellite motion and tracking measurements (Global Positioning System-GPS, Doppler Orbitography and Radiopositioning Integrated by Satellite—DORIS, or Satellite Laser Ranging) between the satellite and observing stations on Earth or on other observing satellites (Rudenko et al. 2012; Couhert et al. 2015). The range from the satellite to the sea, R, must be corrected for various components of the atmospheric refraction as well as for biases between the mean electromagnetic scattering surface and mean sea surface at the air–sea interface in the footprint of the radar. Other corrections due to a number of geophysical effects must also be applied. Chelton et al. (2001) describe the principle of satellite radar altimetry and details of the estimation of the SSH. They also discuss all corrections to be applied to the SSH measurements, including drifts and bias from onboard instruments.

Satellite altimetry was envisaged in the 1960s, was recognized as a high priority measurement at the Williamstown Symposium in 1969 (Kaula 1970), and the first objective was to measure the shape of the Earth. The development was pursued during the 1970s with an experiment onboard Skylab III, which in 1973 produced the first measurements of undulations in the marine geoid. GEOS3 (NASA) was the very first altimetry mission, launched in 1975 and providing data until 1979 (Agreen 1982). It was followed by Seasat (1978; NASA) and Geosat (1985; US Navy). These pioneering missions led to important discoveries (e.g., Lillibridge et al. 2006). They revealed, in particular, that the mean sea surface is not flat but mimics the oceanfloor topography (Fig. 1). In effect, the sea surface consists of two parts: (1) a static (i.e. time invariable) component that coincides with the geoid, an equipotential surface of the Earth's gravity field, and (2) a time-variable component due to ocean dynamics (e.g., ocean tides, currents, waves). At short and medium wavelengths ($\sim$<1000 km), the mean sea surface reflects the topographic features of the ocean floor.

The amplitude of the static component anomalies ranges from a few decimetres to several tens of meters. This explains why the first altimetry missions easily detected these features in spite of their lesser SSH measurement accuracy (uncertainty of several

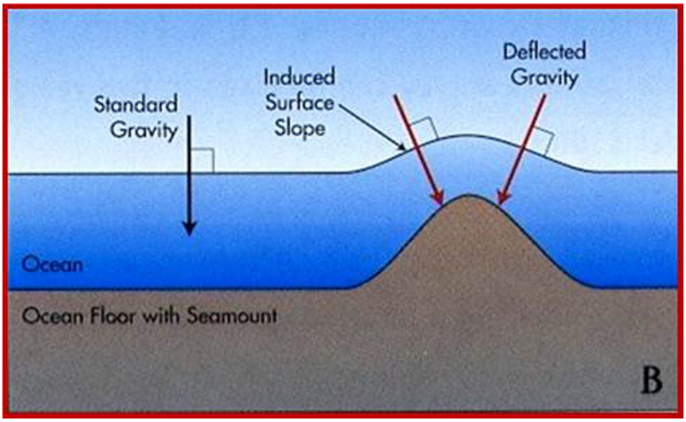

Fig. 1 Sketch of the mean sea surface deformations in response to the gravitational attraction of the sea floor topography

decimetres, mostly due to the orbit error, e.g., Fu and Cazenave 2001) and high instrumental noise.

Nevertheless, these early missions clearly demonstrated the high potential of satellite altimetry to study the dynamics of the world ocean.

The launch of the ERS-1 and TOPEX/Poseidon satellites in 1991 and 1992 opened the era of high-precision altimetry, allowing mapping of the SSH for the first time within a few centimetre accuracy for a single measurement. TOPEX/Poseidon was particularly precise at ocean basin scale and was used as the reference mission while ERS-1 provided the chance to explore the mesoscale variability. They have been followed by several other high-precision altimetry missions with different instrumental characteristics leading to an ever-increasing precision in the SSH measurement. Jason-1, -2, and -3 continued on the tracks of TOPEX/Poseidon, to be succeeded by Sentinel-6/Jason-CS in 2020. Meanwhile ERS-2, Envisat, CryoSat, SARAL/AltiKa and Sentinel-3 supplied and are supplying complementary observations. CryoSat was designed to reveal changing ice fields, but turned out to be an excellent oceanographic mission (Labroue et al. 2012). We now have at our disposal a 25-year-long multi-mission altimetry data set of very high value for studying ocean circulation (because of geostrophy, SSH measurements can be translated in terms of ocean circulation), ocean dynamics and sea level variations.

3 The ESA Climate Change Initiative and the Sea Level ECV

As noted in the introduction, sea level has been identified as a key marine ECV within the CCI programme. Indeed, precise monitoring of changes in the mean level of the oceans is crucial for understanding not just the climate, but also the socio-economic consequences of any rise in sea level.

The sea level project conducted in the CCI programme (SL_cci) gathers a consortium of 15 European partners including experts on altimeter standards as well as a climate research group dedicated to the quality assessment of the products. The first phase of the project (2011–2013) was the opportunity to involve the climate research community and define the user requirements for climate applications. The estimation of the SSH requires not only the knowledge of the altimeter range, but also the instrumental corrections, the satellite orbit and different geophysical corrections to the altimeter range (tides, troposphere and ionosphere corrections, sea state bias, dynamic atmospheric correction; see Table 1) that have to be selected for each altimeter mission. Note that in the following, terms sea level, SSH and SL_cci ECV are used interchangeably.

From the perspective of the production of a sea level ECV, evolutions of these altimeter standards and algorithms were central to the project since they affect the physical content of the SL_cci ECV. The strategy was thus to focus on the improvement of the altimeter corrections which constitute the most important sources of errors at climate scales. Following this strategy, new altimeter algorithms have been developed and tested for all altimeter missions within the phase 1 of the project. Other algorithms from external projects have also been included in the process. A formal validation protocol has been developed (Round Robin approach) for the estimation and the validation of their performances. The evaluation of these standards has been performed, distinguishing different spatial (global and regional) and temporal (long-term, interannual and seasonal) scales. All validation reports are available at www.sea-level-cci.org. A panel of international experts contributed to the selection of the best algorithms for climate

Table 1 Altimeter standards selected for the sea level calculation for the SL_cci products (release 1.1): the choice of these corrections can change with time or from a project to another

Corrections	ERS-1	ERS-2	Envisat	Jason-1	Jason-2	T/P	GFO
Orbit	Reaper combined orbit (Rudenko et al. 2015)		CNES POE-D (Couhert et al. 2015)			GSFC POE (09/2008)	GSFC POE
Sea state bias	BM3 (Gaspar and Ogor 1994)	Nonparametric SSB (Mertz et al. 2005)	Nonparametric SSB V2.1 release	Nonparametric SSB (Tran et al. 2012)	Nonparametric SSB GDR-D release	Nonparametric SSB (Tran et al. 2010)	Nonparametric SSB (Tran et al. 2010)
Ionosphere	NIC09	BENT + GIM	From dual frequency altimeter range measurements (cycles 1–64) and GIM afterwards	From dual frequency altimeter range measurements	From dual frequency altimeter range measurements	From dual frequency altimeter range measurements (TOPEX) and DORIS (Poseidon)	GIM model
Wet troposphere	GPD corrections (Fernandes et al. 2015)						
Dry troposphere	ERA-interim based (Carrere et al. 2016)						
Dynamical atmospheric corrections	ERA-interim based (Carrere et al. 2016)						
Ocean tide	GOT 4.8 (Ray 2013)						
Mean sea surface	DTU 2010 (Andersen 2010)						
Pole tide	(Wahr 1985)						
Solid earth tide	Elastic response to tidal potential (Cartwright and Tayler 1971; Cartwright and Edden 1973)						
Loading tide	GOT4v8 (Ray 2013)						

applications. This has led to a level 2 altimeter database representing more than 50 years of cumulated data from 7 altimeter missions (TOPEX/Poseidon, Jason-1 and 2, ERS-1 and 2, Envisat, and GFO).

The SL_cci ECV consists of monthly maps of sea level anomalies (SLA), and the multi-mission mapping technique used to produce these maps (optimal interpolation) has been optimized for climate scales. The first version of the SL_cci ECV was disseminated in 2012, and the time series has benefited from regular temporal extensions so that the SL_cci v1.1 ECV covers the period 1993–2014 (DOI:10.5270/esa-sea_level_cci-1993_2014-v_1.1-201512). In addition to the monthly SLA maps, the ECV products also include ocean indicators computed over the total period. This includes the temporal evolution of the GMSL and its trend, regional mean sea level trends, and amplitude and phase of the annual signal. The products are available upon request at info-sealevel@esa-sealevel-cci.org, and the Product User Guide can be found on the project website: www.esa-sealevel-cci.org. A full description of the SL_cci v1.1 ECV is provided in Ablain et al. (2015).

The following section provides a detailed discussion of the sea level processing performed in the SL_cci project.

4 The Sea Level Record from High-Precision Satellite Altimetry Missions

This section reviews the altimeter standards and gridding processes used to build the sea level record. One important output of the CCI Programme is the error characteristics of the ECVs, which are described in this section.

4.1 Geophysical Corrections Applied to the SSH Measurements

In this section, we describe the geophysical corrections that are applied to the SSH measurements (hereinafter called ‘altimeter standards’). The processing to provide the mean sea level record depends on the altimeter standards selected to derive the sea level from 1-Hz altimeter measurements, and on the gridding process applied to average the along-track measurements and calculate the GMSL time series. Before describing further this processing, it is worth noting that there are some processing differences between the different groups producing GMSL records. The impact of these differences has been described and quantified in several studies (Masters et al. 2012; Henry et al. 2014). The GMSL trend can be modified by few sub-millimetres per year (0.1–0.2 mm/year) due to these differences.

As briefly described in the previous section, corrections need to be applied to the SSH measurement: propagation corrections as the altimeter radar wave is delayed during atmosphere travel (ionospheric correction, wet tropospheric correction, dry tropospheric correction), ocean surface correction for the sea state which directly affects the radar wave (electromagnetic bias), geophysical corrections for the tides (ocean, solid Earth and polar tides as well as loading effects), and atmospheric corrections for the ocean response to atmospheric dynamics (inverse barometer correction for low frequency, atmospheric dynamics correction for high frequency). Furthermore, SSH is calculated for each altimetric measurement considered as valid according to criteria (e.g., threshold, spline, statistics on the ground track) applied either to the main altimetric parameters, the geophysical corrections or the SSH directly. These criteria may vary from one mission to another depending on the altimeter instrumental characteristics. The precise references for the corrections and orbits used when calculating the mean sea level are given in Table 1 for the SL_cci project. Most of these corrections are not contained in the altimeter level-2 products (e.g., TOPEX M-GDR, Jason-1/Jason-2 GDR). They have been calculated and updated in a multi-mission altimetry database in order to calculate homogenous sea level for all altimetry missions.

4.2 Gridding Process

The recommended method by the SL_cci project in order to produce mean sea level grids has been developed for the SSALTO DUACS (Segment Sol Multimission Altimetrie et Orbitographie, Data Unification and Altimeter Combination System) System (Dibarboure et al. 2011). The main advantages of this method are, first of all, use of TOPEX/Poseidon, Jason-1, Jason-2 and Jason-3 as reference missions in order to obtain the most accurate long-term stability (Ablain, et al. 2009) and use of all other complementary missions (ERS-1, ERS-2, Envisat, Geosat Follow-On, CryoSat, SARAL/AltiKa and Sentinel-3A/B) to increase the spatial resolution of mean sea level grids.

The gridding process is composed of the following steps:

1. Calculation of the along-track sea level over all the altimeter period (1993–2014) for all the altimeter missions with homogenized corrections (as listed in Table 1), after removing spurious data (e.g., impacted by rain cells, sea ice).
2. Calculation of the mean sea level biases between the reference missions, both at global and regional scales. The verification phases between two consecutive missions (i.e. satellites on the same ground track apart from each other by few seconds; e.g., TOPEX/Jason-1, Jason-1/Jason-2, Jason-2/Jason-3) allow estimates of global biases with an accuracy close to 0.5–1 mm in terms of mean sea level (Zawadzki and Ablain 2016). It is worth noting that the absolute GMSL bias is arbitrarily set to 0 at 1993.
3. Reduction of the orbit errors between all the missions through a global minimization of the crossover differences observed within the reference mission and between reference and complementary missions (Dibarboure et al. 2011).
4. Computation of SSH grids (with a spatial resolution of 0.25° using a rectangular projection and a temporal resolution of 1 month) combining data from all missions using an objective analysis approach (Ducet et al. 2000; Le Traon et al. 2003).

The GMSL time series (Fig. 2) is easily deduced from the sea level grids by a area weighting averaging (taking into account the box area dependence with latitude) over the oceanic domain observed by the altimetry data (82°S to 82°N).

Other research teams (University of Colorado, AVISO, CSIRO, NOAA, NASA) only use the reference missions (TOPEX/Poseidon, Jason-1 and Jason-2) to provide GMSL time series. Their method is more simple since steps (3) and (4) described above are replaced by a simple averaging on a cycle basis of each mission (e.g., 1° along the latitudinal axis, 3° along the longitudinal axis for AVISO). Then all the time series are linked together during the verification phases (TOPEX/Jason-1 and Jason-1/Jason-2). The main advantage of this approach is the reduction of the computing time (fewer altimetry missions and no multi-mission adjustments). On the other hand, the GMSL is only estimated between 66°S and 66°N, and the regional sea level variations are not as well-represented as in the SL_cci. Furthermore, errors in altimetry measurements, such as long wavelength orbit errors or oceanic tide errors, are not removed and can impact the mean sea level estimate up to 1–2 mm at each cycle. However, the differences between these gridding process approaches, which each have their own limitations, only slightly impact

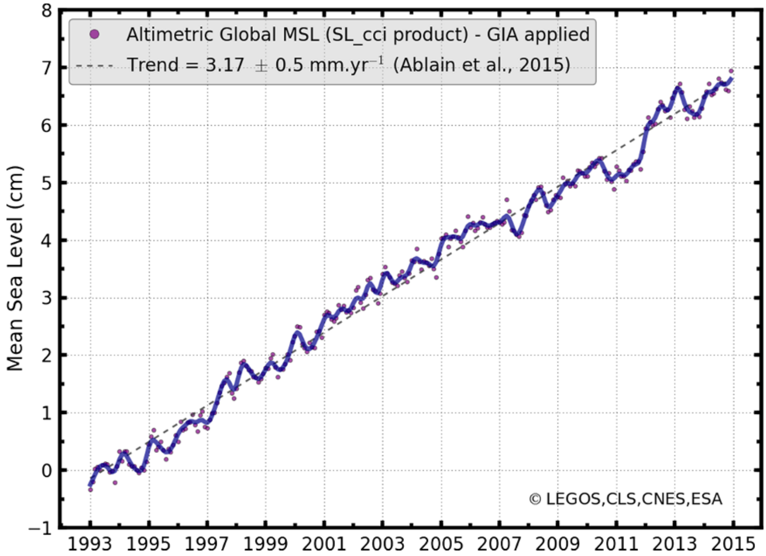

Fig. 2 Global mean sea level evolution over the period 1993–2014 from SL_cci project (DOI:10.5270/esa-sea_level_cci-1993_2014-v_1.1-201512). Annual and semi-annual signals have been removed from the monthly estimates (*red dots*), and a 6-month filter has been applied to produce the *blue curve*

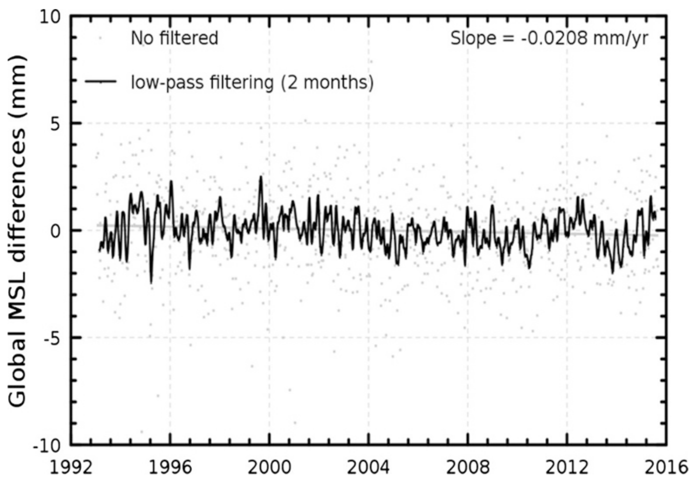

Fig. 3 Global mean sea level differences comparing the method applied to SL_cci products (based on SSALTO/DUACS system) and to AVISO global mean sea level time series. Same altimeter standards are used in both cases

the GMSL trend or the interannual signals (Fig. 3). The differences are lower than 0.05 mm/year over the whole altimetry period for the trend and reach 1–2 mm over shorter periods between 1 and 3 years (Henry et al. 2014).

4.3 Global Mean Sea Level Rise Characteristics

GMSL rises between 3.2 and 3.4 mm/year over the 1993–2014 period, according to the different groups (SL_cci project, AVISO, University of Colorado, NASA, NOAA, CSIRO). Although the global evolution is nearly linear over the period (the linear error adjustment provided by the least squares method is about 0.02 mm/year), interannual variations are also observed. Removing the trend from GMSL time series highlights these variations over a 1-year to 3-year period (Fig. 4). Their magnitudes depend on the period (+3 mm in 1998–1999, -5 mm in 2011–2012, and +10 mm in 2015–2016) and are well-correlated with El Niño Southern Oscillation (ENSO) events. In Fig. 4, the Multivariate ENSO Index (MEI) has been shown to better represent this temporal correlation.

4.4 Global Mean Sea Level Uncertainties

GMSL data contain remaining errors at different time scales. In the SL_cci project, an error budget dedicated to the main temporal scales (i.e. long term—5–10 years or more, interannual—<5 years—and seasonal) has been established (see Table 2). Regarding the GMSL trend, an uncertainty of 0.5 mm/year was estimated over the whole altimetry era (1993–2015) within a confidence interval of 95 % (2-sigma). The main source of error is the radiometer wet tropospheric correction with a drift uncertainty in the range of 0.2–0.3 mm/year (Legeais et al. 2014). To a lesser extent, the orbit error (Couhert et al. 2015) and the altimeter parameters (range, sigma-0, significant wave height) instabilities (Ablain et al. 2012) add additional uncertainty, of the order of 0.1 mm/year. It is worth noting that for these two corrections, the uncertainties are higher in the first altimetry decade (1993–2002) when TOPEX/Poseidon, ERS-1 and ERS-2 measurements display larger errors. Furthermore, imperfect links between TOPEX-A and TOPEX-B (February 1999), TOPEX-B and Jason-1 (April 2003), Jason-1 and Jason-2 (October 2008) lead to errors of 2, 1 and 0.5 mm, respectively (Ablain et al. 2009; Zawadzki and Ablain 2016). They cause a GMSL trend uncertainty of about 0.1 mm/year over the 1993–2014 period. It is relevant to

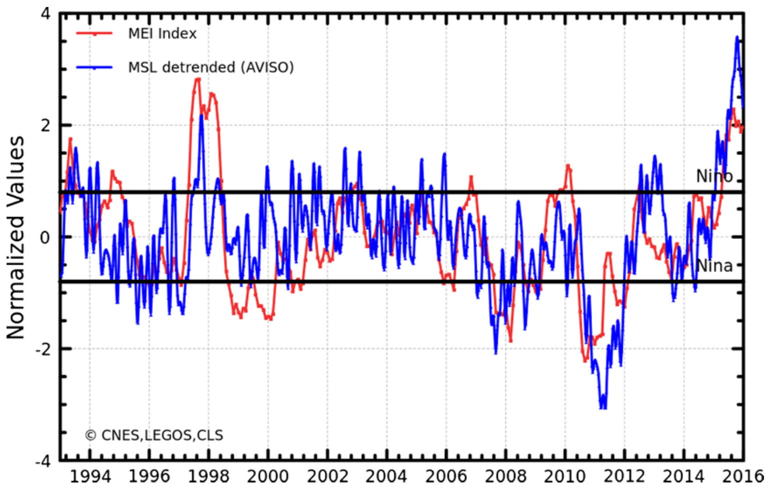

Fig. 4 Comparison of the Multivariate ENSO Index (MEI) and the global mean sea level time series (from AVISO) after removing the global mean trend

Table 2 Mean sea level error budget for the main climate scales (Ablain et al. 2015)

Spatial scales	Temporal scales	Altimetry errors	User requirements
GMSL	Long-term evolution (>10 years)	<0.5 mm/year	0.3 mm/year
	Interannual signals (<5 years)	<2 mm over 1 year	0.5 mm over 1 year
	Annual signals	<1 mm	Not defined
Regional MSL	Long-term evolution (>10 years)	<3 mm/year	1 mm/year
	Annual signals	<1 cm	Not defined

note that the remaining uncertainty of $\sim$0.5 mm/year on the GMSL trend remains 0.2 mm/year higher than the GCOS requirements (of 0.3 mm/year, see GCOS 2011).

All sources of errors described above and the gridding process, already described in Sect. 4.2, also have an impact at interannual time scale (<5 years). The level of error is still 1.5 mm higher than the GCOS requirement of 0.5 mm. This may have consequences on the sea level closure budget studies at interannual time scale. For the annual signal, the amplitude error is estimated lower than 1 mm. Knowing that the annual amplitude of the GMSL is in the order of 9 mm, this error can be considered low.

5 Regional Sea Level

5.1 Spatial Trend Patterns in Sea Level

The regional mean sea level trends (Fig. 5) are directly deduced from the gridded mean sea level time series. As mentioned above, the gridding process applied in the SL_cci project

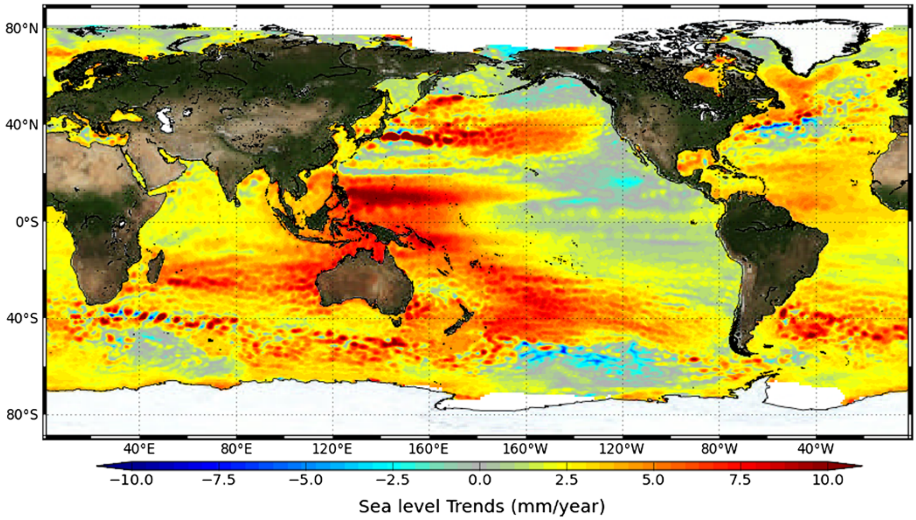

Fig. 5 Regional mean sea level trends over the 1993–2014 period from SL_cci products (release 1.1)

(derived from the SSALTO/DUACS system) provides a spatial resolution of 0.25° between 82°S to 82°N. The results discussed below only apply to the SL_cci products.

5.2 Uncertainties at Regional Scale

At regional scale, trend uncertainty is of the order of 2–3 mm/year (see below). Although the orbit error has been significantly reduced for this spatial scale during the last few years, it remains the main source of uncertainty (in the range of 1–2 mm/year; Couhert et al. 2015) with large spatial patterns at hemispheric scale. The Earth gravity field model errors explain an important part of these uncertainties (Rudenko et al. 2014). Furthermore, errors are higher in the first decade (1993–2002) for which the Earth gravity field models are less accurate due to the unavailability of the Gravity Recovery And Climate Experiment (GRACE) data. Additional errors are still observed, e.g., for the radiometer-based wet tropospheric correction in tropical areas, other atmospheric corrections in high latitudes, and high frequency corrections in coastal areas. The combined errors give rise to an uncertainty of 0.5–1.5 mm/year. Finally, the 2–3 mm/year uncertainty on regional sea level trends remains a significant error compared to the 1 mm/year GCOS requirement, even if this project has led to a 0.5 to 1.5 mm/year error reduction.

In a recent study (Prandi et al., in preparation), uncertainties on sea level trends have been produced. The method to estimate spatial trend uncertainties is based on generalized least-squares (also called inverse method). With this approach, we can separately estimate the errors and the long-term trends, taking into account the natural variability of ocean dynamics (mesoscale circulation, interannual variability). Results (Fig. 6) show that even with no error covariance, trends are not significant in areas of high oceanic variability (Fig. 6, left). When considering measurement errors with 95 % confidence intervals, trend errors generally range from 1 to 3 mm/year (Fig. 6 middle). Adding serial correlation due to natural ocean variability shifts the confidence interval to larger values, from 1 to 4–5 mm/year (Fig. 6, right). In all cases, a large fraction of sea level trends is significant (67 and 52 %, respectively) and cannot be explained by natural variability. It is worth noting that these results rely on numerous assumptions about error covariance shapes and amplitudes.

5.3 New Arctic Products

In this section, a specific focus is performed on the Arctic mean sea level evolution. This is an area of great interest for climate studies with rapid climatic changes, such as the dramatic reduction of sea ice extent. Models also predict that the Arctic Ocean will be

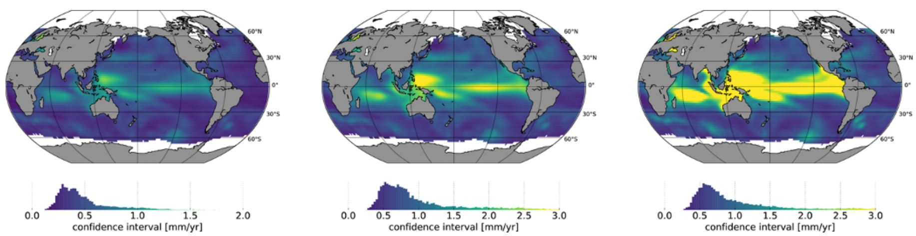

Fig. 6 Uncertainty maps of regional sea level trends. *Left* no error covariance (usual least-squares fit); *middle* measurement error covariance only; *right* measurement error and natural variability error covariance

experiencing large changes in the future (IPCC AR5). However, to date, the Arctic Ocean remains poorly observed by satellite altimetry, mainly due to sea ice cover that prevents accurate sea level measurements.

In recent years, several teams have been working towards a better knowledge of Arctic SSH (e.g., Prandi et al. 2012; Giles et al. 2012; Cheng et al. 2015). Recently, improvements on the processing of altimetry measurements in this area based on a new waveform classification and retracking algorithm (Poisson et al., in preparation) have allowed us to derive improved mean sea level maps with increased data coverage and higher mean sea level accuracy from the ice-covered Arctic (Fig. 7).

6 Validation and Error Assessment of CCI Products at Global and Regional Scales

In situ measurements are used to validate altimeter sea level records. Two types of in situ sensors are generally used: tide gauges and Argo floats. Both provide independent SSH measurements that are very valuable to detect anomalies in the altimeter records.

6.1 Validation with Tide Gauges

Tide gauges are instruments, generally set at the coast, which measure SSH relative to a local datum. There are two methods to compare tide gauges measurements with altimetry data: absolute calibration at dedicated sites, and regional or global comparisons. Absolute calibration requires a carefully monitored tide gauge, along with a precise positioning device (e.g., GPS), placed under or near altimeter ground tracks. There are three such sites in Harvest (Haines et al. 2010), Corsica (Bonnefond et al. 2015) and Bass Strait (Watson et al. 2011), which provide very valuable SSH differences time series from the beginning of the altimeter record. The other approach is to use a much wider network of tide gauges,

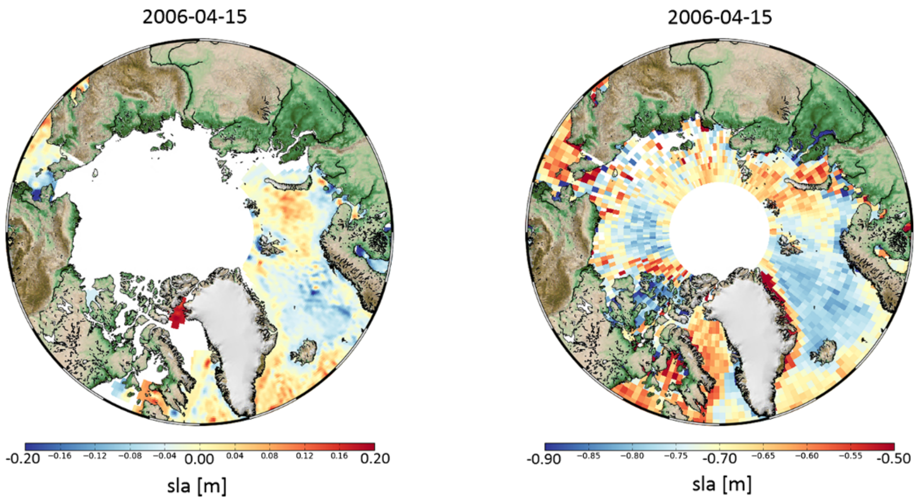

Fig. 7 Maps of sea level anomalies (SLA) in the Arctic Ocean on 15 April 2006. *Left* panel: map derived from global SL_cci products with no specific processing in the Arctic region. *Right* panel: map derived from Envisat data with improved data processing

which are individually less accurate but provide a larger ensemble, to build regional or global biases between an altimetry mission and tide gauges (Nerem et al. 2010; Mitchum et al. 1998, 2010). As the differences between absolute sea level measured by altimetry and relative sea level measured by tide gauges could also partly arise from vertical motion of the land on which the tide gauge is grounded, stations to be used need to be carefully selected and also corrected by vertical land motion if known (Fenoglio-Marc et al. 2004; Santamaría-Gómez et al. 2014).

Tide gauges unevenly sample the global coastlines, and comparisons do not cover the deep open ocean. All comparison methods rely on a similar processing, which is briefly described here. A complete description of the comparison method is available, for example, in Valladeau et al. (2012) and Wöppelmann and Marcos (2016). First, relative SSH measurements from tide gauges are corrected for various effects (tides, atmospheric pressure, vertical land motions) so that the physical content is comparable to absolute SSH measurements from altimetry. Then, altimetry measurements are collocated to tide gauges stations (using different approaches such as bilinear interpolation, area average, etc.), and a time series of altimetry minus tide gauge sea level is extracted at each in situ station. Eventually a global average is estimated from the ensemble of the different times series.

While all groups use similar methods, processing details may vary and result in slightly different estimates of altimeter minus tide gauges biases (Mitchum 1998; Watson et al. 2015). Methods also vary depending on the focus of the comparisons, for example whether it is aimed at obtaining calibrated altimetry records (Watson et al. 2015) or evaluating vertical crustal motions (Wöppelmann and Marcos 2016). But in any case, the advantage of the large number of stations is that a global bias time series can be computed and can then be used to characterize the level of agreement between altimetry and in situ records.

Figure 8 displays two examples of metrics derived from global differences between altimetry and tide gauges. The left panel shows the evolution of global differences between altimetry and tide gauges for the SL_cci and DUACS-DT products (Pujol et al. 2016). In both cases, no significant drift is detected, and differences are generally below 1 cm. The right panel focuses on the residual annual signal observed in the differences. The SL_cci product is found to be in better agreement with tide gauges than the DUACS-DT product regarding the annual signal amplitude.

One objective of such comparisons is to ensure that the altimeter record is not drifting over time. Meanwhile, it is essential to determine the accuracy of tide gauges comparisons. Mitchum (1998) and Watson et al. (2015) claim that the error of the method is about

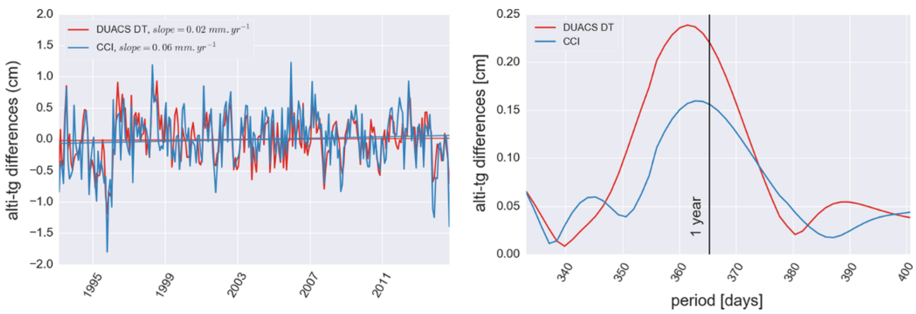

Fig. 8 *Left* time series of global differences between CCI (*red*) or DUACS-DT (*blue*) products and tide gauges. *Right* amplitude of the annual signal in differences between CCI (*red*) or DUACS-DT (*blue*) and tide gauges

0.4 mm/year while Valladeau et al. (2012) provide a 0.7 mm/year estimate and Santamaría-Gómez et al. (2012) found a value of 0.6 mm/year due to vertical land motions. This is actually one important source of error affecting relative SSH measurements by tide gauges. When no precise positioning at the stations exists, these corrections rely on Glacial Isostatic Adjustment (GIA) models (Peltier 2004) that do not account for contemporary vertical land motion sources (present-day ice melt, surface loading, ground water extraction, etc.). Wöppelmann and Marcos (2016) quantified vertical land movements not linked to the GIA process that may reach up to 10 mm/year, although on average they cancel out (0.01 ± 0.27 mm/year) if the number of tide gauge stations used is large enough.

6.2 Validation Using Argo Floats

Data from Argo floats (Roemmich et al. 2009) are another source of in situ information about the state of the ocean. They do not directly measure SSH but vertical profiles of temperature and salinity. These can be converted into density anomalies and integrated over depth to provide dynamic height anomalies (DHA), which can then be compared to altimetry-based SSH data (Valladeau et al. 2012; Legeais et al. 2016). DHA and altimeter SSH do not have consistent physical contents, as DHA are only the steric part of total sea level as measured by altimetry and, unlike tide gauges, cannot be used for absolute calibration of altimeter data but are rather used as a reference to compare two altimeter products or standards. If needed, the mass component can be derived from GRACE measurements. Argo floats are deployed at sea and, since 2005, provide a homogeneous sampling of the upper 2000 m of the global ocean, thus complementing tide gauges stations (Roemmich et al. 2009). Altimeter SSH measurements are interpolated at the time and position of Argo profiles to form an ensemble of SSH minus DHA differences from which various metrics are drawn.

Figure 9 contains a Taylor diagram that compares the CCI and DUACS-DT sea level products to a reference formed by the sum of Argo DHA and GRACE mass component. The diagram visualizes the closeness of altimetry to the reference in terms of correlation and RMS of the differences. Figure 9 shows the total signal separated into different frequencies. The results indicate that at low frequencies the SL_cci product is more consistent with Argo data than DUACS-DT (similar correlation but lower RMS). When all frequencies are considered, differences between the two products are low. A comprehensive review of uncertainty sources for Argo/altimetry comparisons can be found in Legeais et al. (2016).

6.3 Regional Validation

In addition to the global validation described above, a regional validation of the SL_cci products is performed based on the comparison with in situ data for selected regions: North Sea and Mediterranean Sea. These regions have been chosen for the availability of dense and accurate in situ measurements and ocean model data.

Regional closure of the sea level budget was investigated in the Mediterranean Sea. Figure 10 shows the smoothed monthly SL_cci series over January 2003–December 2014 and the sum of the steric and ocean mass components estimated from Argo temperature and salinity data of the EN4 database (Good et al. 2013) and GRACE data (Fenoglio-Marc et al. 2012). The sea level derived from the SL_cci products is in agreement with sea level derived from the sum of steric and mass

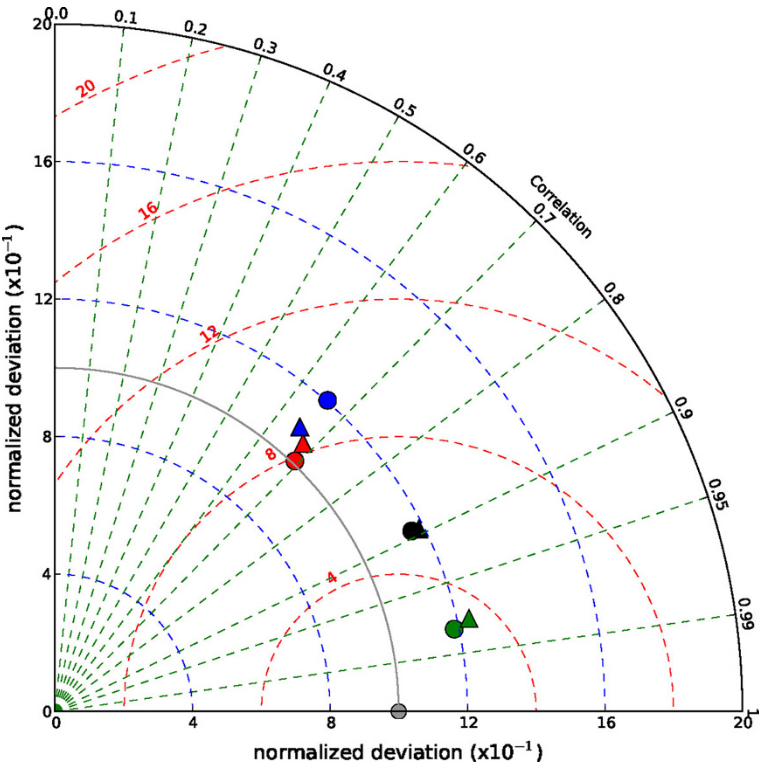

Fig. 9 Taylor diagram of the SL_cci (*triangles*) and SSALTO/DUACS-DT (*circles*) time series compared with the sum of Argo DHA (referenced to 900 dbar) and ocean mass from GRACE GRGS RL03v1 times series (*grey dot*) over 2005–2014. Total time series are in *black* and annual signals in *green*. High (in *red*) and low (in *blue*) frequencies are first adjusted from annual signal and detrended. Taylor diagrams are used to quantify the degree of correspondence between modeled and observed parameters according to 3 variables: correlation coefficient, root-mean-squares error and standard deviation

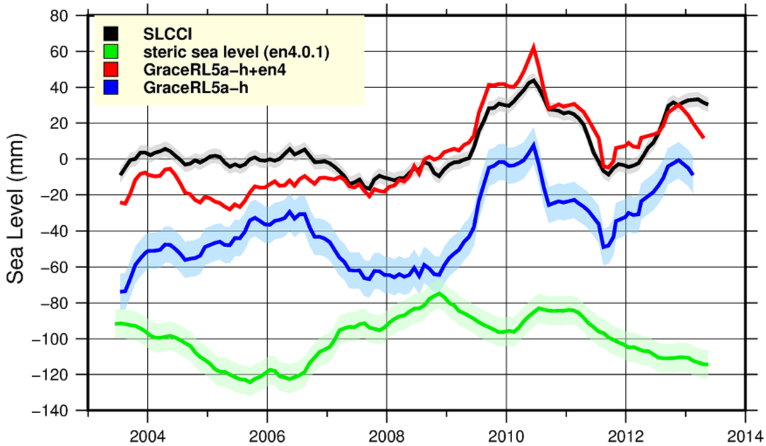

Fig. 10 SL_cci-based regional mean sea level (2004–2014) in the Mediterranean Sea (*black*) and sea level computed as sum of steric and mass components (*red*), with steric (*green*) and mass (*blue*) components

components, with a difference in trend and interannual signals of 0.8 m/year and 10.9 mm, respectively.

In the North Sea, SL_cci data are validated by comparing with tide gauges, quality-controlled with geodetic-referenced data in the German Bight and at a few other stations in the North Sea. In this case, the primary goal is to validate products and estimate errors for the along-track altimetric SSH, to verify their regional mission-long sea level trends and errors, and to compare signals and errors with the gridded sea level solutions. The same analysis has been performed for CryoSat-2 data processed with the SAMOSA model and retracker (Ray et al. 2014) in the ESRIN/GPOD SARvatore service. In the along-track comparison, the uncorrected sea level from tide gauges, expressed in ellipsoidal heights above the reference ellipsoid GRS80, are compared to the SL_cci products corrected as described in Fenoglio-Marc et al. (2015). Figure 11 shows a standard deviation of the differences. It amounts about 7 cm, which reduces to 4 cm when the tidal model TPX08 is used (http://volkov.oce.orst.edu/tides/global.html). The impact of the choice of the improved GNSS Path Delay (GPD+) wet tropospheric correction (Fernandes et al. 2015) in the coastal zone is not significant in this area. We have compared in the same region the monthly time series SL_cci gridded products and tide gauges. They agree well in terms of annual amplitude (differences <1.0 cm) and phase, with statistically significant correlations at all stations. Altimetry and tide gauge sea level trends are not statistically different at any station. The comparison of GPS-derived vertical land motion with the trend of the difference between altimetry and tide gauge shows differences in the order of 1 mm/year, which is within the trend uncertainty (Fig. 12). This uncertainty appears large for an accurate computation of vertical land motion rates from tide gauge and altimetry data. However, we notice a better agreement between altimeter and tide gauge (correlation, standard deviation and difference of trends) when SL_cci data are used, which indicates a higher quality of the SL_cci compared to other altimeter products.

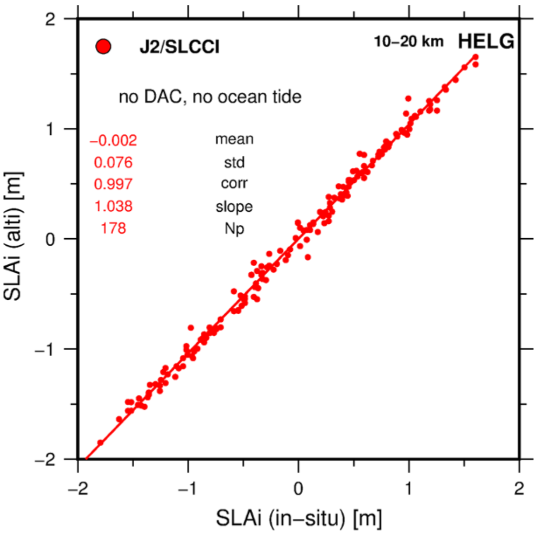

Fig. 11 Scatterplot of instantaneous SLA and statistic of differences for the complete Jason-2 SL_cci along-track data and from in situ data at the Helgoland tide gauge. Data are selected with spatial distance from the station between 10 and 20 km and temporal difference of 30 min. Np is the number of data points

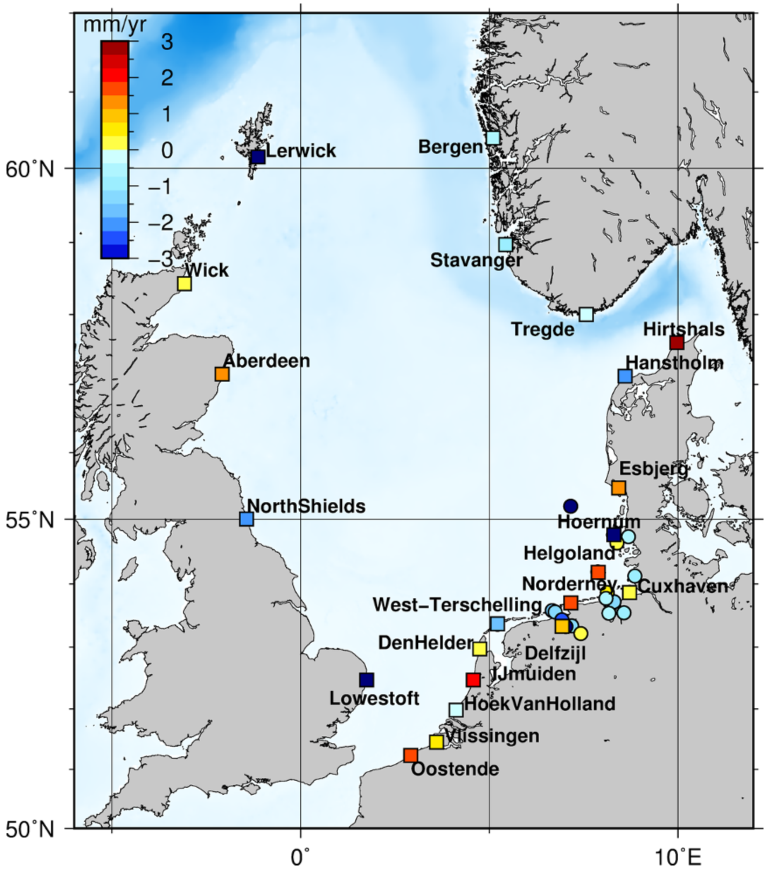

Fig. 12 Vertical land motion from GPS (*circle*) and from SL_cci altimetry minus tide gauges (*square*) in the North Sea, in mm/year

7 The CCI Sea Level Project: A Summary

Compared with previously existing products, the major evolutions of the SL_cci product are related to the following parameters. First, the orbit solutions of the different altimeter missions have been chosen so that the homogeneity of the regional sea level trends has been improved. Secondly, the GPD altimeter wet troposphere correction allows an improved estimation of the wet troposphere path delay in coastal areas. It also improves the sea level estimation in the open ocean, at high latitudes, correcting for invalid observations due to land, ice and rain contamination, and instrument malfunction. This correction exploits the data from various sources, including the Global Navigation Satellite Systems (GNSS). In addition, new dynamic atmospheric corrections computed with the ERA-Interim reanalysis lead to a strong sea level error reduction (Fig. 13) and strong improvement of the regional sea level trends over the early altimetry years.

The most impressive result of the SL_cci project is obtained using a new instrumental correction for the Envisat mission (Garcia and Roca 2010; Thibaut et al. 2012). It is illustrated in Fig. 14 by separating the ERS-1 and 2/Envisat and TOPEX/Jason-1 and 2

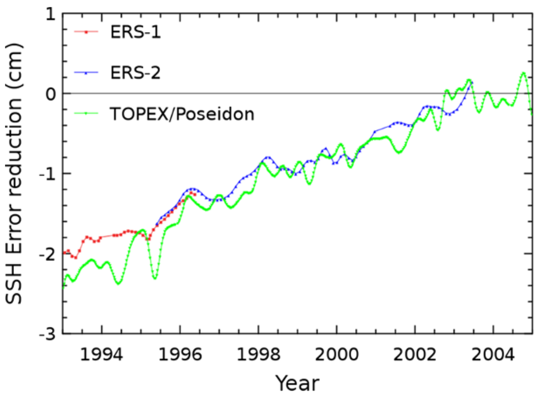

Fig. 13 Sea surface height error reduction for ERS-1 and 2 and TOPEX/Poseidon missions using a dynamic atmospheric correction forced by the ERA-Interim reanalysis compared with the operational ECMWF atmospheric fields

GMSL time series using alternately the old and new altimeter corrections: the trend difference between both time series has been significantly reduced thanks to the new instrumental correction (by 0.9 mm/year). The work performed contributed to better characterize and reduce altimetry errors at climate scales.

New level 2 altimeter algorithms have been developed, focusing on improving the ECV homogeneity and reducing the errors. Compared with the v1.1 SL_cci ECV, the major improvements that can be found in the reprocessed version are associated with the following aspects:

- New GFZ and CNES orbit solutions (Rudenko et al. 2015; Jalabert et al. 2015) have been selected for the SSH calculation of past and present altimeter missions. Compared with the previous POE-D version, the POE-E solution improves the sea level estimation and has a significant impact on the regional sea level trends (Fig. 15, left).
- The FES 2014 ocean tide model (Carrere et al. 2015) is used in the SLA calculation. Compared with other model (GOT 4.8), it leads to a reduced variance of the sea level in many coastal areas and at high latitudes (Fig. 15, right).
- An enhanced radiometer wet troposphere correction, called GPD+ (Fernandes et al. 2015), was selected for the SLA calculation of all altimeter missions. External independent measurements have been used to ensure the stability of this new correction. It significantly impacts the global decadal signals and also the sea level estimation in coastal areas.

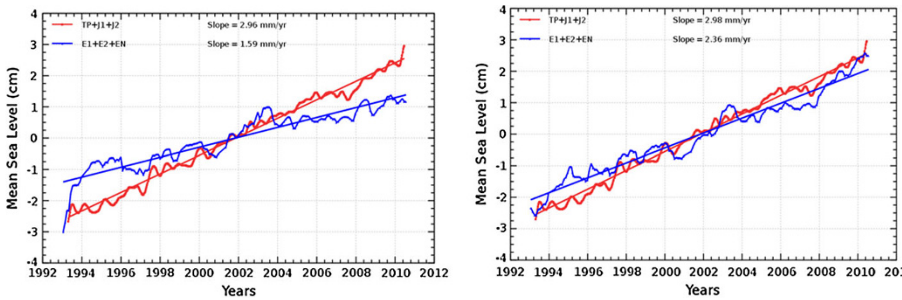

Fig. 14 GMSL evolution and associated trends computed with the TOPEX/Poseidon, Jason 1 and 2 (*red*), and ERS-1, ERS-2 and Envisat (*blue*) altimetry missions

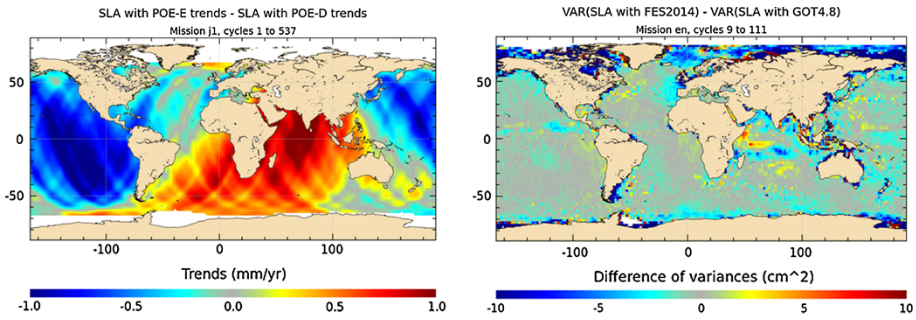

Fig. 15 *Left* map of the difference of Jason-1 (cycles 1–537) mean sea level trends computed successively with POE-D and POE-E orbit solutions. *Right* map of the difference of variance of the SSH computed successively with GOT 4.8 and FES 2014 ocean tide model for the Envisat mission (cycle 9–111)

The SL_cci products benefit from a quality control that includes internal validation, consistency check, and comparison with in situ data. In addition to this validation process, the scientific quality assessment of the ECV is an important ongoing task of the SL_cci project. Two types of assessments are investigated: (1) comparison of ocean model-based sea level with the CCI products and (2) study of the sea level budget. In (1), different methodologies are developed: (a) study of the sensitivity of an ocean reanalysis (the GECCO general ocean circulation model with data assimilation) to the new CCI sea level data via inclusion of these data in the assimilation procedure; (b) comparison with ocean-only simulation at different resolutions and with existing ocean reanalyses, which assimilate subsurface data; (c) assessment of sea level changes at high altitudes and in the Arctic Ocean by comparison of the SL_cci products with simulation runs of the Norwegian Earth System Model (NorESM).

The sea level budget approach consists in computing the sea level components using different observing systems, and comparing their sum to the SL_cci GMSL (Dieng et al. 2015a, b). Figure 16 shows the globally averaged SL_cci time series over January 2003–December 2014 with the sum of the steric and ocean mass components (estimated from Argo temperature and salinity data down to 2000 m depth and GRACE data). Over this time span, there is a very good agreement between the CCI sea level and sum of components, both in terms of trend and interannual variability. Therefore, the SL_cci data lead to quasi-closure of the sea level budget.

Within the second phase of the SL_cci project (2014–2016), updated altimeter standards and corrections are developed in the perspective of a full reprocessing of the sea level ECV (delivered end 2016). By the end of the project, this v2.0 time series will cover the period 1993–2015. Nine altimeter missions will be included, with SARAL/AltiKa and CryoSat-2 missions being new in the dataset.

8 Conclusions

Sea level, a climate variable that integrates changes of several components of the climate system, was identified by GCOS as an ECV and was further selected by ESA to be included in the first phase of the CCI programme. In this paper, we have reported how altimetry-based sea level products from different missions are built, what the current levels of uncertainties of the global and regional products are and how they have been validated.

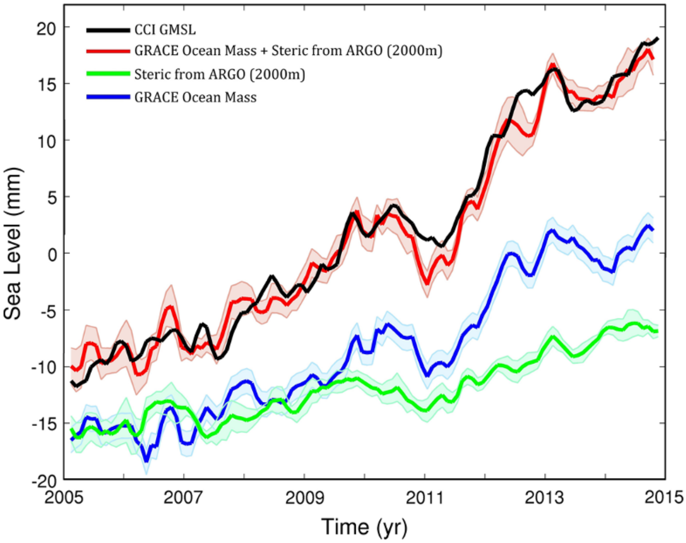

Fig. 16 SL_cci-based GMSL (*black*); Argo-based steric sea level (*green*) GRACE-based ocean mass (in equivalent of sea level, *blue*) over January 2005–December 2014 (update from Dieng et al. 2015b). The *red curve* is the sum of the steric and ocean mass components. An arbitrary vertical offset was applied to the *green* and *blue curves* for clarity

SL_cci products have been significantly improved, revisiting a myriad of instrumental and geophysical corrections. An important outcome of the CCI is that the SL_cci products are now well-characterized in terms of errors. Accounting for the ESA altimetry missions, which have a high-inclination orbit, a specific effort was dedicated to the Arctic region where the sea level evolution was poorly known until recently.

Despite the important effort invested so far, the sea level products provided within the CCI programme still do not fully satisfy the GCOS requirements, in particular at inter-annual time scales. Thus, further improvements of the altimetric standards are needed. The next inclusion of Jason-3 and Sentinel-3A (100 % SAR mode) data to the nearly 25-year-long time series will certainly lead in the near future to more accurate sea level time series, provided that long-term drifts of these new missions are carefully accounted for.

The implementation of the ESA CCI programme has led to the coordination of the Earth Observation and the Climate Research communities. This is a valuable outcome of the programme, and the CCI framework should be sustained in the future, conquering new space-based ECVs, improving existing ECVs, further assimilating ECVs in models and closing imbalances involving climate variables.

Finally, concerning the closure of the sea level budget, efforts are still needed to further improve the accuracy and to characterize the remaining uncertainties of components contributing to sea level, such as glaciers and ice sheet mass balances, ocean heat content and salinity changes, and land water storage changes.

Scientific analysis of the long-term sea level evolution and its societal impacts requires the implementation of an operational and sustainable production of the sea level Climate Data Record (CDR). Regular updates of the time series are also necessary so that the period covered by the dataset is always current. Such challenge has been addressed by the Copernicus Climate Change Service (C3S), which aims at combining observations of the climate system with the latest science to produce a consistent, comprehensive and credible description of the past and present-day climate in Europe and worldwide. It will become a major contribution from the European Union to the WMO Global Framework for Climate Services and its Climate Monitoring Architecture.

The C3S will ensure the production of the sea level CDR. The sea level record is highly dependent on the altimetry data used as input of the production system. First, the maintenance of the historical altimetry databases is required since the reprocessing of the measurements of past missions will lead to an improved quality of the whole CDR. Secondly, the integration of recent (CryoSat-2, Jason-3, Sentinel-3A) and future (Sentinel-3B, Sentinel-6, SWOT) altimetry missions are of crucial importance to guarantee the future of the sea level record.

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References

Ablain M, Cazenave A, Valladeau G, Guinehut S (2009) A new assessment of the error budget of global mean sea level rate estimated by satellite altimetry over 1993–2008. Ocean Sci 5:193–201

Ablain M, Philipps S, Urvoy M, Tran N, Picot N (2012) Detection of long-term instabilities on altimeter backscattering coefficient thanks to wind speed data comparisons from altimeters and models. Mar Geod 35(S1):42–60. doi:10.1080/01490419.2012.718675

Ablain M, Cazenave A, Larnicol G, Balmaseda M, Cipollini P, Faugère Y, Fernandes MJ, Henry O, Johannessen JA, Knudsen P, Andersen O, Legeais J, Meyssignac B, Picot N, Roca M, Rudenko S, Scharffenberg MG, Stammer D, Timms G, Benveniste J (2015) Improved sea level record over the satellite altimetry era (1993–2010) from the Climate Change Initiative project. Ocean Sci 11:67–82. doi:10.5194/os-11-67-2015

Agreen RW (1982) The 3.5-year GEOS-3 data set. NOAA Technical Memorandum NOS NGS 33, NOAA, Rockville, MD

Andersen OB (2010) The DTU10 Gravity field and mean sea surface (2010) Second international symposium of the gravity field of the earth (IGFS2), Fairbanks, Alaska, 20–22 September 2010. http://www.space.dtu.dk/english/~/media/Institutter/Space/English/scientific_data_and_models/global_marine_gravity_field/dtu10.ashx. Access 20 June 2014

Bonnefond P, Exertier P, Laurain O, Guillot A, Picot N, Cancet M, Lyard F (2015) SARAL/AltiKa absolute calibration from the multi-mission Corsica facilities. Mar Geod 38(S1):171–192

Carrere L, Lyard F, Cancet M, Guillot A, Picot N, Dupuy S (2015) FES 2014: a new global tidal model. Ocean Surface Topography Science Team, Reston, Virginia, USA, October 2015. http://meetings.aviso.altimetry.fr/fileadmin/user_upload/tx_ausyclsseminar/files/OSTST2015/TIDE-01-Carrere.pdf

Carrere L, Faugère Y, Ablain M (2016) Major improvement of altimetry sea level estimations using pressure derived corrections based on ERA-interim atmospheric reanalysis. Ocean Sci Discuss. doi:10.5194/os-2015-112

Cartwright DE, Tayler RJ (1971) New computations of the tide-generating potential. Geophys J Int 23(1):45–73

Cartwright DE, Edden AC (1973) Corrected tables of tidal harmonics. Geophys J Int 33(3):253–264

Cazenave A, Dieng H, Meyssignac B, von Schuckmann K, Decharme B, Berthier E (2014) The rate of sea level rise. Nat Clim Change 4:358–361. doi:10.1038/NCLIMATE2159

Chelton DB, Ries JC, Haines BJ, Fu LL, Callahan PS (2001) Satellite altimetry. In: Fu L-L, Cazenave A (eds) Satellite altimetry and earth sciences, a handbook of techniques and applications. Academic Press, London. Int Geophys Ser 69:1–131

Cheng Y, Andersen O, Knudsen P (2015) An improved 20-year Arctic Ocean altimetric sea level data record. Mar Geod 38(2):146–162

Church JA, White NJ, Konikow LF, Domingues CM, Cogley JG, Rignot E, Gregory JM, van den Broeke MR, Monaghan AJ, Velicogna I (2011) Revisiting the earth's sea-level and energy budgets from 1961 to 2008. Geophys Res Lett. doi:10.1029/2011gl048794

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn PD, Payne AJ, Pfeffer WT, Stammer D, Unnikrishnan AS (2013) Sea level change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Clark PU et al (2015) Recent progress in understanding and projecting regional and global mean sea level. Curr Clim Change. doi:10.1007/s40641-015-0024-4

Couhert A, Luca Cerri L, Legeais JF, Ablain M, Zelensky NP, Haines BJ, Lemoine FG, Bertiger WI, Desai SD, Michiel Otten M (2015) Towards the 1 mm/y stability of the radial orbit error at regional scales. Adv Space Res 55:2–23

Dibarboure G, Pujol M-I, Briol F, Le Traon PY, Larnicol G, Picot N, Mertz F, Ablain M (2011) Jason-2 in DUACS: updated system description, first tandem results and impact on processing and products. Mar Geod 34(3–4):214–241

Dieng H, Palanisamy H, Cazenave A, Meyssignac B, von Schuckmann K (2015a) The sea level budget since 2003: inference on the deep ocean heat content. Surv Geophys 36:1. doi:10.1007/s10712-015-9314-6

Dieng H, Cazenave A, von Shuckmann K, Ablain M, Meyssignac B (2015b) Sea level budget over 2005–2013: missing contributions and data errors. Ocean Sci 11:789–802. doi:10.5194/os-11-789-2015

Dieng H, Champollion N, Cazenave A, Wada Y, Schrama E, Meyssignac B (2015c) Total land water storage change over 2003–2013 estimated from a global mass budget approach. Environ Res Lett 10:124010. doi:10.1088/1748-9326/10/12/124010

Ducet N, Le Traon PY, Reverdin G (2000) Global high resolution mapping of ocean circulation from the combination of TOPEX/POSEIDON and ERS-1/2. J Geophys Res (Oceans) 105(C8):19477–19498

Fenoglio-Marc L, Groten E, Dietz C (2004) Vertical land motion in the Mediterranean Sea from altimetry and tide gauge stations. Mar Geod 27(3–4):683–701

Fenoglio-Marc L, Becker M, Rietbroeck R, Kusche J, Grayek S, Stanev E (2012) Water mass variation in Mediterranean and Black Sea. J Geodyn. doi:10.1016/j.jog.2012.04.001

Fenoglio-Marc L, Dinardo S, Scharroo R, Roland A, Dutour M, Lucas B, Becker M, Benveniste J, Weiss R (2015) The German Bight: a validation of CryoSat-2 altimeter data in SAR mode. Adv Space Res. doi:10.1016/j.asr.2015.02.014

Fernandes MJ, Lázaro C, Ablain M, Pires N (2015) Improved wet path delays for all ESA and reference altimetric missions. Remote Sens Environ 169(2015):50–74. doi:10.1016/j.rse.2015.07.023

Fu L-L, Cazenave A (2001) Satellite altimetry and earth sciences; a handbook of techniques and applications. Academic Press, San Diego. Int Geophys Ser 69

Garcia P, Roca M (2010) ISARD_ESA_L1B_ESL_CCN_PRO_064, issue 1.b, 1 November 2010, "On-board PTR processing analysis: MSL drift differences"

Gaspar P, Ogor F (1994) Estimation and analysis of the sea state bias of the ers-1 altimeter. Rapport technique, Report of task B1-B2 of IFREMER Contract n° 94/2.426016/C. 84

GCOS (2011) Systematic observation requirements for satellite-based data products for climate (2011 update)—supplemental details to the satellite-based component of the "Implementation plan for the global observing system for climate in support of the UNFCCC (2010 update)". GCOS-154 (WMO, December 2011)

Giles KA, Laxon SW, Ridout AL, Wingham DJ, Bacon S (2012) Western Arctic Ocean freshwater storage increased by wind-driven spin-up of the BeaufortÂ Gyre. Nat Geosci 5(3):194–197

Good SA, Martin MJ, Rayner NA (2013) EN4: quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. J Geophys Res Oceans 118:6704–6716. doi:10.1002/2013JC009067

Haines BJ, Desai SD, Born GH (2010) The harvest experiment: calibration of the climate data record from TOPEX/Poseidon, Jason-1 and the ocean surface topography mission. Mar Geod 33(S1):91–113

Hay CC et al (2015) Probabilistic reanalysis of twentieth-century sea level rise. Nature 517(7535):481

Henry O, Ablain M, Meyssignac B, Cazenave A, Masters D, Nerem S, Garric G (2014) Effect of the processing methodology on satellite altimetry-based global mean sea level rise over the Jason-1 operating period. J Geod 88:351–361. doi:10.1007/s00190-013-0687-3

Jalabert E, Couhert A, Moyard J, Mercier F, Houry S, Rios-Bergantinos S (2015) Jason-2, SARAL and CryoSat-2 status. Ocean surface topography science team meeting, Reston, Virginia, USA, October 2015. http://meetings.aviso.altimetry.fr/fileadmin/user_upload/tx_ausyclsseminar/files/OSTST2015/POD-01-Jalabert.pdf

Jevrejeva S, Moore JC, Grinsted A, Woodworth PL (2008) Recent global sea level acceleration started over 200 years ago? Geophys Res Lett 35:L08715. doi:10.1029/2008GL033611

Jevrejeva S et al (2014) Trends and acceleration in global and regional sea levels since 1807. Glob Planet Change 113:11–22

Kaula W (1970) The terrestrial environment: solid earth and ocean physics. Williamstown report, M.I.T., Cambridge, MA, NASA CR-1579, April 1970. http://ilrs.gsfc.nasa.gov/docs/williamstown_1968.pdf

Labroue S, Boy F, Picot N, Urvoy M, Ablain M (2012) First quality assessment of the CryoSat-2 altimetric system over ocean. Adv Space Res 50(8):1030–1045. doi:10.1016/j.asr.2011.11.018

Le Traon PY, Faugère Y, Hernandez F, Dorandeu J, Mertz F, Ablain M (2003) Can we merge GEOSAT follow-on with TOPEX/Poseidon and ERS-2 for an improved description of the ocean circulation? J Atmos Ocean Technol 20:889–895. doi:10.1175/1520-0426(2003)020<0889:CWMGFW>2.0.CO;2

Legeais J-F, Ablain M, Thao S (2014) Evaluation of wet troposphere path delays from atmospheric reanalyses and radiometers and their impact on the altimeter sea level. Ocean Sci 10:893–905. doi:10.5194/os-10-893-2014

Legeais J-F, Prandi P, Guinehut S (2016) Analyses of altimetry errors using Argo and GRACE data. Ocean Sci 12:647–662. doi:10.5194/os-12-647-2016

Lillibridge J, Smith WHF, David Sandwell D, Scharroo R, Frank G, Lemoine FG, Zelensky NP (2006) 20 years of improvements to GEOSAT altimetry. Symposium: 15 years of progress in radar altimetry, Venice, Italy, March 13–18, 2006. http://earth.esa.int/workshops/venice06/participants/509/paper_509_lillibridge.pdf

Masters D, Nerem RS, Choe C, Leuliette E, Beckley B, White N, Ablain M (2012) Comparison of global mean sea level time series from TOPEX/Poseidon, Jason-1, and Jason-2. Mar Geod 35(1):20–41

Mertz F, Mercier F, Labroue S, Tran N, Dorandeu J (2005) ERS-2 OPR data quality assessment; long-term monitoring—particular investigation. CLS.DOS.NT-06.001. http://www.aviso.altimetry.fr/fileadmin/documents/calval/validation_report/E2/annual_report_e2_2005.pdf. Access 11 May 2016

Mitchum GT (1998) Monitoring the stability of satellite altimeters with tide gauges. J Atmos Ocean Technol 15(3):721–730

Mitchum GT, Nerem RS, Merrifield MA, Gehrels WR (2010) Modern estimates of sea level changes. In: Church J, Woodworth P, Aarup T, Wilson WS (eds) Understanding sea level rise and variability. Wiley-Blackwell, New York, pp 122–142

Nerem RS, Chambers DP, Choe C, Mitchum GT (2010) Estimating mean sea level change from the TOPEX and Jason altimeter missions. Mar Geod 33(1):435–446

Peltier WR (2004) Global glacial isostasy and the surface of the ice-age earth: the ICE-5G (VM2) model and GRACE. Annu Rev Earth Planet Sci 32:111–149

Prandi P, Ablain M, Cazenave A, Picot N (2012) A new estimation of mean sea level in the arctic ocean from satellite altimetry. Mar Geod 35(1):61–81

Pujol M-I, Faugère Y, Taburet G, Dupuy S, Pelloquin C, Ablain M, Picot N (2016) DUACS DT2014: the new multimission altimeter dataset reprocessed over 20 years. Ocean Sci Discuss. doi:10.5194/os-2015-110 **(in review)**

Ray RD (2013) Precise comparisons of bottom-pressure and altimetric ocean tides. J Geophys Res Oceans 118:4570–4584. doi:10.1002/jgrc.20336

Ray C, Martin-Puig C, Clarizia MP, Ruffini G, Dinardo S, Gommenginger C, Benveniste J (2014) SAR altimeter backscattered waveform model. IEEE Trans Geosci Remote Sens 53(2):911–919. doi:10.1109/TGRS.2014.2330423

Roemmich D, Johnson GC, Riser S, Davis R, Gilson J, Owens WB, Garzoli SL, Schmid C, Ignaszewski M (2009) The Argo program: observing the global ocean with profiling floats. Oceanography 22:34–43

Rudenko S, Otten M, Visser P, Scharroo R, Schöne T, Esselborn S (2012) New improved orbit solutions for the ERS-1 and ERS-2 satellites. Adv Space Res 49(8):1229–1244

Rudenko S, Dettmering D, Esselborn S, Schöne T, Förste Ch, Lemoine J-M, Ablain M, Alexandre D, Neumayer K-H (2014) Influence of time variable geopotential models on precise orbits of altimetry satellites, global and regional mean sea level trends. Adv Space Res 54(1):92–118. doi:10.1016/j.asr.2014.03.010

Rudenko R, Neumayer K-H, Dettmering D, Esselborn S, Schöne T (2015) Improvements in precise orbit determination of altimetry satellites. Ocean Surface Topography Science Team meeting, Reston, Virginia, USA, October 2015. http://meetings.aviso.altimetry.fr/fileadmin/user_upload/tx_ausyclsseminar/files/OSTST2015/POD-04-Rudenko_OSTST2015_20151021new.pdf

Santamaría-Gómez A, Gravelle M, Collilieux X, Guichard M, Martín Míguez B, Tiphaneau P, Wöppelmann G (2012) Mitigating the effects of vertical land motion in tide gauge records using a state-of-the-art GPS velocity field. Glob Planet Change 98–99:6–17

Santamaría-Gómez A, Gravelle M, Wöppelmann G (2014) Long-term vertical land motion from double-differenced tide gauge and satellite altimetry data. J Geod 88:207–222. doi:10.1007/s00190-013-0677-5

Thibaut P, Poisson J-C, Roca M, Nilo Garcia P (2012) WP2100 altimeter instrumental processing: RRDP and validation reports, sea level climate change initiative project, phase I. Algorithm selection meeting, Toulouse, 2 May 2012. http://www.esa-sealevel-cci.org/webfm_send/77

Tran N, Labroue S, Philipps S, Bronner E, Picot N (2010) Overview and update of the sea state bias corrections for the Jason-2, Jason-1 and TOPEX missions. Mar Geod 33(S1):348–362. doi:10.1080/01490419.2010.487788

Tran N, Philipps S, Poisson J-C, Urien S, Bronner E, Picot N (2012) Oral: impact of GDR-D standards on SSB corrections. Aviso, OSTST. http://www.aviso.altimetry.fr/fileadmin/documents/OSTST/2012/oral/02_friday_28/01_instr_processing_I/01_IP1_Tran.pdf

Valladeau G, Legeais JF, Ablain M, Guinehut S, Picot N (2012) Comparing altimetry with tide gauges and argo profiling floats for data quality assessment and mean sea level studies. Mar Geod 35(1):42–60

Von Schukmann K, Palmer MD, Trenberth KE, Cazenave A, Chambers D, Champollion N (2016) An imperative to monitor Earth's energy imbalance. Nat Clim Change 6:138–144

Wahr JM (1985) Deformation induced by polar motion. J Geophys Res 90(B11):9363–9368. doi:10.1029/JB090iB11p09363

Watson C, White N, Church J, Burgette R, Tregoning P, Coleman R (2011) Absolute calibration in bass strait, Australia: TOPEX, Jason-1 and OSTM/Jason-2. Mar Geod 34(3–4):242–260

Watson CS, White NJ, Church JA, King MA, Burgette RJ, Legresy B (2015) Unabated global mean sea-level rise over the satellite altimeter era. Nat Clim Change. doi:10.1038/nclimate2635

Wöppelmann G, Marcos M (2016) Vertical land motion as a key to understanding sea level change and variability. Rev Geophys. doi:10.1002/2015RG000502

Woppelmann G, Letetrel C, Santamaria A, Bouin MN, Collilieux X, Altamimi Z, Williams SDP, Miguez BM (2009) Rates of sea-level change over the past century in a geocentric reference frame. Geophys Res Lett. doi:10.1029/2009gl038720

Zawadzki L, Ablain M (2016) Accuracy of the mean sea level continuous record with future altimetric missions: Jason-3 vs. Sentinel-3a. Ocean Sci 12:9–18. doi:10.5194/os-12-9-2016

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