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- Vertical land motion: a key element to understanding sea level change along the coasts
- Updated results on vertical land motion from the primary space geodetic methods
- Discussion on the predominance of subsidence or uplift along the world coasts

Supporting Information:
- Figures S1–S8

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Vertical land motion as a key to understanding sea level change and variability

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Abstract Vertical land motions are a key element in understanding how sea levels have changed over the past century and how future sea levels may impact coastal areas. Ideally, to be useful in long-term sea level studies, vertical land motion should be determined with standard errors that are 1 order of magnitude lower than the contemporary climate signals of 1 to 3 mm/yr observed on average in sea level records, either using tide gauges or satellites. This metrological requirement constitutes a challenge in geodesy. Here we review the most successful instrumental methods that have been used to determine vertical displacements at the Earth's surface, so that the objectives of understanding and anticipating sea levels can be addressed adequately in terms of accuracy. In this respect, the required level of uncertainty is examined in two case studies (global and local). A special focus is given to the use of the Global Positioning System (GPS) and to the combination of satellite radar altimetry with tide gauge data. We update previous data analyses and assess the quality of global satellite altimetry products available to the users for coastal applications. Despite recent advances, a near-plateau level of accuracy has been reached. The major limitation is the realization of the terrestrial reference frame, whose physical parameters, the origin and the scale factor, are beyond the scope of a unique technique such as the GPS. Additional practical but nonetheless important issues are associated with the installation of GPS antennas, such as ensuring that there is no unknown differential vertical motion with the tide gauge.

1. Introduction

1.1. The Importance of Vertical Land Motion

Vertical land motion has become a prominent issue in studies of sea level rise over the past multidecadal to century timescales [*Douglas*, 1991, 2001; *Woodworth*, 2006; *Blewitt et al.*, 2010; *Church et al.*, 2013; *Pugh and Woodworth*, 2014]. Over these timescales, a wide range of natural and anthropogenic processes can cause vertical land motion along the coasts [*Emery and Aubrey*, 1991; *Conrad*, 2013] with temporal signatures and amplitudes comparable to the sea level signals expected from land-ice melting or ocean thermal expansion. On the one hand, vertical land motion can hamper the detection of these sea level signals associated with climate change and their associated spatial variations or fingerprints [*Conrad and Hager*, 1997; *Mitrovica et al.*, 2001; *Douglas*, 2008]. On the other hand, vertical land motion can locally exacerbate (coastal subsidence) or mitigate (coastal uplift) the risk of flooding in the coming century and control rates of coastal inundation [*Day*, 2004; *Hanson et al.*, 2011]. Depending on local uplift or subsidence, the change in sea level relative to land observed using tide gauges varies considerably from place to place and can deviate from the rate of global mean sea level [*Church et al.*, 2013]. The primary source of instrumental data on sea levels over multidecadal to century timescales is tide gauges [*Intergovernmental Oceanographic Commission* (*IOC*), 1985; *Pugh and Woodworth*, 2014], which record the level of the sea surface at a particular location on the coast, where tide gauge benchmarks are attached (see Figure 1). Poor knowledge of vertical land motion can bias estimates of global mean sea level rise and sea level projections, which in turn hinders the assessment of the impacts on coastal population and assets [*Ballu et al.*, 2011; *Hanson et al.*, 2011; *Hallegatte et al.*, 2013; *Han et al.*, 2015; *Le Cozannet et al.*, 2015]. Therefore, increasing our knowledge of vertical land motion for both the detection and attribution of climate change signals in sea level records as well as the assessment of coastal impacts of future sea levels has become a pressing issue.

Despite the attention given in the past quarter century to the measurement of vertical displacements of the Earth's surface using the most advanced geodetic methods [*Carter et al.*, 1989; *Carter*, 1994; *Neilan et al.*, 1998; *Schöne et al.*, 2009; *Blewitt et al.*, 2010], it remains a challenging research area in geodesy. Sea level is estimated to have risen globally at an average rate of 1.7 ± 0.2 mm/yr over the past century [*Church et al.*, 2013]. To be

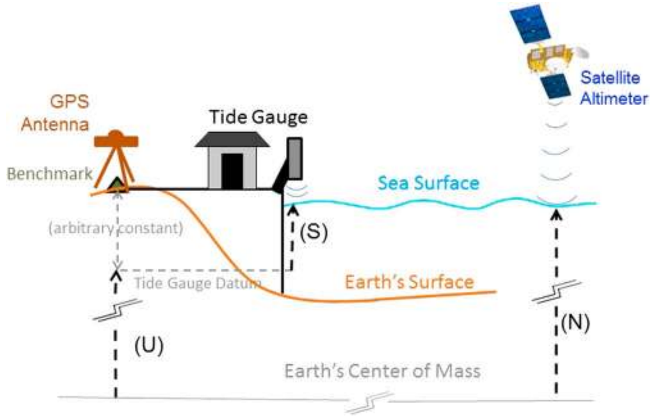

Figure 1. Sketch showing basic observational quantities and instruments discussed in this article.

useful for studies on long-term sea level trends and their coastal impacts, vertical land motion should be determined at a commensurate uncertainty level with respect to the Earth's center of mass. In other words, the resulting uncertainty should be a small fraction of the magnitude of the sought-after signals. For instance, considering an ideal set of 25 perfect globally representative tide gauges, and assuming random noise and independence, an uncertainty of 0.2 mm/yr for the rate of global sea level rise requires a determination of vertical land motion at each tide gauge with standard errors of ~1 mm/yr, or ~0.5 mm/yr if the desired confidence interval is 95%. In this ideal example, systematic errors are neglected, and the attributes of "precision" and "accuracy" for the estimate can be mixed. The number of 25 roughly corresponds to the number of stations used by *Douglas* [1991, 1997] or by *Spada and Galassi* [2012]. For coastal management, the level of uncertainty is associated with the upper bound dimension of coastal defenses. For sensitive coastal assets, an uncertainty of 5 cm in the location of this upper bound over a time span of 50 years translates into standard errors of ~1 mm/yr at a tide gauge near the coastal location of interest, or ~0.5 mm/yr if the desired confidence interval is 95%.

This uncertainty level raises an important metrological issue in relation to the use of space geodetic methods [*Blewitt et al*., 2010] and underscores the central problem of realizing an accurate and stable terrestrial reference frame [*Morel and Willis*, 2005; *Beckley et al*., 2007; *Collilieux and Wöppelmann*, 2011]. In this area, much research in the past quarter century has been focused on the long-term stability of the terrestrial reference frame [*Altamimi et al*., 2002, 2005, 2009, 2011; *Argus*, 2007; *Collilieux et al*., 2014]; alternative strategies to deal with the issue of vertical land motion at tide gauges have been devised too. Figure 1 illustrates the observational situation of the geodetic monitoring of tide gauges using GPS. While tide gauges can provide an estimate for the rate of relative sea level change (*S*) with respect to the nearby land represented by the grounded tide gauge benchmarks (or, to within a constant, the tide gauge datum), the rate of geocentric vertical land motion (*U*) of these benchmarks can be estimated using GPS. Hence, a basic expression for the absolute (geocentric) sea level change (*N*) is as follows:

$$U + S = N$$

The sketch in Figure 1 coarsely delineates a radar type of tide gauge. However, there are multiple types of tide gauge technologies. Some of them (mechanical) date back a couple of hundred years [e.g., *Wöppelmann et al*., 2006]. For the reader not familiar with tide gauges and interested in knowing more, there is an abundant literature available; in particular, we recommend the online manual on basic procedures for sea level measurement and interpretation by the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO) [*IOC*, 1985], or the recent textbook on sea level science by *Pugh and Woodworth* [2014]. Figure 1 also shows that satellite radar altimeters can provide an independent estimate for the absolute sea level change (*N*), and subsequently, the above expression can be used all the way around to estimate vertical land motion (*U*) from the combination of tide gauge and satellite radar altimetry data as follows:

$$U = N - S$$

It is worth noting that other methods can provide estimates for the above quantities (e.g., geophysical models). In addition, the reality is more complicated than Figure 1 conveys. An important complexity of the observational situation arises from the way the origin of the terrestrial reference frame is defined, and the stability of its practical realizations over time [*Altamimi et al*., 2005]. Ideally and conventionally

[*IERS*, 2010], the origin of the International Terrestrial Reference Frame (ITRF) is the center of mass of the entire Earth, including the oceans and atmosphere. Currently, the best reference frame for scientific applications that require a very high degree of accuracy is indeed the ITRF. However, the practical and numerical realizations of the ITRF can differ from one release to another [e.g., *Altamimi et al*., 2007, 2011]. In addition, a particular technique can provide an implementation of the ITRF that differs from another (e.g., GPS and satellite radar altimetry). What is more, within the same technique, one implementation of the ITRF can differ from another. In this respect, *Beckley et al*. [2007] and *Wöppelmann et al*. [2009] provide illustrations for sea level applications. Of particular importance here is the stability of the physical parameters of the terrestrial reference frame (i.e., the origin and the scale factor). It is a rather complicated metrological issue [*Blewitt*, 2003; *Altamimi et al*., 2005], which ultimately defines the concept of accuracy for positions and velocities, i.e., with respect to the ideal reference frame [*Kovalevsky et al*., 1989] that has no systematic errors in its physical parameters. Of particular concern in the sea level change applications illustrated above are the drifts in these parameters [*Morel and Willis*, 2005; *Collilieux and Wöppelmann*, 2011].

1.2. Previous Analyses

Until the mid-1980s, most data analysis strategies to estimate the long-term rise in global mean sea level considered time series longer than a decade or two from a large number of tide gauges [*Emery*, 1980; *Gornitz et al*., 1982; *Barnett*, 1984]. Accordingly, these studies assumed that the vertical land motion at many stations was negligible or would be compensated in the mean, in particular if the stations most clearly impacted were discarded. This assumption was subject to a scientific debate [*Pirazzoli*, 1986], which was exacerbated when it became clear that the number of useful tide gauge records for studies of long-term trends in sea level is considerably reduced with the increase in record length. With a couple of dozens records left, the assumption of compensation in the mean was further challenged. The increase in record length is required to mitigate the biases that may be introduced in the trends by decadal sea level oscillations [*Douglas*, 1991]. Despite promising results [*Sturges and Hong*, 2001], the ocean processes causing sea level variability at the interannual to decadal timescales are often not fully understood yet (e.g., El Niño–Southern Oscillation and Pacific Decadal Oscillation), making them difficult to predict and to correct at the required uncertainty level. By imposing a selection criteria on the records length, typically longer than 50 to 60 years (i.e., a duration longer than several decadal oscillations), *Douglas* [1991, 1997, 2001] showed that the overall impact on the trend estimates was negligible. In addition, some scientists have argued that generally speaking, the processes causing subsidence may be more frequent at the coast than those causing uplift [*Pirazzoli*, 1986; *Emery and Aubrey*, 1991]. Interestingly, a couple of early studies had already identified these important issues of record length and influence of vertical land motion in determining a long-term trend in sea level from tide gauge records [*Vignal*, 1935; *Gutenberg*, 1941].

A more rigorous strategy developed later when Earth models became available that enable the prediction and correction of vertical land motion at tide gauges. The use of this strategy has become widespread since the article of *Peltier and Tushingham* [1989]. Unfortunately, the only geophysical process for which models can predict vertical land motion at the global scale is the postglacial rebound of the solid Earth surface or Glacial Isostatic Adjustment (GIA; a glossary is provided at the end of the text, spelling-out the acronyms) due to the land ice retreat and redistribution of masses subsequent to the end of the last ice age [*Peltier*, 2004]. Furthermore, some details of GIA models are still poorly known such as the volume of land ice distribution and its retreat history and the rheology of the Earth's interior. At the level of accuracy considered in the previous section, these uncertainties can yield large differences in the magnitude and sometimes even in the sign of the GIA predictions in certain areas of the world [*Woodworth*, 2003; *Bouin and Wöppelmann*, 2010; *King et al*., 2012; *Spada and Galassi*, 2012]. In a recent study, *Jevrejeva et al*. [2014] pointed out differences over century timescales of up to 8 mm/yr for individual tide gauge records, up to 2 mm/yr for regional sea levels, and up to 0.3–0.6 mm/yr in global mean sea level reconstructions, depending on the choice of the GIA model. These figures should be considered as upper bounds, since outdated GIA models were considered in this study [e.g., *Peltier and Andrews*, 1976], and progress has been accomplished since the first GIA model [*Spada et al*., 2011]. Accordingly, due to their increased general performances, most studies carried out on the rate of global sea level change have progressively included corrections from GIA models, whether these studies were based on the simplest approach of averaging trends from long tide

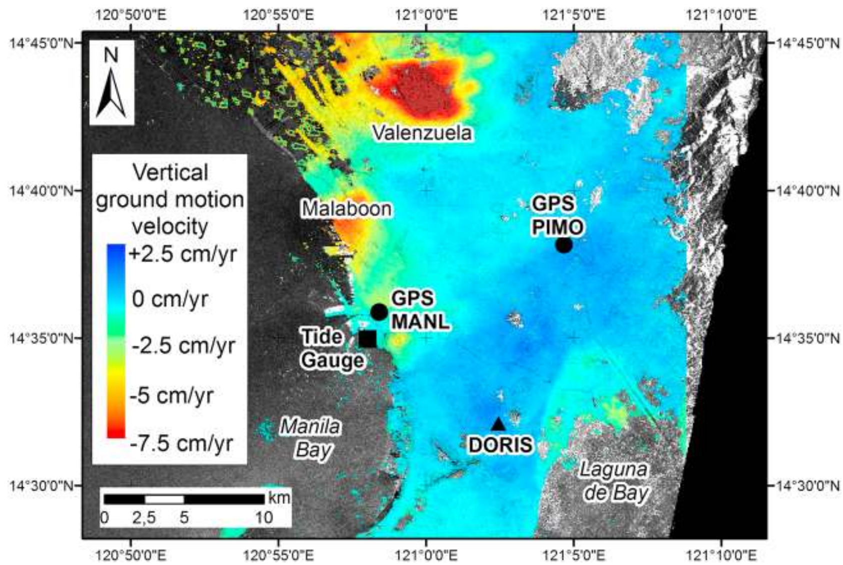

Figure 2. Vertical ground motion over the 2003–2010 period in Manila (Philippines) obtained from InSAR data, assuming horizontal ground motions are negligible (data from *Raucoules et al*. [2013]). Negative values indicate subsidence (in red). The reference (zero velocity) is located at the DORIS point on the map.

gauge records [*Douglas*, 1991] or based on the most sophisticated approaches of building regional and global mean sea level reconstructions [*Church et al*., 2004; *Jevrejeva et al*., 2006; *Church and White*, 2011; *Ray and Douglas*, 2011; *Hay et al*., 2015]. For a rather exhaustive review of these types of global studies, the reader is referred to *Spada and Galassi* [2012]. In addition, it should also be underlined that strictly speaking, GIA models provide relative sea level corrections, i.e., corrections of the geoid change due to the gravitational attraction of the water mass redistribution minus the GIA-related vertical motion of the Earth's surface. As illustrated in Figure 1, the geoid component is not measured by space geodetic methods such as the Global Positioning System (GPS), which estimates vertical crustal displacements in an absolute (geocentric) reference frame.

In addition to the GIA effect, other processes can cause vertical land motion at tide gauges. For example, ground deformations are also associated with other natural causes such as plate tectonics, volcanism or sediment compaction, or with anthropogenic causes such as groundwater extraction or settling of landfill in urban areas [e.g., *Bock et al*., 2012; *Raucoules et al*., 2013]. The resulting vertical land motions have relatively short spatial scales, and consequently, it is much more difficult to model them at the global scale for prediction and correction than the GIA effects. For example, Figure 2 shows differential motion of several millimeters per year over nearly a decade between points less than a kilometer away. Another example of a similar situation is found in Japan and is associated with tectonics [*Aoki and Scholtz*, 2009, Figure 5]. As a matter of fact, the vertical land motions associated with these ground deformations were not corrected for in general [*Church et al*., 2013], except by discarding from the study the tide gauge records that were clearly affected [e.g., *Douglas*, 1991; *Spada and Galassi*, 2012]. Consequently, the remaining non-GIA vertical land motions were assumed to compensate on average. Note that a very cautious approach should be adopted to discarding data; for instance, tide gauge records located in regions known to be affected by large non-GIA vertical land motion. This inevitably raises the issue of representativeness and of possible bias in the associated trend estimate of global mean sea level [*Hamlington and Thompson*, 2015; *Hay et al*., 2015]. At the level of accuracy required in studies of long-term sea level change (climate signals in sea levels of the order of 2 mm/yr), no region can be assumed stable at the surface of the Earth [*Emery and Aubrey*, 1991; *Conrad*, 2013].

1.3. Measuring Approach

Because of the small magnitude of the sea level signals we are aiming at, the idea of determining vertical land motion by means of space geodetic methods (rather than with geophysical models) has been elusive for nearly the past quarter century since its expression in *Carter et al*. [1989]. The first effective results at the global scale for sea level studies were published using the Global Positioning System (GPS) [*Wöppelmann et al*., 2007]. Since then, estimates from GPS have been progressively introduced in long-term sea level studies; for instance, in reconstructions of sea level curves [*Meyssignac et al*., 2011] or in assessing coastal impacts of future sea levels considering future land levels—in other words, considering the ("total" or relative) sea level rise experienced by coastal populations [*Becker et al*., 2012; *Palanisamy et al*., 2014]. However, the number of useful GPS stations colocated with tide gauges is limited [*King et al*., 2012; *Santamaría-Gómez et al*., 2012; *Watson et al*., 2015] despite the overall recommendations from international programs such as the Global Sea Level Observing System (GLOSS) [*IOC*, 2012] to install GPS stations at as many tide gauges as possible. For instance, only 120 GLOSS core network tide gauges (out of 289) are reported to have a permanent GPS antenna less than a kilometer away [*Gravelle et al*., 2015].

Consequently, other geodetic methods have been investigated to extend the data set of geodetically monitored tide gauges [*Blewitt et al*., 2010]. One noteworthy idea is to combine satellite radar altimetry and tide gauge data [*Cazenave et al*., 1999]. Figure 1 illustrates how satellite altimetry minus tide gauge data can yield an estimate for vertical land motion ($U = N - S$). However, the accuracy of this method is usually in excess of 1 mm/yr, whatever its implementation [*Nerem and Mitchum*, 2002; *Fenoglio-Marc et al*., 2004; *Garcia et al*., 2007; *Ray et al*., 2010; *Braitenberg et al*., 2011; *Wöppelmann and Marcos*, 2012]. In some cases, the uncertainty of the results is omitted [*Ostanciaux et al*., 2012], thus reducing the usefulness of the data set for application in sea level change studies. Interestingly, advanced data analysis strategies have been proposed to increase the precision of the vertical land motion estimates from satellite altimetry and tide gauge data combinations [*Kuo et al*., 2004, 2008; *Santamaría-Gómez et al*., 2014]. Unfortunately, the trade-off with respect to these analysis strategies is a considerable reduction in the set of stations for which results can be provided because longer record lengths are involved.

The determination of vertical land motion using geodetic methods thus remains a challenging issue. Here we review the past quarter century of geodetic progress in monitoring the geocentric stability of tide gauges during which we have (1) recognized and quantified the significant contribution of vertical land motion in tide gauge records and (2) narrowed the spatial variability in long-term sea level changes observed from tide gauge records once they are corrected for vertical land motion. The latter achievement should contribute to an early detection and attribution of fingerprints in sea level trends associated with land ice melting as the climate warms [*Mitrovica et al*., 2001; *Kopp et al*., 2010; *Spada et al*., 2013; *Stammer et al*., 2013]. In this review, we focus on the two most employed and promising methods in terms of precision, cost-effective implementation, and relative ease of data acquisition, namely, GPS and combining satellite altimetry and tide gauge data. For a more general review on the geodetic methods that are useful to understanding sea level rise and variability, the reader is referred to *Blewitt et al*. [2010]. In the following, we discuss the important milestones that were reached on the road to achieving the stringent uncertainty of less than 1 mm/yr. In particular, we carefully examine the uncertainties associated with the method of combining satellite altimetry and tide gauge data. We update the application of this method by increasing the data coverage with many more tide gauges from the Permanent Service for Mean Sea Level (PSMSL) [*Holgate et al*., 2013] and by considering various satellite altimetry products widely available from the major data suppliers (Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO), Climate Change Initiative (CCI), Commonwealth Scientific and Industrial Research Organization (CSIRO), Colorado University, Goddard Space Flight Center (GSFC)). The time span covered by the satellite altimetry data considered here extends at maximum from 1993 to 2014, although the final year depends on the particular data set. We investigate the linearity of the differenced (satellite minus tide gauge data) time series and evaluate their noise content using the Maximum Likelihood Estimator (MLE) method implemented by *Williams* [2008]. Finally, we use the new combined satellite altimetry and tide gauge data set to estimate vertical land motion at 478 coastal sites around the world and compare the results with the latest GPS solution dedicated to tide gauge monitoring [*Santamaría-Gómez et al*., 2012]. Using the best comprehensive data set from both methods, we discuss the current limitations of each and revisit the underlying assumption of past studies on global sea level rise, namely, that in the mean, vertical land motions are canceled out along the coastlines. We then revisit the issue of sea level change due to climate contributions and its spatial variability and discuss the key role of the terrestrial reference frame.

2. The Use of Global Positioning System

2.1. Milestones in Addressing the Demand for Accuracy

Among the space geodetic techniques, GPS has been the most used for monitoring tide gauge benchmarks due to the relatively low cost of the equipment and its availability, easy implementation, and maintenance, and above all due to its positioning performances, which have considerably improved over the past quarter century. It is anticipated that other Global Navigation Satellite Systems (GNSS) may contribute in the near future too [*Blewitt et al*., 2010].

First applied in a campaign ("episodic" or "epochal") observation mode of several days repeated every year or so [e.g., *Ashkenazi et al*., 1993; *Zerbini et al*., 1996], the installation of permanent GPS stations at tide gauges rapidly revealed an important element in identifying centimeter level offsets that can prevent the detection of millimeter per year-level signals due to vertical land motion [*Neilan et al*., 1998; *Sanli and Blewitt*, 2001]. Changes in the equipment, whether antenna or receiver (sometimes even software), or in the local environment near the antenna, have proven to introduce millimeter- to centimeter-level offsets in GPS position time series [*Bruyninx*, 2004] that can substantially bias the vertical velocity estimates at the level of uncertainty aimed at here (section 1). By contrast, a continuous observation strategy supplemented by reliable information on antenna mounting and equipment changes can be used to detect many of these offsets, identify their origin, and hopefully take them into account in the data analysis, so that the results can confidently be interpreted later on in terms of Earth surface displacements associated with geophysical processes. Note, however, that this observation strategy does not solve the problem of the offsets that can impact the velocity estimates. However, this impact can be mitigated if the offset is identified, and an additional parameter is added to the observation model of the adjustment procedure [*Williams*, 2003a; *Gazeaux et al*., 2013; *Griffiths and Ray*, 2015].

When determining velocities at the submillimeter per year level of accuracy, the data analysis strategy needs to be carefully devised. In particular, the observation model (the mathematical model describing how the observations are related to the unknown parameters of interest) should take into account any effect that can yield millimeter-level changes on the vertical component of the positioning. This component is especially sensitive to numerous error sources. For instance, an incorrect modeling of either the transmit or receive antenna instrumental phase center offsets and variations [*Ge et al*., 2005; *Schmid et al*., 2007], or the delay of the GPS signals propagating through the atmosphere, either the troposphere [*Boehm et al*., 2006] or the ionosphere [*Petrie et al*., 2010], or an incomplete satellite orbit model [*Rodriguez-Solano et al*., 2011], as well as local effects of multipath and electromagnetic coupling with the antenna [*Ray et al*., 2007; *King and Watson*, 2010], can propagate into the vertical component of the GPS positioning in a complex way that is difficult to assess [*Stewart et al*., 2005]. In addition, surface loading deformation induced by changes in atmospheric, oceanic, and continental water mass at subdaily to interannual timescales can also impact the GPS velocity estimates, if not properly taken into account [*Penna et al*., 2007; *Tregoning and Watson*, 2010; *Santamaría-Gómez and Mémin*, 2015]. In particular, the noise content of the position time series can also be affected by these errors and mismodeled effects [*Williams*, 2003b; *Santamaría-Gómez et al*., 2011].

A milestone in the use of GPS for monitoring vertical land motion at tide gauges was reached with the definition and application of a GPS data analysis strategy in a loosely constrained network of globally distributed stations [*Blewitt et al*., 1992; *Davies and Blewitt*, 2000]. In this strategy, loose a priori constraints (as opposed to tight constraints) are applied to the station coordinates and the satellite orbits so as not to bias the solution in the inversion procedure of the normal equations. For instance, a 1 m constraint was applied to the station coordinates processed by *Santamaría-Gómez et al*. [2012] in the final iteration, while an equivalent 1 m level constraint was applied to the orbital parameters of the GPS satellites. On the one hand, the global distribution of stations is an important element for the optimal (unbiased) computation of the satellite orbits. On the other hand, the global distribution has also been found to be important for adequately aligning the GPS solution to the geocentric terrestrial reference frame [*Altamimi et al*., 2005; *Collilieux et al*., 2011]. In this respect, systematic errors of several millimeters per year in the vertical component between global *versus* region-wide GPS networks of stations were revealed in a case study on the European GPS network [*Legrand et al*., 2010]; the magnitude of the systematic errors decreased with the increase in the spatial geographic extent of the station network. It should also be noted that a global distribution of stations of sufficient number is also needed to enable effective phase ambiguity resolution in these solutions [*Blewitt et al*., 1992].

In addition to the geographic extent of the station network, the use of a consistent GPS data analysis strategy right across the data time span has proven to be an essential issue too. Any change in the models, corrections, and parameterization used to analyze the GPS data has been shown to introduce systematic errors in the GPS products [*Steigenberg et al*., 2006], especially in the vertical component of the station position and velocity estimates [*Collilieux et al*., 2011]. A rigorous and complete reanalysis of all the past and present data sets is therefore mandatory as soon as an important change in the data analysis strategy is shown to be critical; for instance, the introduction of new antenna phase center corrections [*Schmid et al*., 2007] or an improved model for the propagation of GPS signals through the ionosphere [*Petrie et al*., 2010].

The corollary of the above mentioned milestones is the need to have access to a computing facility large enough to cope with the reanalysis of nearly 20 years of GPS data from several hundreds of permanent stations distributed globally whenever an important aspect of the analysis strategy needs to be changed. This partly explains why few groups have been able to implement a full state-of-the-art analysis strategy, and only a limited number of solutions have been made available to the sea level community. These issues can be appraised from the International GNSS Service (IGS) portal (www.igs.org), its associated TIGA (TIde GAge) working group [*Schöne et al*., 2009], and data assembly center (www.sonel.org) [*Gravelle et al*., 2015]. In any event, GPS velocities stemming from nonreanalyzed data analysis strategies (i.e., including heterogeneous models and/or corrections implemented as they become available without a reanalysis of the past data) and/or regional solutions [*Snay et al*., 2007; *Mazzotti et al*., 2008; *Teferle et al*., 2009] may sometimes be better than nothing, in particular, if data analysis methods were implemented to overcome some of the above mentioned limitations. For instance, absolute gravity data were used by *Teferle et al*. [2009] to fix the origin of a regional GPS solution. The associated results from the regional or the nonreanalyzed GPS solutions should, however, be considered with caution in the context of an application demanding high-accuracy levels.

Another corollary is to have access to a data center able to efficiently manage the whole data and metadata sets (equipment types, changes, etc.). To take up these technical and operational challenges, distributed observation and research infrastructures have been set up at the regional [e.g., *Bruyninx*, 2004] and international levels [*Dow et al*., 2009]. At the international level, since 1994 the GPS activities have been structured around what is today known as the International GNSS Service (IGS). It is within this international service that the TIGA (GPS Tide Gauge Benchmark Monitoring) [*Schöne et al*., 2009] pilot project was launched in 2001 with the overall objective of addressing the geodetic challenges raised by the sea level community. This latter community is itself well structured around the above mentioned GLOSS program of the Intergovernmental Oceanographic Commission (IOC) of UNESCO [*IOC*, 2012].

2.2. Application and Performance

Figure 3 is adapted from *Wöppelmann et al*. [2007] using the latest global GPS data reanalysis in *Santamaría-Gómez et al*. [2012]. Figures 3a, 3d, and 3g show annual mean sea levels from high-quality long tide gauge records grouped into three different regions, and Figures 3c, 3f, and 3i show those records corrected with the GPS velocities. As a guideline for comparison, Figures 3b, 3e, and 3h display the records corrected with the GIA radial crustal displacement predicted by the ICE-5G VM2 model [*Peltier*, 2004]. Thus, the geoid component associated with the GIA process is not used to produce the time series in Figures 3b, 3e, and 3h so that they can be compared to the GPS-corrected time series in Figures 3c, 3f, and 3i, which are geocentric (Figure 1). The other way around would be adding the GIA geoid component to the GPS-corrected time series in Figures 3c, 3f, and 3i, but the results in terms of comparing the spread of the individual trends would remain unchanged. Within each region, the spread (standard deviation or RMS) observed in the rates of individual station records (Figures 3a, 3d, and 3g) are substantially reduced once corrected with the GPS velocities (Figures 3c, 3f, and 3i).

The Fennoscandia area in Northern Europe is a region dominated in the first instance by GIA. Accordingly, GIA corrections are effective in reducing the spread of sea level rates observed in tide gauge records (Figure 3b). By contrast, GIA corrections are less effective in northwestern America (Figure 3e) where the effects of the complex tectonic setting are superimposed on the GIA effects [*Mazzotti et al*., 2008]. In this region as well as in the Gulf of Mexico (Figures 3g–3i), which is far from the formerly ice-covered areas of the last ice age, processes other than GIA may dominate and little reduction can thus be noticed in the spread of sea level rates from tide gauge records when applying GIA corrections. On the other hand, GPS velocities have been

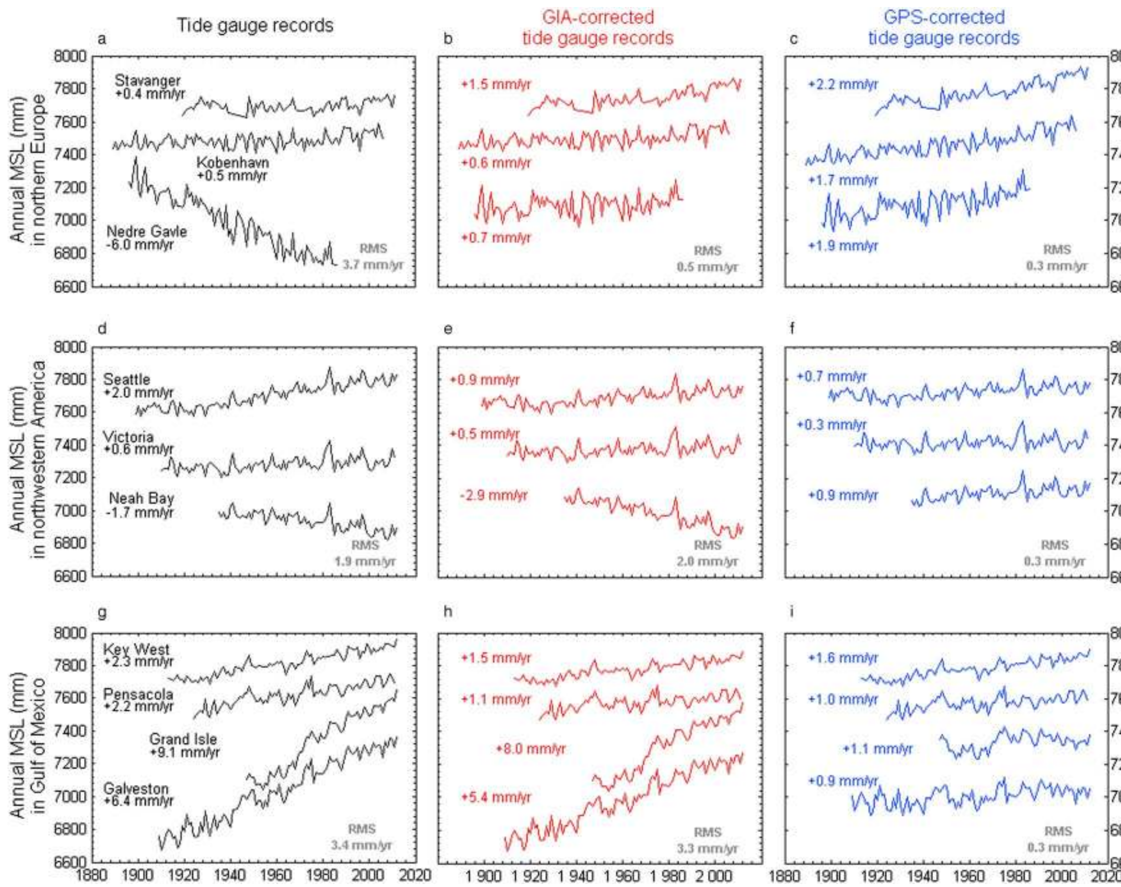

Figure 3. Time series of annual mean sea levels (MSL) from (a, d, and g) tide gauges, (b, e, and h) corrected for the radial crustal displacement due to GIA with ICE-5G (VM2) model [*Peltier*, 2004], and (c, f, and i) corrected with GPS velocities from *Santamaría-Gómez et al*. [2012], northern Europe (Figures 3a–3c), northwestern America (Figures 3d–3f), and Gulf of Mexico (Figures 3g–3i). The time series are displayed with arbitrary offsets for presentation purposes. The units are in millimeters.

successful in capturing and reducing the spatial variability in the rates of sea level change observed by these tide gauges. The success of this measuring approach (geocentric; Figure 1) was achieved in all of these three regions and whatever the cause of vertical land motion, in particular in the northern Gulf of Mexico, where the coastlines are known to be affected by various large subsidence processes [*Kolker et al*., 2011], such as sediment compaction or underground fluid extraction (e.g., Grand Isle in Louisiana or Galveston in Texas). Certainly, a GIA model cannot be expected to correct for tectonic effects or vertical land motion other than the GIA (e.g., due to sediment compaction or contemporary land ice melting effects).

As illustrated in Figure 3, not all regions may display the same results. This is the case in particular for regions where vertical land motion cannot be adequately modeled by a linear trend computed over a decade-long GPS record (this issue is discussed in the next section). But overall the conclusion has been a much greater spatial coherence within regions when the GPS corrections were applied. For instance, a reduction of spread by as much as 34% was observed on average by *Wöppelmann et al*. [2014] (a maximum reduction of 93%; the minimum was no reduction at all), whatever the region considered in that study (13 regions and 76 stations) and the underlying vertical land motion process. The spatial coherency similarly improved at the interregional scale between the regional rates of sea level change; the spread was reduced from 1.4 mm/yr (no correction) to 0.5 mm/yr (GPS-corrected) [*Wöppelmann et al*., 2014] (Table 1). The different levels of spread (intraregional and interregional) are indicative of the presence of nonclimatic signals which tend to dominate the spatial variability in the rates of relative sea level change from tide gauge records. It is worth noting, however, that there will be a limit in the reduction of spread due to vertical land motion corrections as rates of sea level change are indeed expected to vary spatially as a result of the redistribution of water from continents or ocean heat content [*Conrad and Hager*, 1997; *Mitrovica et al*., 2001; *Milne et al*., 2009; *Tamisiea*, 2011].

Table 1. Spread (as Measured by Standard Deviations in mm/yr) of Individual and Regional Rates of Sea Level Change From Tide Gauges Corrected for Vertical Land Motion Using Different GPS Solutions [*Wöppelmann et al.*, 2007, 2009; *Santamaría-Gómez et al.*, 2011, 2012], Produced Successively as Advances in GPS Data Analysis (Models, Corrections) Were Accomplished and Incorporated[a]

		GPS Corrected				
Land Motion Correction	No Correction	ULR1 ITRF2000 1999.0–2005.7	ULR2 ITRF2000 1997.0–2006.9	ULR3 ITRF2005 1997.0–2006.9	ULR4 ITRF2005 1996.0–2009.0	ULR5 ITRF2008 1995.0–2011.0
GPS solution reference		*Wöppelmann et al.* [2007]	*Wöppelmann et al.* [2009]	*Wöppelmann et al.* [2009]	*Santamaría-Gómez et al.* [2011]	*Santamaría-Gómez et al.* [2012]
Spread of individual trends in mm/yr	2.1	1.2	1.1	1.0	0.6	0.8
Spread of regional trends in mm/yr	1.4	0.9	0.8	0.6	0.6	0.6

[a]The solution code (ULR), the terrestrial reference frame, and the period of observation are given in the first row (details can be found in the references).

2.3. State of the Art and Limitations

Despite the recent advances in GPS observation and data analysis strategies, a near-plateau level of performance has been reached. Table 1 shows this in terms of the reduction in the spread of individual and regional rates of sea level change (as measured by standard deviations) obtained from GPS-corrected tide gauge records using different GPS solutions [*Wöppelmann et al.*, 2007, 2009; *Santamaría-Gómez et al.*, 2011, 2012] produced successively as advances in GPS data analysis (models and corrections) were accomplished and incorporated. Of course, the comparison is not fully rigorous as each data set incorporates new observations (increased time span) and new terrestrial reference frame realizations were available [*Altamimi et al.*, 2002, 2007, 2011]. By contrast, the number of individual records and their grouping into regions following the approach of *Douglas* [2001] remains constant across the columns in Table 1 (27 and 10, respectively). Using another grouping approach [*Jevrejeva et al.*, 2006] and an increased number of records (76 records grouped into 13 groups), *Wöppelmann et al.* [2014] found similar spreads of 0.6 mm/yr and 0.5 mm/yr, respectively, for individual and interregional sea level trends.

The precision considered for rate uncertainties should be understood as taking into account the spatial and temporal correlations in the errors of the residual GPS position time series [*Santamaría-Gómez et al.*, 2011]. Indeed, neglecting the temporal correlation can yield a noticeable underestimate of the actual rate uncertainty [*Williams*, 2003b] of between 2 and more than 3 times what would be estimated by assuming white noise. Consistently, the rate estimates remain within the largest statistical uncertainty. Fortunately, it has become relatively straightforward to account for the temporal correlation in GPS position time series with the help of powerful tools that have become available [e.g., *Williams*, 2008]. Using the Maximum Likelihood Estimator (MLE) method [*Williams*, 2008], *Santamaría-Gómez et al.* [2011] confirmed that the power spectral density of residual position time series is better described by a power law stochastic model of flicker noise type. In addition, the level of noise decreased in GPS solutions stemming from data reanalyzes compared to cumulative solutions [e.g., *Williams et al.*, 2004]. Interestingly, the minimal time span needed for the statistical error in GPS velocity to drop below 0.5 mm/yr was, on average, of about 12 years [*Wöppelmann et al.*, 2009], whereas not taking into account the noise content (type and magnitude) yielded less than 2 years. For the most recent GPS data reanalysis by *Santamaría-Gómez et al.* [2012], it ranged between 8 years and more than a decade. Of course, these minimal lengths are gross estimates since they will vary from station to station and at a specific station over time, according to the specific noise content and its evolution [*Santamaría-Gómez et al.*, 2011].

Data sets of continuous GPS observations are still relatively short compared to tide gauge records (Figure 4). This introduces an additional source of uncertainty as to how representative the GPS estimates of recent vertical land motion are of long-term land motion at tide gauges. The subsequent necessary working hypothesis in using GPS to correct long tide gauge records is that vertical land motion was at a steady rate over the decades to century timescales in which the tide gauge was operational and that it is continuing at the same steady rate over the GPS period. In other words, the nonlinear deformation component is of second-order importance. This is a hypothesis that studies using GIA corrections are implicitly assuming too, when neglecting other (non-GIA) land motion processes. This issue becomes a concern especially for areas affected by tectonics or local ground deformation such as settling of landfill or underground fluid extraction. In such cases, the associated vertical land motion signal can display rather complicated temporal (and spatial)

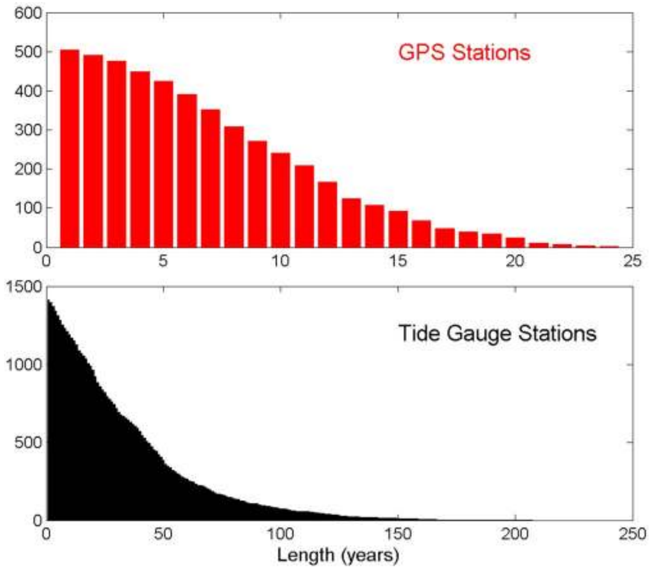

Figure 4. Number of stations with a minimum record length (in years): (top) from SONEL (www.sonel.org) data holdings for GPS and (bottom) from PSMSL (www.psmsl.org) datum controlled data set (revised local reference or RLR).

patterns which are certainly not adequately modeled by a linear trend computed over a decade-long record [e.g., *Raucoules et al*., 2013] or simply by assuming it to be zero. The above comments on this working hypothesis underline the important role played by the tide gauge records selection process when estimating the trend in global mean sea level over the past century, and it further underscores the need for geodetic monitoring of vertical land motion at tide gauges to determine future sea levels.

Another important working hypothesis is introduced by the local character of many ground deformation processes. That is, the land motion detected by the GPS antenna corresponds to the vertical land motion actually affecting a distant tide gauge. Few GPS stations have indeed been installed at the tide gauge itself. For instance, less than 14% of the GLOSS core network stations are reported to have a GPS station installed directly on top of the tide gauge structure in a way that ensures its motion will match the motion of the tide gauge itself [*Santamaría-Gómez et al*., 2015]. What is more, only 22% of the GPS stations near to a GLOSS core tide gauge gather leveling information that can be made available. Hence, a working hypothesis of relative ground stability between the tide gauge reference (benchmarks) and the GPS antenna phase center is required, even though this could easily be avoided if appropriate measures were taken. In other words, if the GPS antenna is not located “near” the tide gauge such that there is no unknown differential in vertical land motion, then this differential motion must be monitored either by periodical leveling or by other geodetic means [e.g., *Teferle et al*., 2002]. The level connection (or height difference) between a GPS antenna reference point and the tide gauge reference is usually designated as the geodetic tie. However, even a single geodetic tie can be challenging to obtain despite its usefulness for other applications such as the unification of height systems [*Woodworth et al*., 2012, 2015]. The general lack of leveling information or geodetic ties coincides with the relatively poor number of dedicated GPS at tide gauge installations. As a matter of fact, most so-called “colocated” stations are often serendipitous cases; i.e., the GPS antenna appears to be located near to a tide gauge by chance. This is because in most cases GPS installations were not foreseen originally to monitor the tide gauge, neither as a primary application nor as supplementary, even later on when its coincident location became obvious. Consequently, the basic requirement (the geodetic tie) for sea level applications is often missing.

In this context, considering that GPS has reached the maturity to monitor vertical land motions at the required level of uncertainty for climate-related sea level studies, the latest GLOSS implementation plan calls for an important upgrade of its core network of tide gauges with continuous GNSS stations, and that their observations and metadata be provided to its dedicated data assembly center (Systeme d’Observation du Niveau des Eaux Littorales (SONEL), http://www.sonel.org) so that the observations and generated products be public and free to anyone, in line with the IOC/UNESCO oceanographic data exchange policy [*IOC*, 2012] and particularly to those groups with the knowledge and experience to analyze the data using state-of-the-art data analysis strategies. Most of these groups are committed to the IGS working group named TIGA [*Schöne et al*., 2009]. The technical issue of GPS installation at tide gauges has been discussed previously [*Bevis et al*., 2002; *Teferle et al*., 2002]. There is no configuration standard. Ultimately, it appears to be considerably dependent on the local geological and environmental settings. It should thus be handled on a case-by-case basis, often considering trade-offs between the sea level application and the technical constraints (sky clearance, multipath and electromagnetic environment, equipment security, etc.).

Table 2. Characteristics of the Satellite Altimetry Data Sets Used in This Study and Number of Associated Tide Gauges (TG)

Product	Type	Resolution	Sampling	Period	IB Correction	# of TGs
AVISO	Gridded—all satellites	1/4°	Daily	1993 to April 2014	DAC	478
CCI	Gridded—all satellites	1/4°	Monthly	1993–2013	ERA Interim-based product	478
CSIRO	Gridded—all satellites	1°	Monthly	1993 to April 2015	ERA	342
CU	Gridded—TP, J1, and J2	1°	~10 days	1993–2015	DAC	365
GSFC	Along track—TP, J1, and J2	-	~10 days	1992–2012	DAC	446

A final remark: the rate uncertainties in GPS vertical velocities discussed in this section are purely statistical errors, i.e., with no account taken of systematic errors induced by nonlinear surface loading deformation [*Santamaría-Gómez and Mémin*, 2015] or due to the stability of the physical parameters (origin and scale) of the terrestrial reference frame realization in which the GPS velocities are expressed. The limitation in the reference frame realization will be discussed in section 4. It depends on external information from techniques other than GPS.

3. The Use of Satellite Altimetry

3.1. Combining Satellite Altimetry and Tide Gauge Data

3.1.1. Data Sets

We used time series of satellite altimetry mean sea level anomalies (SLA), i.e., sea surface heights with respect to an arbitrary temporal mean (different from one provider to the other), whose primary *raison d'être* is to avoid large numerical values (decametric ellipsoidal heights with regard to the expected centimeter level changes in mean sea levels). SLA products are routinely processed and distributed by five major data providers, namely, Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO; http://www.aviso.altimetry.fr/en/data.html), Climate Change Initiative (CCI) Sea Level Project (http://www.esa-sealevel-cci.org), Commonwealth Scientific and Industrial Research Organization (CSIRO; http://www.cmar.csiro.au/sealevel/), Colorado University (CU; http://sealevel.colorado.edu/content/map-sea-level-trends), and Goddard Space Flight Center (GSFC; http://podaac.jpl.nasa.gov/highlights/MEaSUREs_TPJAOSv1.0_SSH). Table 2 summarizes the main characteristics of these five data sets. It is worth noting that four of them consist of interpolated data over grids with spatial resolutions of between 1/4° and 1°. The fifth consists of along-track data. Temporal sampling, which differed among products, was homogenized to monthly observations for all cases.

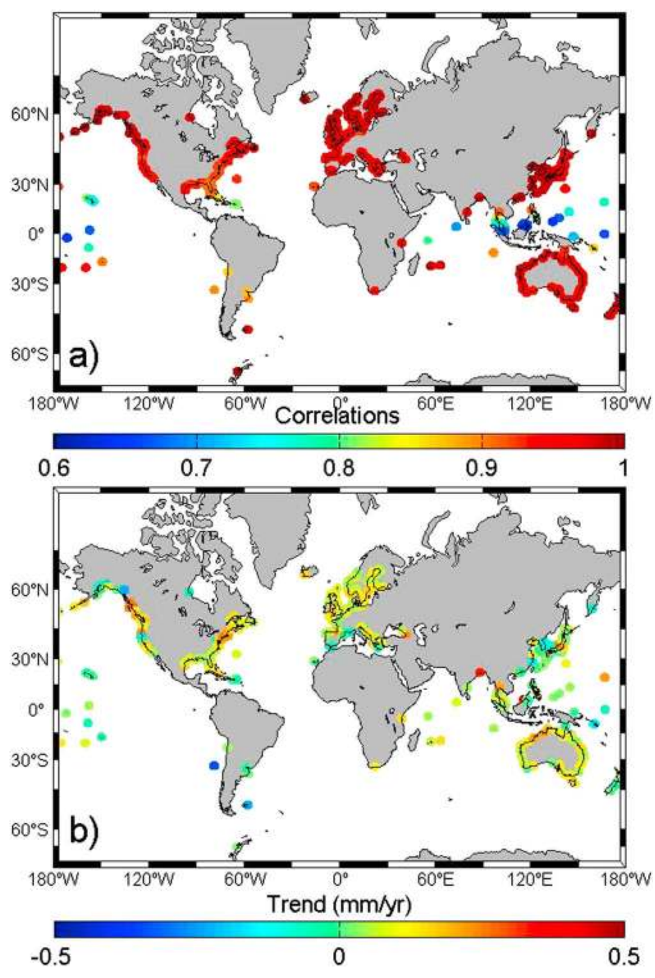

Figure 5. (a) Correlations between DAC and IB corrections and (b) linear trends in the DAC minus IB differences at each tide gauge location.

In addition to satellite altimetry data, we used monthly mean sea level time series from the PSMSL [*Holgate et al.*, 2013], and more specifically from the datum-controlled tide gauge data set or the

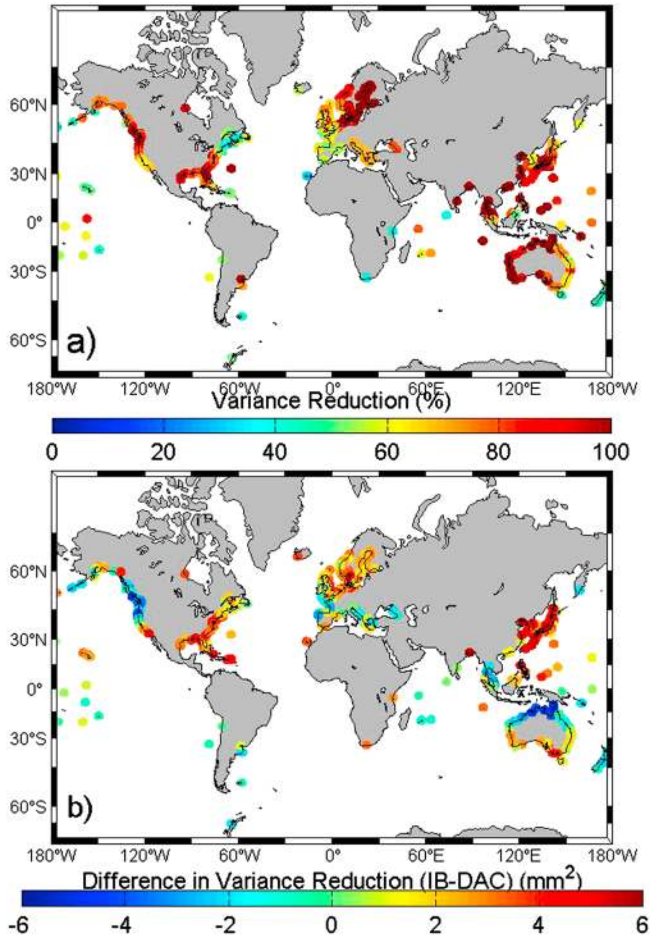

Figure 6. (a) Percentage of variance reduction at the tide gauges using DAC and (b) difference in variance reduction between IB and DAC.

Revised Local Reference (RLR) in PSMSL terminology. Tide gauge records with at least 15 years of valid observations during the satellite period 1993–2014 and located at latitudes between ±66° were initially selected, resulting in 598 station records. All records were first visually inspected to detect the remaining datum shifts, outliers, or the signature of nonlinear processes such as earthquakes or river discharges. The series affected by these problems were discarded from subsequent analyses. Tide gauge data posterior to February 2011 from Japanese stations located within a radius of 500 km from the epicenter of the Pacific earthquake in the Tohoku Region were also removed.

Series of differences between monthly tide gauge and satellite altimetry data were built using three variants of satellite altimetry time series, namely, the closest grid point, the most correlated grid point (both only for interpolated products), and the average within a 1° radius from the tide gauge location. In the second case, the best correlated grid point was chosen using deseasoned and detrended time series within a radius of 4° from the tide gauge. Once computed, the time series of differences were checked visually to discard those that were clearly nonlinear, i.e., for which vertical land motion would not be adequately modeled by a linear trend. In addition, tide gauges in rivers or small basins without an associated satellite altimetry time series were also discarded. This selective process resulted in a final set of 478 tide gauge stations at most (Table 2).

Prior to carrying out any comparison or combination, the atmospherically induced sea level (i.e., the effect of the atmospheric pressure and wind) was removed from the tide gauge records for consistency with the satellite altimetry data. The atmospheric correction is indeed typically applied to satellite altimetry data to ensure that high-frequency atmospheric signals do not yield aliasing into longer periods due to the temporal satellite sampling rate of 10–30 days. Two types of corrections were applied to the SLA data sets considered here (Table 2). On the one hand, the inverted barometer (IB) correction, which accounts for the static response of the ocean to atmospheric pressure while neglecting wind effects, was applied to the CCI and CSIRO data sets. In these two cases, the atmospheric pressure fields are products delivered by the European Centre for Medium-Range Weather Forecasts (ECMWF). On the other hand, the Dynamic Atmospheric Correction (DAC), which accounts for the effects of atmospheric pressure and wind [*Carrère and Lyard*, 2003], was applied to the AVISO, CU, and GSFC data sets. The two atmospheric corrections, DAC and IB, were used consistently in each set of SLA-tide gauge pairs. The closest grid points of the atmospheric correction to each tide gauge were selected.

Differences in the results obtained when using IB or a barotropic model including wind to correct for the atmospheric effects have been reported previously at the regional scale [*Pascual et al.*, 2008]. To appraise the importance of these differences between atmospheric corrections, we compared them (DAC and IB) at all tide gauge locations. Correlations were found to decrease around the equatorial region only, where the

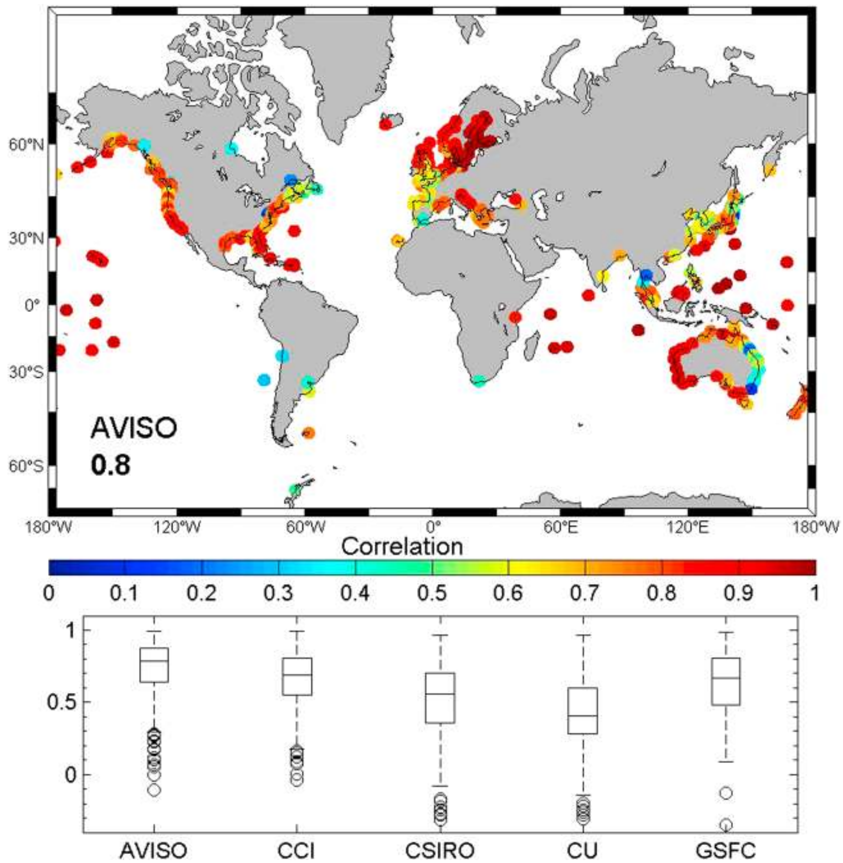

Figure 7. (top) Correlations between SLA (AVISO product) and tide gauge data (detrended and deseasoned). The value in the bottom left corner of the map is the median. (bottom) The boxplots for all satellite altimetry products. (Boxplots indicate the median, degree of asymmetry and spread as the interquartile range). Maps for the other satellite products can be found in Figure S1 in the supporting information.

role of the winds is greater [*Ponte*, 2006] (Figure 5a). Likewise, differences of ±0.5 mm/yr in the linear trends between the two corrections (median value of 0.08 mm/yr) were found (Figure 5b). In addition, DAC generally reduced a larger amount of variance (Figure 6), in agreement with the findings by *Pascual et al*. [2008] in the Mediterranean Sea. We conclude that overall DAC performs better than IB corrections at coastal locations.

3.1.2. Variants of Satellite Time Series

Differences in satellite altimetry data sets were investigated by comparison to the atmospherically corrected monthly tide gauge records. Among the three selections of SLA grid points (variants), the one producing the best agreement with tide gauges in terms of correlations and reduced variance was chosen. The results are only shown for the SLA averaged within a radius of 1° around the tide gauge location since the two other variants (the closest grid point and the best correlated) resulted, on average, in slightly lower correlations and less reduced variances. The correlations between SLA and tide gauge data (Figure 7) as well as the standard deviations of their differences (Figure 8) are mapped for the AVISO data set; boxplots summarizing the mapped information are also plotted in Figures 7 and 8. The results for the other satellite products (CCI, CSIRO, CU, and GSFC) are shown in Figures S1 and S2 in the supporting information.

In terms of correlation values (Figure 7), the largest values were found using the AVISO data set with a median value of 0.8, followed by CCI and GFSC (median of 0.7). Nonetheless, the high correlation values observed, whatever the product, emphasize the notion that coastal sea levels can reasonably be recovered by satellite altimetry at monthly timescales, especially in regions such as Northern Europe or Western Australia (Figure 7). The standard deviations of the differences (Figure 8) were also consistently lower when the AVISO data set was used, with a median value of 36 mm, which was significantly smaller than for the other four satellite altimetry data sets. The annual cycle in the differenced time series was also investigated (Figure 9). This signal

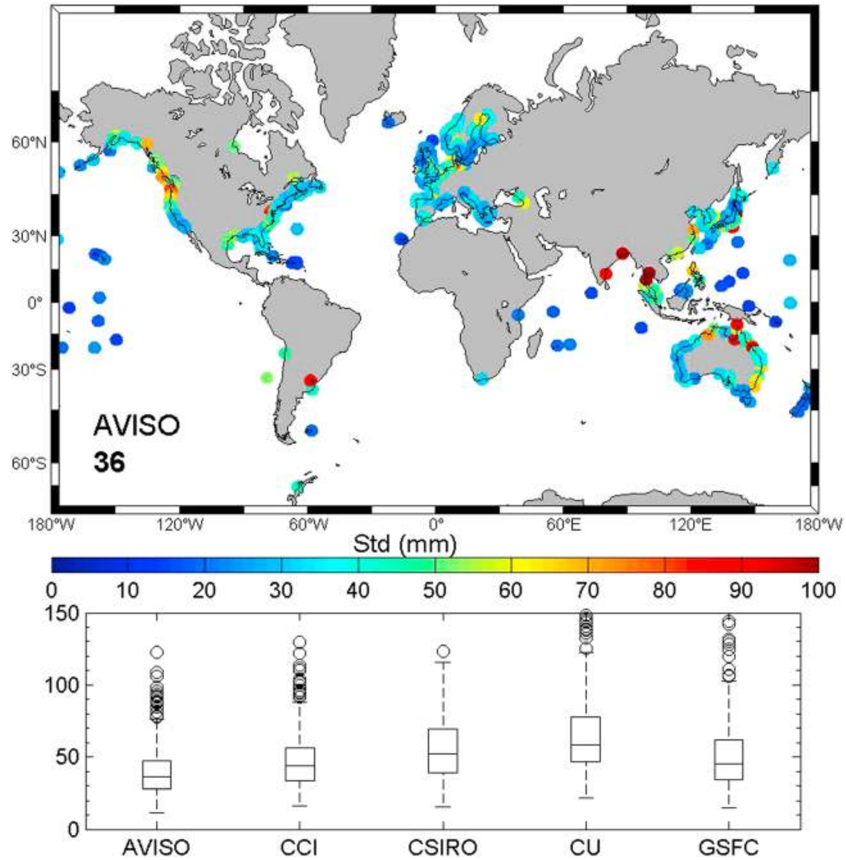

Figure 8. (top) Standard deviations between monthly SLA (AVISO product) and tide gauge data (detrended and deseasoned). The value in the bottom left corner of the map is the median. (bottom) The boxplots for all satellite altimetry products. Maps for the other satellite products can be found in Figure S2 in the supporting information. The units are in millimeters.

is not expected to show up in the differences, and its presence indicates that SLA does not capture the whole annual signal observed at the coast. Small values were found for most stations with a median not exceeding 2 cm, except for the CSIRO and CU products (2.7 cm). Not surprisingly, the larger amplitudes in the annual cycle coincided with the stations with the larger standard deviations (Figure 8).

3.2. Application and Uncertainties

Vertical ground displacements at tide gauges were estimated from the differenced time series of monthly satellite altimetry SLA minus tide gauge data using a robust linear regression [*Street et al.*, 1988] (Figure 10). The color scale in Figure 10 was adapted to cover the large uplift rates observed in Northern Europe due to GIA as well as the large coastal subsidence rates in Southeast Asia or in the northern Gulf of Mexico. The boxplots indicate the median, degree of asymmetry, and spread (interquartile range) of the linear trends (velocities) distribution for all satellite altimetry products. Figure S4 in the supporting information provides the maps for the other satellite products (CCI, CSIRO, CU, and GSFC).

The rate uncertainties were computed taking into account the noise content in the differenced time series. The presence of temporal autocorrelations in geophysical records is well known and may lead to a significant underestimation of the uncertainties in linear trends, if neglected [*Williams*, 2003b; *Hughes and Williams*, 2010; *Bos et al*., 2014]. Similarly to section 2, we used the MLE method implemented by *Williams* [2008] to assess the noise content in the differenced time series and derive uncertainties. Each differenced time series between SLA and monthly coastal tide gauge data was analyzed by considering a linear trend (intercept and slope) and an annual cycle, whereas a combination of white noise and power law noise of an a priori unknown spectral index (estimated along with the other parameters) was assumed. As a guideline for comparison, the analyses were repeated assuming white noise.

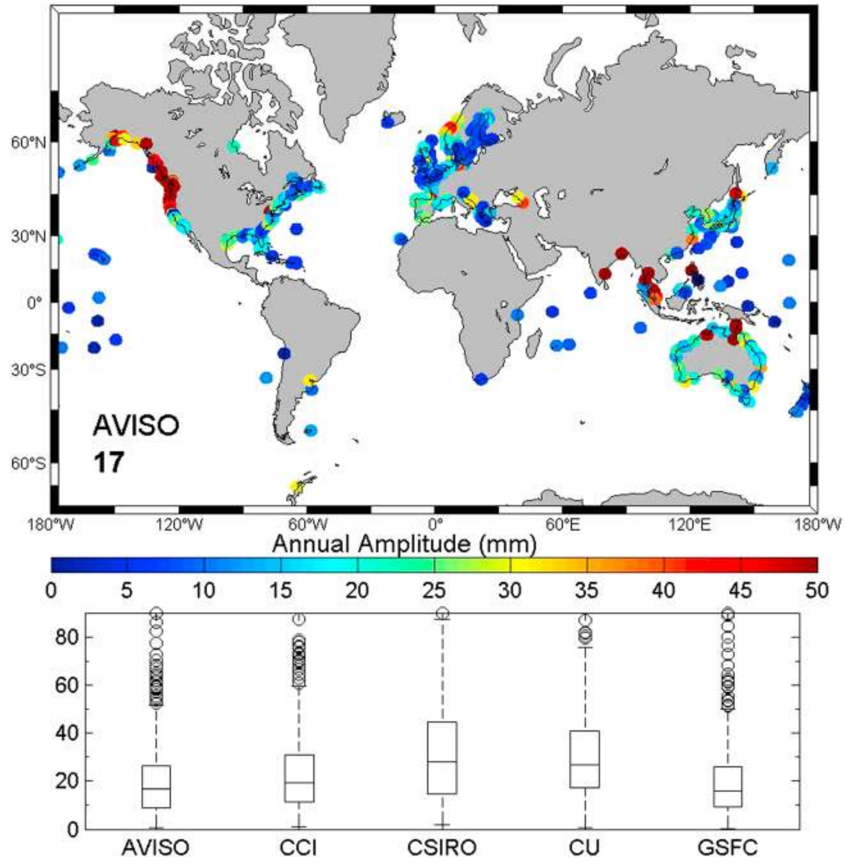

Figure 9. Map of annual amplitudes of the seasonal cycle in the differenced time series of SLA (AVISO Product) and tide gauge data. Maps for the other satellite products can be found in Figure S3 in the supporting information. The units are in millimeters.

Figure 11 represents the spectral indices derived from the MLE analysis at the 478 coastal stations where the differenced time series were formed using the AVISO product. Figure S5 in the supporting information provides the maps for the other satellite products (CCI, CSIRO, CU, and GSFC). The more negative the value of the spectral index, the redder the noise type, and the higher degree of temporal correlation in the differenced time series, which in turn will translate into a higher rate uncertainty compared to the case in which only white noise (uncorrelated) is considered. The interpretation of these results is, however, not straightforward and requires some comments. First, white noise in the differenced time series can be theoretically anticipated; if both the satellite altimeter and the tide gauge were recording the same sea level signals, the vertical land motion was linear and their instrumental errors were negligible. Second, the amplitude of the noise content also plays a role. For instance, a strong white noise can mask the detection of temporal correlations (the power law component of the noise). To avoid misinterpretation, the spectral indices should be analyzed along with the amplitude of the white noise, or equivalently, with the variability in the time series as shown in Figure 8. According to our results, the GSFC product yielded the most uncorrelated time series with a median value of −0.4. By contrast, AVISO, CCI, and CSIRO resulted in median values of −0.5, whereas the CSIRO median value was −0.7.

Figure 12 shows the ratios between rate uncertainties estimated using a power law plus white noise model and using only white noise. These ratios illustrate the importance of temporal correlations on the statistical significance of the estimated rates, a metric of paramount relevance to assess the existence of a trend, and subsequently for its geophysical interpretation. The results shown in Figure 12 indicate that the rate uncertainties for all data sets considered here were on average between 2 and 3 times higher if temporal correlation was accounted for. In the case of the lowest rate uncertainties (AVISO), these were increased by a factor of 2.4.

Figure 13 represents the rate uncertainties associated with the estimates of vertical land motion (Figure 10) taking into account the noise content in the differenced monthly SLA minus tide gauge time series.

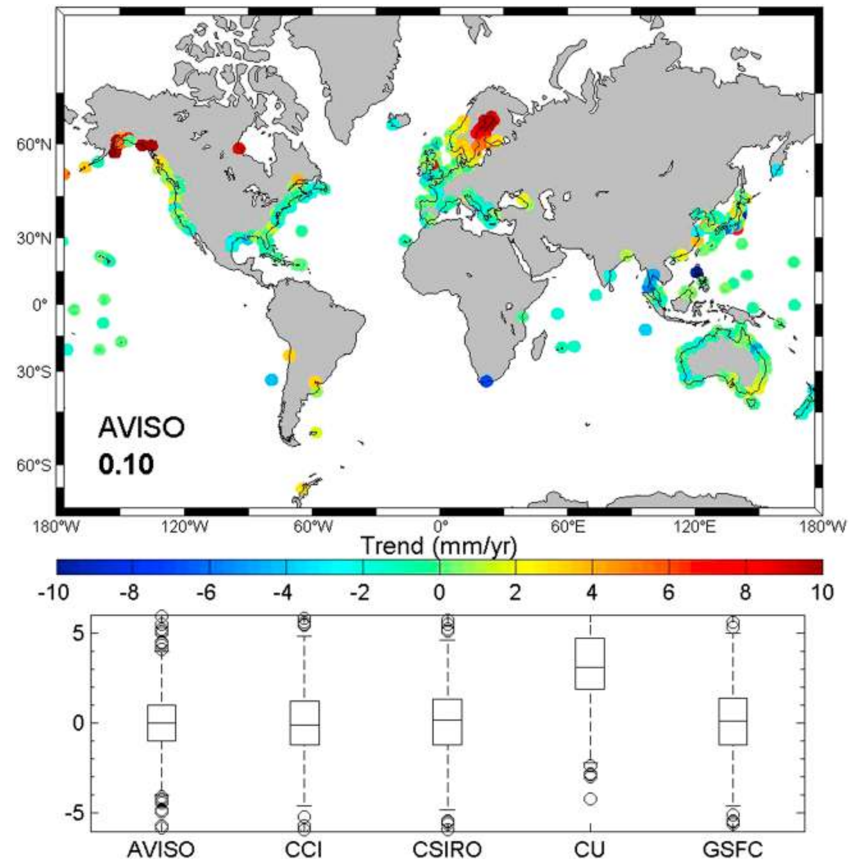

Figure 10. (top) Map of vertical land motion at coastal stations estimated from the differenced time series of monthly satellite altimetry (AVISO product) minus tide gauge data. The value in the bottom left corner of the map is the median. (bottom) The boxplots for all satellite altimetry products. Maps for the other satellite products can be found in Figure S4 in the supporting information. The units are in mm/yr.

Uncertainties up to 3 mm/yr were observed, although the median values were around 1 mm/yr for all the satellite altimetry products. As expected from the variance analysis (Figure 8) and the spectral indices (Figure 11), the highest rate uncertainties were associated on average with the use of the CSIRO data set, whereas the lowest stemmed from AVISO with a median value of 0.80 mm/yr. It is convenient to note here that these analyses aimed at quantifying the statistical errors only, that is to say, with no account taken of systematic errors (e.g., instrumental or geophysical corrections).

4. Discussion

4.1. Vertical Velocity Fields

Estimates of vertical land motion obtained from GPS and from the combination of satellite radar altimetry minus tide gauge data were compared at sites where both type of measurements were available (i.e., a total of 107 sites). On the basis of the overall results shown in the previous section, in particular considering the smallest rate differences with those from tide gauges and uncertainties, the AVISO product was adopted. It is used hereinafter in all the results involving satellite radar altimetry. The scatter plot in Figure 14 reflects the overall agreement between the two approaches, with values close to the bisector. The median of the differences was −0.25 mm/yr (lower GPS velocities) with an RMS of 1.47 mm/yr. The scatterplot also highlights large differences in the magnitude of the uncertainties between the two velocity fields, which is indicated by the error bars. While the GPS velocity uncertainties ranged between 0.1 and 1.3 mm/yr with a median of 0.21 mm/yr, they were 3–4 times greater on average for the combination of satellite radar altimetry minus tide gauge data, ranging between 0.3 and 3.0 mm/yr with a median of 0.80 mm/yr.

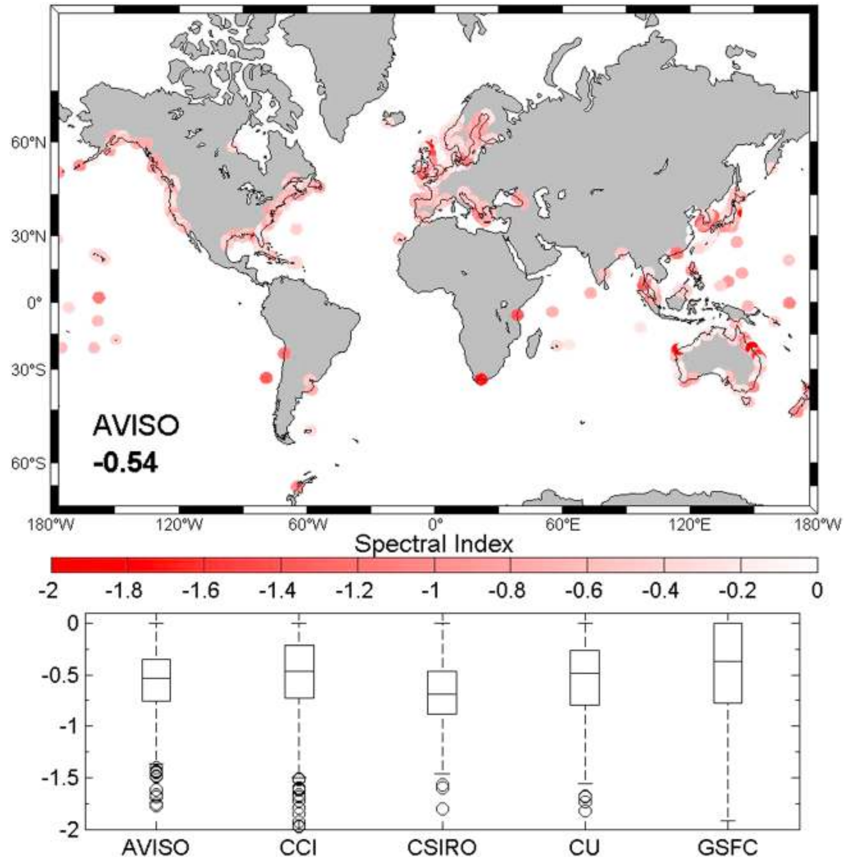

Figure 11. (top) Map of spectral indices (see text) associated with the differenced time series between monthly satellite altimetry (AVISO product) minus tide gauge data. The value in the bottom left corner of the map is the median. (bottom) The boxplots for all satellite altimetry products. Maps for the other satellite products can be found in Figure S4 in the supporting information.

As mentioned previously, to be useful, uncertainties on vertical land motion estimates should be a small fraction of the magnitude of the expected contemporary climate signals embedded in sea level records (i.e., a fraction of 2–3 mm/yr). A subsequent practical question is how long a record should be to reach a value equal to or below a given uncertainty level. This question was examined for GPS in previous studies, taking into account the noise content in the associated position time series (section 2). By contrast, it has not been investigated for the combination of satellite radar altimetry minus tide gauge data. As a matter of fact, most sites required nearly 20 years to yield a high-precision estimate of vertical land motion from this approach (Figure 13); it is fortunate that today the satellite altimeter record has just passed this milestone. Hence, our findings call for caution regarding previously published vertical land motion derived from short records, especially at sites where the vertical displacements of the Earth's surface are of the order of a few millimeters per year. As with GPS, reanalyzed satellite altimeter data using homogeneous analysis strategies [e.g., *Beckley et al*., 2007] may reduce the noise content in the associated time series and consequently also reduce the required record length necessary to attain a given uncertainty level.

4.2. Coastal Land Level Changes

To investigate whether it was reasonable to assume, in past global sea level change studies (section 1) that vertical land motion was canceled out on average on the coast, where tide gauges are located, we examined the joined vertical velocity field obtained from both approaches. Considering the overall smallest uncertainties of the GPS velocities, their use was preferred whenever they were available, provided their formal uncertainty proved indeed lower (94% of the 107 common sites). Alternatively, the satellite radar altimetry minus tide gauge velocities were used. (Details on the joined vertical velocity field are provided in Table S1 in the supporting information.) It is noteworthy that both sources of vertical land motion estimates showed a small

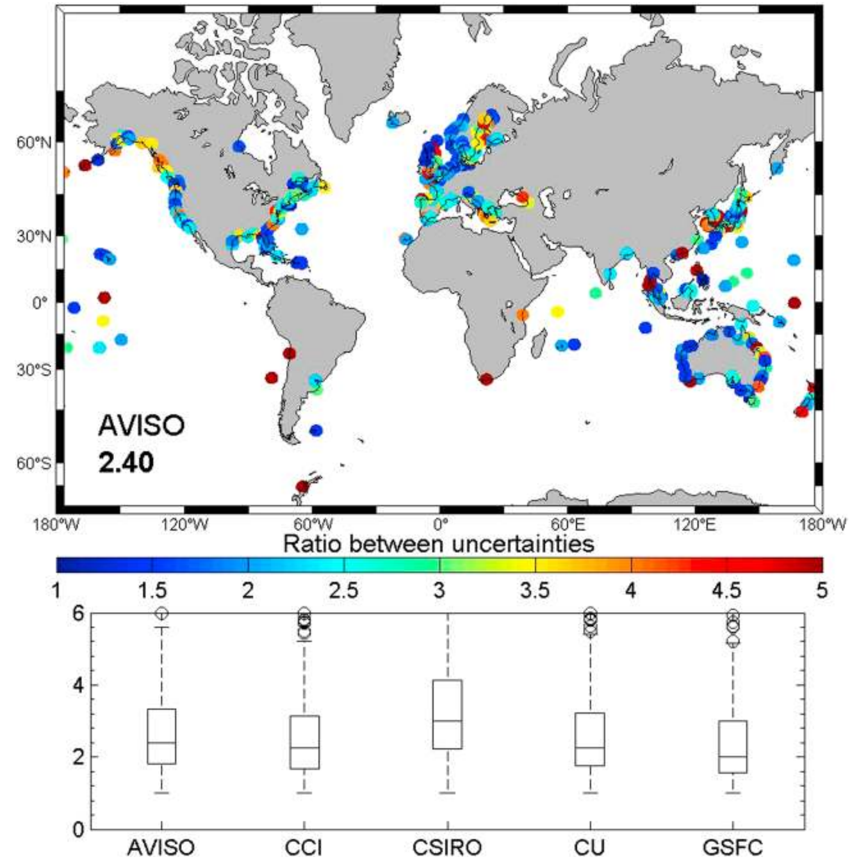

Figure 12. (top) Ratios between uncertainties derived from using a power law plus white noise stochastic model and assuming white noise only. The value in the bottom left corner of the map is the median. (bottom) The boxplots for all satellite altimetry products. Maps for the other satellite products can be found in Figure S6 in the supporting information.

median difference of −0.25 mm/yr, suggesting that both velocity fields are indeed expressed in the same terrestrial reference frame, i.e., well within the bound of 0.5 mm/yr presently reported in terrestrial reference frame realizations [*Collilieux et al*., 2014]. The joined velocity field comprises the 478 sites considered in the previous section and 7 GPS sites that were not considered because no robust estimates from satellite radar altimetry minus tide gauge data were available for the comparison. Thus, there were a total of 485 sites (Figure 15).

Two situations were considered, each corresponding either to the earliest studies which assumed a canceling out of any vertical land motion or to the most recent ones which have corrected for GIA effects and assumed the other displacements of the Earth's surface are canceling out, on average. The importance of the remaining (non-GIA) vertical land motion processes is illustrated in Figure 15b. Note that our non-GIA vertical land motion estimates can also contain errors from the GIA model predictions [*Peltier*, 2004] in addition to errors from the geodetic methods used here. When all the processes were considered, vertical land motion was, on average, 0.22 ± 0.30 mm/yr (uplift), whereas the remaining processes yielded, on average, −0.01 ± 0.27 mm/yr. The uncertainties correspond to 95% confidence intervals. As a result, our data set failed to provide clear statistical evidence for a predominance of uplift or subsidence (at the 5% significance level).

Interestingly, the median of non-GIA vertical land motions was 0.05 mm/yr with a 95% confidence interval of (−0.07, 0.14) mm/yr, which is in remarkable agreement with the corresponding average, indicating a symmetric distribution. By contrast, considering all processes yielded a median of −0.10 mm/yr with a 95% confidence interval of (−0.20, 0.10) mm/yr, hence pointing to a slightly asymmetric distribution toward uplifting sites (average of 0.22 mm/yr). Further tests carried out with different subsets of sites confirmed the potential for a bias. For example, we considered three subsets of velocities with uncertainties of less than 1 mm/yr (339 sites), 0.7 mm/yr (273 sites), and 0.5 mm/yr (191 sites). The smaller the subset, the greater the

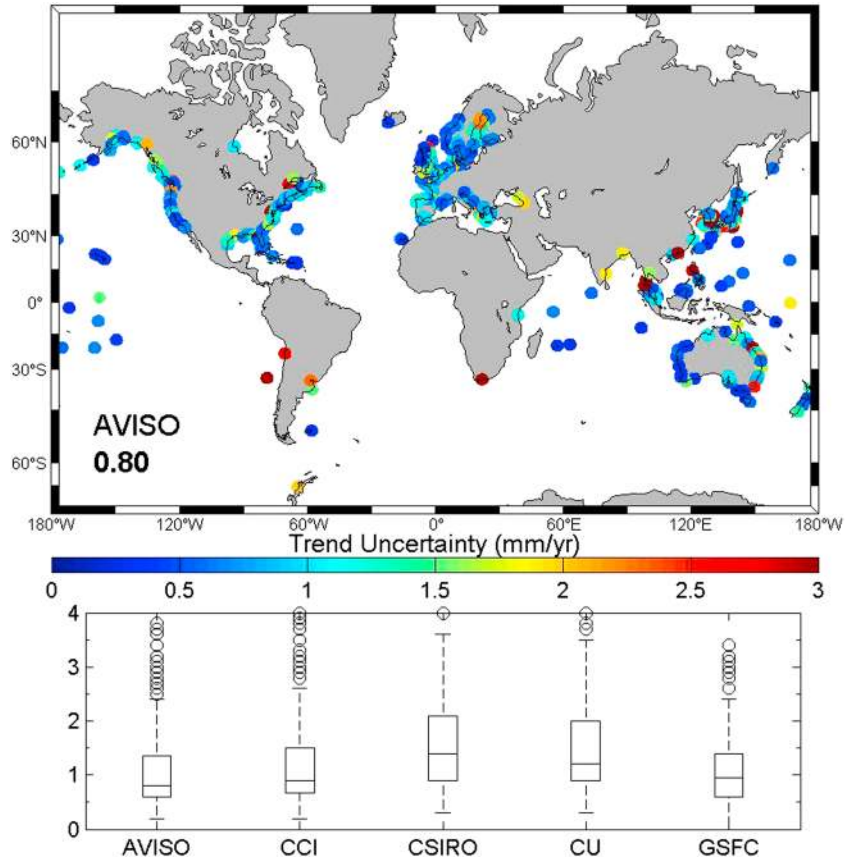

Figure 13. (top) Rate uncertainties associated with the vertical land motion estimates (Figure 10) taking into account the noise content in the differenced time series of the monthly satellite altimetry SLA (AVISO product) minus tide gauge data. The value in the bottom left corner of the map is the median. (bottom) The boxplots for all satellite altimetry products. Maps for the other satellite products can be found in Figure S7 in the supporting information. The units are in mm/yr.

mean obtained (0.36 ± 0.26 mm/yr, 0.39 ± 0.29 mm/yr, and 0.52 ± 0.36 mm/yr, respectively), which is consistent with a geographical sample biased toward the northernmost latitudes dominated by GIA-induced radial crustal uplift (Figure 16). No such evidence could be found for non-GIA vertical land motions since the means remained stable when the data set was restricted in the way described here.

Based on the vertical velocity field of 485 globally distributed sites, this study found no evidence that the processes causing subsidence are more frequent at the coast than those causing uplift, or vice versa. In addition, at first sight our findings support the early studies that used a large amount of tide gauge records without vertical land motion corrections (assuming these would cancel out) to derive trends in global mean sea level, or the recent studies interested in global mean sea level projections [*Moore et al*., 2013]. Nonetheless, our results also point to a possible average bias toward uplift when the number of tide gauge records reduces from the initial set of 485 sites to 191 sites. This reduction is bound to happen whenever the selection criteria becomes more stringent in terms of data quality. The obvious consequence of an average uplift bias is a lower rate in the global mean sea level estimate, which is what one can actually observe from the early studies [*Spada and Galassi*, 2012, Table 1]. It is also important to note that the associated estimates of the early studies can be affected by other sources of bias, notably because of the trade-off between a large number of tide gauges (several hundreds) and the minimum record length that is required to overcome the influence from decadal sea level oscillations [*Douglas*, 1991]. In this respect, the most recent studies build upon high-quality long-tide gauge records, typically longer than 50 years (thus considerably reducing the number of useful sites to a couple of dozen or so) [e.g., *Douglas*, 1991; *Spada and Galassi*, 2012], and apply GIA model corrections. Yet here too our findings tend to support their implicit assumption that non-GIA vertical land motions cancel out, on average. But overall, our results also show that caution is mandatory when dealing with small size samples and warrant future work on non-GIA vertical land motion. In particular, the

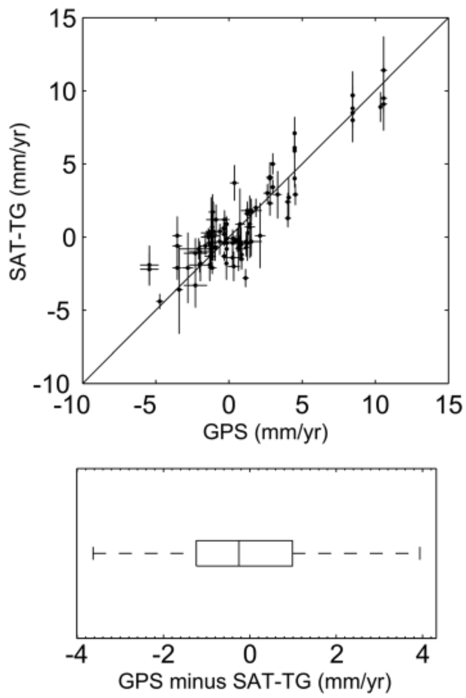

Figure 14. Comparison between estimates of vertical land motion from GPS and from satellite radar altimetry minus tide gauge (SAT-TG) data: (a) scatterplot and (b) boxplot of the differences in vertical land motion estimates (GPS minus SAT-TG). The units are in mm/yr.

issue is critical at regional or local scales for studies on the coastal impacts of future sea levels. At these scales, the assumption of vertical land motion canceling out will likely not hold, whether one corrects for GIA or not. For instance, we found overall uplift in northwestern America or in the North Sea with medians of 1.0 and 0.2 mm/yr with confidence intervals of (0.4, 2.2) and (0.0, 0.5) mm/yr, respectively, once corrected for GIA.

4.3. Coastal Absolute Sea Level Changes

The joined vertical velocity field from both approaches (section 4.2) is used to correct for vertical land motion and convert the observed relative sea level changes from tide gauges over multidecadal to century timescales into absolute (geocentric) sea level changes. The associated working hypothesis is that vertical land motions determined over the past two decades or so remained constant over the decades to century timescales in which the tide gauge was operational (section 2). The tide gauge records considered in this study (485 sites) passed the standard quality control selection criteria described in section 3, in particular the requirements of 70% of valid data over a given period, datum continuity, and visual inspection of the time series for detection of nonlinear behavior. Table 3 summarizes the average estimates of coastal sea level changes over two different periods, namely, 1950–2014 and 1900–2014, using vertical velocity uncertainty criteria for the vertical land motion corrections of less than 0.5 mm/yr (Figure 17), 0.7 mm/yr, and 1 mm/yr. The choice of the median (robust estimator) instead of the average was preferred since the previous section pointed to possible biases arising from small samples.

Once corrected for vertical land motion using our joined vertical velocity field, the tide gauge records were further corrected with the geoid rate of change component of the GIA, but not for its radial crustal component. This was performed using the values of the ICE5G model of the rate of change of geoid provided at tide gauge sites [*Peltier*, 2004]. The rationale was to allow comparisons with published estimates of changes in ocean volume due to climate change. Table 3 indicates a remarkable agreement between the estimates within a given period, despite the reduction in the number of sites as the uncertainty thresholds become stringent for the vertical land motion correction. The associated 95% confidence intervals in Table 3 were calculated using 10,000 bootstrap samples. Overall, our estimates in Table 3 are in good agreement with the trends published in the literature for global sea levels. On longer timescales, the values in Table 3 confirm that estimates of global sea level change from records longer than 50 years agree to within 0.2 mm/yr over the past century and become slightly higher when the time span reduces to the last six decades because of the leverage effect on the trend of the largest rate observed over the most recent period. These results indicate that the longer the timescale of sea level signals, the larger the spatial extent of the underlying processes of these signals (climate related). Consequently, they support the working hypothesis that the determination of a secular trend in global mean sea level may rely on a small set of carefully selected tide gauge records [*Douglas*, 1991; *Holgate*, 2007; *Spada and Galassi*, 2012].

4.4. The Key Role of the Terrestrial Reference Frame and Other Geodetic Techniques

It is now well recognized that an accurate and stable terrestrial reference frame is needed [*Carter et al.*, 1989; *Carter*, 1994; *Neilan et al.*, 1998; *Blewitt et al.*, 2010] and that origin and scale uncertainties in the reference frame affect sea level change estimation from either satellite radar altimetry data [*Morel and Willis*, 2005; *Beckley et al.*, 2007] or tide gauge data [*Collilieux and Wöppelmann*, 2011]. The demand for accuracy is particularly challenging at a fraction of a millimeter per year level (section 1). Despite the remarkable advances made in GPS (section 2), we are aiming at a level of accuracy for geocentric velocity estimates where, for instance,

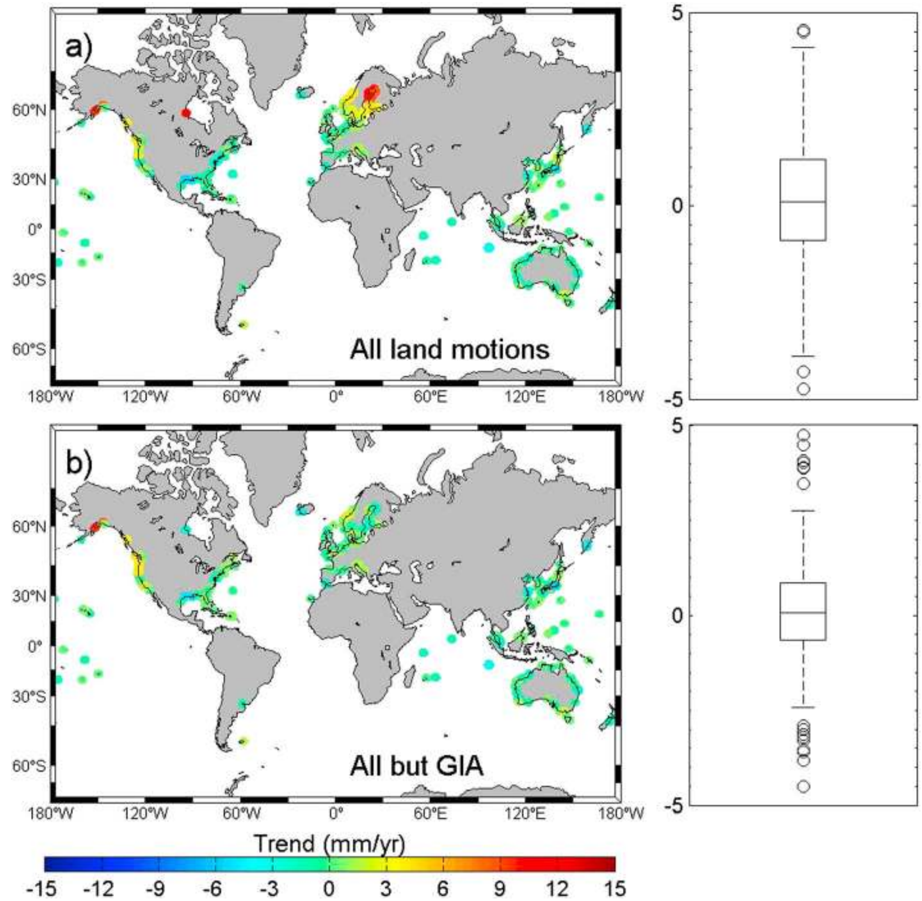

Figure 15. (a) Map showing the joined GPS vertical land motion and SAT-TG estimates of vertical land motion (485 sites), and (b) same as Figure 15a but corrected for GIA radial crustal displacements from the ICE-5G VM2 model [*Peltier*, 2004] to highlight vertical land motion processes other than GIA.

the reference frame origin and its long-term stability are beyond the reach of a single technique such as GPS. The best reference frames for scientific applications requiring a very high degree of accuracy are the realizations of the International Terrestrial Reference Frame (ITRF), which take advantage of the strengths of different space geodetic techniques [*Altamimi et al*., 2002, 2005, 2009, 2011]. For instance, the origin of the ITRF is presently defined via Satellite Laser Ranging (SLR), which yields the most sensitive solutions with respect to the Earth's center of mass position. In this respect, serious concerns have been raised on the origin stability of the ITRF realization [e.g., *Argus*, 2007]. Figure 18 illustrates how a drift in the *Z* component of the origin of a reference frame (e.g., ITRF) affects the vertical component of a station (as the sine of its latitude).

The *Z* component (along the mean Earth's rotation axis) of the ITRF origin is indeed suspected to have a drift due to the SLR station measurement network, which has deteriorated (poor number and inhomogeneous distribution) over the past 10 years [*Collilieux et al*., 2009]. *Collilieux and Wöppelmann* [2011] investigated the associated impact on global mean sea level rise estimates. They showed that the error bar of the global mean sea level rise estimate obtained using the tide gauges and GPS corrections in *Wöppelmann et al*. [2009] would substantially increase from 0.2 to 0.7 mm/yr if the uncertainties in the ITRF origin and scale factor were taken into account. An update using uncertainties in the origin and the scale factor of 0.5 mm/yr and 0.3 mm/yr, respectively [*Wu et al*., 2011; *Collilieux et al*., 2014], and using the reanalyzed GPS solution in *Santamaría-Gómez et al*. [2012], yields a slightly reduced uncertainty of 0.5 mm/yr for the global mean sea level rise estimate. Overall, these results signify that the main factor limiting the determination of vertical land motion and geocentric sea level trends from geodetic observations is the realization of the terrestrial reference frame. Furthermore, uncertainties related to origin stability may explain a substantial part of the unexpected latitudinal (nearly hemispheric) differences

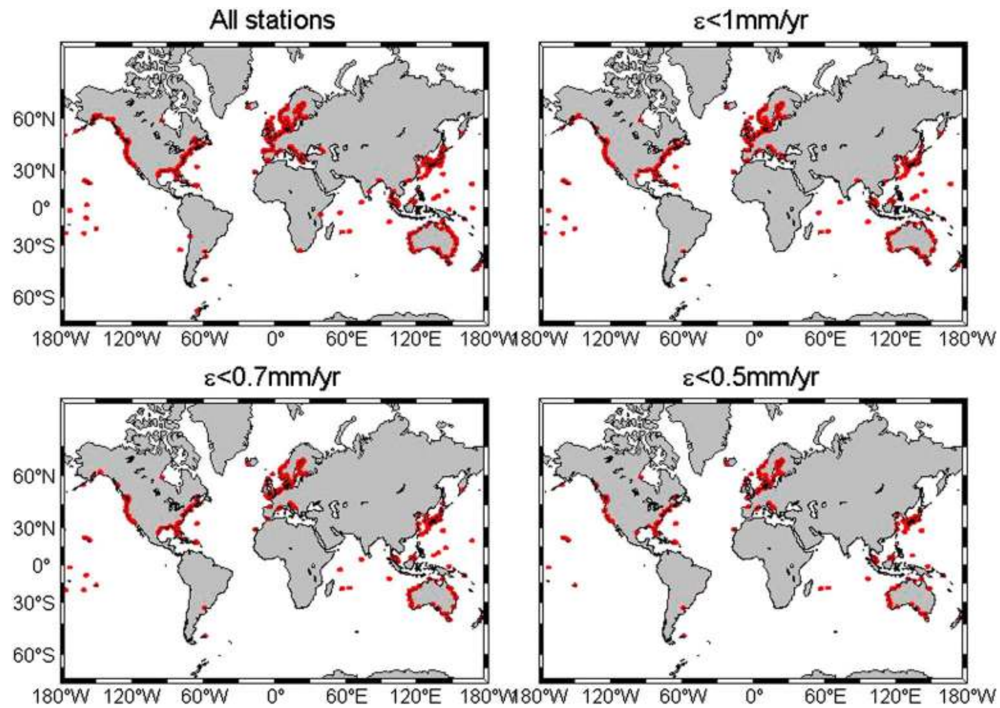

Figure 16. Maps showing the distribution of subsets of stations (out of the 485 stations) with uncertainties in vertical land motion estimates less than 1 mm/yr (339 sites), 0.7 mm/yr (273 sites), and 0.5 mm/yr (191 sites).

observed by *Wöppelmann et al.* [2014] in long-term (secular) sea level trends over the twentieth century. However, we do not clearly know what secular changes (land-ice melting, geocenter motion, etc.) one should expect to observe between hemispheres due to the lack of observations in the past and to the understanding of the processes. Future work is definitively needed to address this issue, either by gathering more observational data on sea and land levels or by improving our understanding of the various physical processes involved.

An interesting outcome of our study is the small −0.25 mm/yr difference between the medians of the two velocity fields (section 4.1), indicating that no substantial bias was introduced at the global scale. This result is in good agreement with *Watson et al.* [2015], who found a mean difference of −0.13 mm/yr computed from 71 common sites between their GPS solution and the one used in this study [*Santamaría-Gómez et al.*, 2012]. This is in spite of the fact that GPS solutions may actually differ in a number of important data analysis options, such as the size and geometry of the stations network, the data time span period, the satellite orbits, models, corrections, parameterization, realization, and alignment to a terrestrial reference frame. However, even though the resulting GPS solutions can be considered independent in many respects, they remain confined to a specific technique. By contrast, the above mentioned assessment in our study stems from an external source of measurement (satellite radar altimetry minus tide gauge) over 107 common sites.

Table 3. Median Estimates of Coastal Sea Level Change Over Two Long Time Periods (1950–2014 and 1900–2014) From Tide Gauges Corrected for Vertical Land Motion Using the Joined Vertical Velocity Field (See Text)[a]

	≤0.5 mm/yr	≤0.7 mm/yr	≤1 mm/yr
1950–2014	1.92 [1.73, 2.17] (123)	1.91 [1.73, 2.14] (158)	2.00 [1.87, 2.25] (186)
1900–2014	1.67 [1.44, 1.87] (70)	1.67 [1.44, 1.86] (78)	1.73 [1.48, 1.88] (81)

[a]Three uncertainty thresholds are considered for selecting these corrections (less than 0.5 mm/yr, 0.7 mm/yr, or 1 mm/yr). The 95% bootstrap confidence intervals associated with each estimate are given in square brackets, and the number of sites in brackets. Units are in mm/yr.

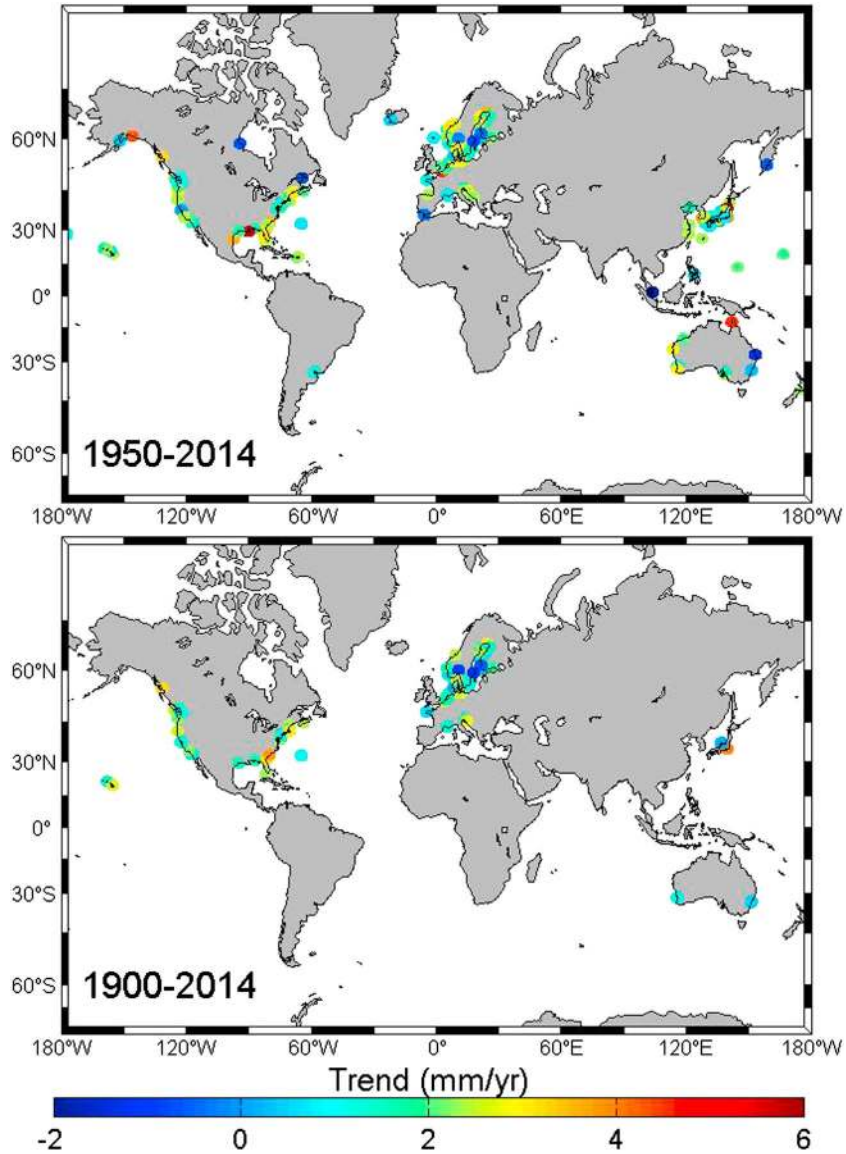

Figure 17. Maps showing rates of absolute sea level change for different time periods, namely, 1950–2014 and 1900–2014.

The availability of independent techniques and solutions is of paramount importance in several respects [*Altamimi et al*., 2009; *Blewitt et al*., 2010], some of which were illustrated above (supplementing the specific weaknesses of a technique with a high-quality terrestrial reference frame, detecting biases, and assessing the quality of individual solutions). However, another important and related aspect should be underlined here from the original work by *Brooks et al*. [2007]. That is, even extensive networks such as those deployed in California (United States) or Japan are essentially a collection of point measurements that are sparse compared to the spatial scales of vertical land motion along many coastlines where information is needed to determine relative sea level change. The authors propose to combine pointwise but accurate geocentric measurements (e.g., GPS) with spatially dense but relative (to an arbitrary point on land) measurements from Interferometric Synthetic Aperture Radar (InSAR). They show that the combined GPS and InSAR products could yield deeper physical understanding and predictive power for beach morphology evolution. Subsequent studies have explored various methods based on InSAR measurements to further explore its applicability in different coastal environments [*Raucoules et al*., 2013; *Wöppelmann et al*., 2013], confirming its usefulness in sea level studies.

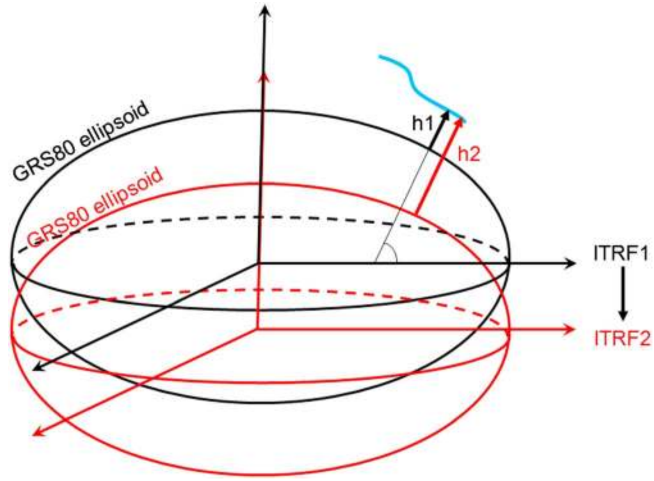

Figure 18. Impact of a drift in the *Z* component of the origin of a reference frame (e.g., ITRF) on the vertical component of a station.

5. Concluding Remarks

In this review, we discussed how advances in our knowledge of vertical land motion during the past 30 years have led to greater understanding of contemporary sea level rise. Despite these advances, in particular in GPS observation and analysis, a plateau has been reached. There remains ample room for progress during the coming years. On the one hand, to address the demand for accuracy in studies of global sea level change involving either tide gauges or satellite radar altimeters, the major limiting factor remains the definition of the terrestrial reference frame, whose physical parameters, the origin, and the scale factor are beyond the scope of a unique technique such as GPS. Hence, independent techniques such as SLR (see *Altamimi et al.* [2011] for a complete list of useful techniques), or ambitious projects such as Geodetic Reference Antenna in Space, will be worth developing to achieve the much sought-after long-term stability of the reference frame in the origin and the scale factor at better than 0.1 mm/yr and 0.01 ppb/yr, respectively (1 ppb, part per billion, corresponds to 6 mm at the Earth's surface). Concerning the SLR technique, its main limitation today is the sparse and uneven network of tracking stations. Note also the role that absolute gravity can play in assessing reference frame parameters [*Mazzotti et al.*, 2011; *Teferle et al.*, 2009] or in monitoring vertical land motion at or nearby tide gauges [*Baker*, 1993; *Zerbini et al.*, 1996; *Williams et al.*, 2001; *Van Camp et al.*, 2005; *Amalvict et al.*, 2009].

On the other hand, the new implementation plan of the international GLOSS program [*IOC*, 2012] calls for an important upgrade to its core network by requesting the installation of continuous GNSS stations at the tide gauges. Presently, less than 14% of the GLOSS tide gauge stations are directly (on top of the tide gauge) equipped with a permanent GNSS station. This figure increases to 24% for all the GNSS at or near tide gauge stations in the GLOSS GNSS data center (http://www.sonel.org). Filling these gaps in geodetic measurement at tide gauges must be a major priority of the various national and international programs. Hopefully, this recommendation will be implemented by the participant countries and future work will benefit from these measurements. First, the working hypothesis of previous studies, namely, that the nearby (sometimes up to tens of kilometers) GPS station is sensing the same vertical land motion as the tide gauge, could then be avoided. This hypothesis was necessary to demonstrate a concept that is now over 20 years old, but it is an approximation resulting from a lack of dedicated GPS stations on the tide gauges themselves and can be incorrect on certain coastlines. Second, geodetic monitoring is a necessary complement at the tide gauge stations in order to devise sustainable development plans of the coastline by understanding the causes that underlie the observed relative sea level changes and the respective magnitudes of these causes. Indeed, the factors controlling relative sea level differ from one coastline to another, and climate effects may not be the biggest. In some coastal regions of the world, vertical land motion clearly dominates (Figure 3). In other areas, they might be of the same order of magnitude as climate factors.

A final remark relates to our conclusion in section 3. Based on our results, AVISO-gridded SLA was found to be the most suitable data set among the freely distributed global satellite altimetry products that were considered in this study for a combination with tide gauge data to estimate vertical land motion at the coast. Of course, this conclusion is limited to the specific data sets examined here within the scope of this study. The usefulness of the satellite altimetry products will differ in other contexts, for instance, if other reference periods are used, or, especially near the coast if different algorithms are used for instrumental and tidal corrections. In this respect, it should be mentioned that we also explored whether dedicated regional coastal satellite altimetry products may give better performances than the global products over long time scales [*Birol and Delebecque*, 2014], but the results were inconclusive and future work is needed in this field too (Figure S8 in the supporting information).

Notation

AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data, France (http://www.aviso.altimetry.fr/en/data.html).
CCI	Climate Change Initiative (CCI) sea level project of the European Space Agency (http://www.esa-sealevel-cci.org).
CSIRO	Commonwealth Scientific and Industrial Research Organization, Australia (http://www.cmar.csiro.au/sealevel/).
CU	Colorado University, United States (http://sealevel.colorado.edu/content/map-sea-level-trends).
DAC	Dynamic Atmospheric Correction.
ECMWF	European Centre for Medium-Range Weather Forecasts.
ERA Interim	ECMWF Re-Analysis of meteorological observations.
GFSC	Goddard Space Flight Center, United States (http://podaac.jpl.nasa.gov/highlights/MEaSUREs_TPJAOSv1.0_SSH).
GIA	Glacial Isostatic Adjustment; the deformation of the Earth and its gravity field due to past deglaciation and redistribution of ice and water masses.
GLOSS	Global Sea Level Observing System; an international program under the auspices of the IOC, formerly known as Global Level Of the Sea Surface.
GPS	Global Positioning System.
GNSS	Global Navigation Satellite Systems.
IB	Inverted Barometer effect; adjustment of sea level to changes in barometric pressure.
ICE-5G	a global ice sheet reconstruction produced by W. R. Peltier of the Department of Physics in the University of Toronto, Canada. It provides model data on global ice sheet coverage, ice thickness and paleotopography for 21 ka to the present day. Details in *Peltier* [2004].
IGS	International GNSS Service, formerly known as International GPS Service for geodynamics.
IOC	Intergovernmental Oceanographic Commission of the UNESCO.
ITRF	International Terrestrial Reference Frame.
MLE	Maximum Likelihood Estimator; a statistical technique.
PSMSL	Permanent Service for Mean Sea Level.
SLA	Sea level anomaly; difference between a sea level height and a mean sea level height.
SONEL	Systeme d'Observation du Niveau des Eaux Littorales (http://www.sonel.org).
TIGA	GPS Tide Gauge benchmark monitoring working group of the IGS.
UNESCO	United Nations Educational, Scientific and Cultural Organization.

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