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► **To cite this version:**

Emilie Ostanciaux, Laurent Husson, Gael Choblet, Cécile Robin, Kevin Pedoja. Present-day trends of vertical ground motion along the coast lines. *Earth-Science Reviews*, 2012, 110 (1-4), pp.74-92. 10.1016/j.earscirev.2011.10.004 . insu-00665616

**HAL Id: insu-00665616**

**<https://insu.hal.science/insu-00665616>**

Submitted on 23 Sep 2019

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# Present-day trends of vertical ground motion along the coast lines

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Vertical ground motion (VGM) rates stand as crucial information, either for predicting the impact of the actual sea level rise along low-lying coasts or refining geodynamic problems. Because present day VGM rates have a magnitude smaller than 10 mm/yr, they remain challenging to quantify and often elusive. We focus on the quantification of global-scale VGM rates in order to identify global or regional trends. We computed VGM rates by combining tide gauges records and local satellite altimetry, which yield a new dataset of 634 VGM rates. We further compare this database to previous studies that use geodetic techniques and tide gauges records in order to evaluate the consistency of both our results and previous ones. The magnitudes differ by less than 5 mm/yr, and similar subsidence and uplift general tendencies appear. Even if the asset of our database stands in the greater number of sites, the combination of all studies, each with different pros and cons, yields a hybrid dataset that makes our attempt to extract VGM trends more robust than any other, independent study. Fennoscandia, the West coast of North America, and the eastern coast of Australia are uplifting, while the eastern coast of North America, the British Isles and Western Europe, the eastern Mediterranean Sea, Japan, and the western coast of Australia are subsiding. Glacial Isostatic Adjustment (GIA) is expected to provide a major contribution to the present-day signal. Aside from Fennoscandia, observed VGM often depart from the GIA model predictions of Peltier (2004). This either results from an under-estimate of the model predictions or from the influence of other processes: indeed, the influence of the geodynamic setting appears in particular along the coasts of western North America or Japan, where the alternation of transform faults and subduction zones makes it possible to assign contrasted behaviours to the local geodynamic context. Local mechanisms like anthropogenic processes or sediment compaction, also contribute to VGM. This remains true for the critical cases of Venice, the Gulf of Mexico, the Ganges delta, and the Maldives, which are particularly exposed to the current sea level rise.

## 1. Introduction

Vertical Ground Motion (VGM) is a major issue for anthropisation of the coastal areas that are exposed to the recent sea level rise, which occurs at 2–3 mm/yr on average (Cazenave et al., 2008) but that spatially varies by several mm/yr. Only a good knowledge of VGM may help to decipher their various causes and contribute to the resolution of such a crucial societal challenge. Understanding the causes of VGM and predicting their impacts is a possibility but uncertainty remains large. Alternatively, a variety of techniques provides means to collect direct observations of such processes. Matching the two approaches is key and requires a clear view of both observations and processes.

Anthropogenic causes, active tectonics, volcanism, mantle dynamics and glacio-isostatic adjustments are among the main contributors responsible for vertical ground motion. Anthropogenic causes include hydrocarbon or water pumping (such as in the emblematic case of Venice, e.g. Holzer and Johnson, 1985), and sediment starvation resulting from river diversion, irrigation, or dams (like in Bangladesh, e.g. Johnson and Nur Alam, 1991). Because of their impact on the morphology, the role of tectonic activity or volcanism is conceptually straightforward at active plate margins, although it is sometimes challenging to quantify. Last, mantle flow constantly shapes the solid Earth by modifying the heterogeneous distribution of its internal masses. On the long-term, dynamic topography, i.e. the departure of the Earth's surface from a static equilibrium as a response to the viscous flow in the mantle, affects all parts of the world with a magnitude that may exceed 1000 m (Gurnis, 1993; Ricard et al., 1993; Conrad and Husson, 2009), but at slower rates than 0.1 mm/yr (e.g. Husson and Conrad, 2006; Moucha et al., 2008). The most important contribution in terms of rates is the Glacio Isostatic Adjustment (GIA), which is the response of the solid Earth's surface to periods of loading/unloading by polar caps and glaciers. As opposed to dynamic topography, the associated rates of VGM are high but the integrated magnitude barely exceeds 100–200 m. The visco-elastic rheology of the Earth's mantle and crust delays this response, so that the GIA process still continues to have a significant impact. The so-called Sea Level Equation, formerly derived by Farrell and Clark (1976), can be used to evaluate the feedback effects of ice, seawater, the mantle, and the lithosphere on ground elevation (Peltier et al., 1978). On this basis, several studies have modelled and quantified the GIA at a global or local scale (e.g., Lambeck et al., 1998; Mitrovica et al., 2001; Peltier, 2004; Stocchi and Spada, 2007). However, the uncertainties in the rheological structure of the Earth make it difficult to give reliable forward predictions of the GIA (see e.g., Spada et al., 2006; Mitrovica et al., 2011), and estimates often vary from one study to another. Therefore, although the physical processes that operate at all time and space ranges are rather well understood, their relative contributions remain poorly known.

Measuring VGM – as opposed to predicting VGM – is not a trivial issue either, firstly because vertical motion rates are typically smaller than horizontal components of ground motion, often at the edge of the resolving capacity of the current observatory techniques. Geodetic devices are technically capable of measuring these low VGM rates, but all are restrained by limited time-series (Nerem and Mitchum, 2002; Ray et al., 2010). Alternatively, ground motion can be quantified by

direct measurements of sea level change along shorelines. Tide gauges are attached to the coasts and therefore the signal they measure is just the difference between mean sea level variations and VGM. These motions can thus be quantified, provided that sea level variations are known during the time period of recording. Such correction can be calculated using satellite altimetry, which only measures sea level variations (Cazenave et al., 1999; Nerem and Mitchum, 2002; Prandi et al., 2009). The vast majority of dedicated studies are optimistic regarding our capability of providing accurate measurements of VGM. In this paper, we review the various databases that may lead to a reasonable knowledge of global VGM, on the basis of previous studies that we eventually compare to a new global analysis of tide gauges and satellite altimetry data. Our target differs from previous works that generally aim to quantify sea level change (often its mean rate) rather than net ground motion. Here, our goal is to constrain VGM as a starting point in order to directly quantify the various contributions to VGM, particularly GIA. In addition, because researchers from a variety of fields commonly use GIA models blindly, we feel that those models need to be critically exposed to observations. We first present previous studies that have provided estimates of VGM and the methods they have used. We then reappraise the VGM data sets and compare all studies.

## 2. Methods for quantifying the trends of vertical ground motion

In this section, we present the advantages and drawbacks of various methods to estimate vertical ground motion (VGM) rates.

### 2.1. Ground motion from geodetic measurements

The VLBI and SLR networks can provide estimates of vertical ground motion (see Heki, 1996 and Argus et al., 1999 for VLBI) but the scarcity of the stations prevents a global analysis of ground motion from being carried out. In addition, DORIS and GPS networks have naturally superseded these devices.

DORIS (Doppler Orbit determination and Radiopositioning by Satellite) is based on Doppler shifts measurements on a radio-frequency signal transmitted by ground stations and received on-board by the DORIS receivers (Jayles et al., 2006). In turn, it indicates the location and displacement of each of the sixty permanent ground stations. Although primarily developed to track the Topex/Poseidon satellite, it has been proved to be a powerful tool for tectonic measurements. For instance, Crétaux et al. (1998) showed that DORIS can provide accurate velocity measurements. While Mangiarotti et al. (2001) showed that the annual vertical oscillation of the ground is difficult to detect because of a high signal-to-noise ratio, Soudarin et al. (1999) demonstrated that secular vertical motion could be detected on the basis of a good agreement between DORIS and GPS estimates. In addition, Cazenave et al. (1999) compared the vertical crustal motion rates derived from DORIS to those from Topex/Poseidon and tide gauges. They observed that the values were consistent; their conclusion was further corroborated by the recent analysis of Ray et al. (2010). However, the stations that form this geographically uniform network are too sparse to envision a global study.

GPS (Global Positioning System) devices measure the travel time of microwaves from a source transmitter to a receiver on the ground.

Unlike VLBI, artificial satellites emit the signals. The amplitude of the signal is higher, and accordingly the receiving antennas can be smaller, rendering this system reasonably priced and easy to implement. Formerly designed as a navigation aid, it has been routinely used for more than fifteen years for horizontal tectonic applications, particularly plate kinematics (e.g. Argus and Heflin, 1995; McClusky et al., 2000). Nonetheless, the accuracy of GPS data in the vertical component is lower. The precision is limited by the receiver and transmitter clock errors, and by disturbances due to the travel of the wave through the non-uniform atmosphere (e.g. see Schaer et al., 1999). In order to overcome these issues and obtain reliable trends of VGM rates, the time series need to be long enough to give consistent trends. At a regional scale, many researchers have used GPS data to determine the interseismic vertical velocity field (e.g., Aoki and Scholz, 2003 in the Japanese islands, Vigny et al., 2005 in southeast Asia, and Ruegg et al., 2009 in Chile). The recent global analysis of Bouin and Wöppelmann (2010) was designed to probe the quality of GPS vertical motion rates in supposedly stable areas by comparing their results to a selection of neighbouring tide gauge records. They gave predictions with GPS observations from 1997 to 2006, on the basis of ~200 permanent stations using the same GPS solutions (ULR3, Wöppelmann et al., 2009), produced by the ULR analysis centre consortium and expressed in the ITRF2005 reference frame. The latest solution called ULR4 (see Santamaría-Gómez et al., 2011) provide longer time series with a maximum of 13 years of observations expressed in the ITRF2005 reference frame too. In order to carry out reliable global studies, it is necessary to have more continuous records, at least decennial. Many time series are now meeting the length requirements and dense networks are spreading. The GPS system is thus on the verge of becoming a fundamental tool to detect VGM at global scale.

2.2. Ground motion from records of sea level variations: discrete studies and mean estimates

As tide gauges measurements integrate ground motion and sea level motion, estimating VGM by combining tide gauges data and an independent evaluation of absolute sea level may seem straightforward. But, because it requires a high level of accuracy in both the tide gauges time series and absolute sea level change at the given locations (Fig. 1), its use remains a serious endeavour.

One common method to calculate the net VGM is to subtract the mean estimate of sea level change from the relative, local, sea level measurements at tide gauges, which presumably only leaves the local net VGM. The strength of this method relies on the possibility to use tide gauges time series of different lengths and to therefore include the longest ones, which are a priori more reliable. However, this is founded on the rather strong assumptions that absolute sea level change is uniform at the Earth's surface and that its variation is constant over time. Satellite altimetry has revealed that both assertions are erroneous to a certain extent (Cazenave et al., 2003), which renders the interpretation of the residual signal uncertain. The subtraction of satellite and tide gauges data was formerly used to compare the results obtained by both devices at reference locations (Chambers et al., 1998; Mitchum, 1998, 2000). The drift of the satellite altimeters was found to be lower than 1 mm/yr (Cheney et al., 1994; Nerem and Mitchum, 2002) for Topex/Poseidon as well as for Jason-1 satellites (Jason's mission; Lafon, 2005).

Bouin and Wöppelmann (2010) used this method in order to compare estimates of VGM, which were independently derived from GPS time series. They opted for an estimate of absolute and uniform sea level change across the 20th century of 1.8 mm/yr. The comparison was established on the basis of a careful selection of 117 long (up to 20 years) and consistent tide gauges time series at presumably stable stations. They extracted tide gauge data from the PSMSL (Permanent Service for Mean Sea Level, Woodworth and Player, 2003) and the annual and monthly sea level mean. They conclude that approximately 84% of the GPS derived estimates are compatible with the tide gauge derived estimates within an error smaller than 2 mm/yr. They assumed that the error introduced by the estimate of the mean absolute sea level was less than the possible errors introduced by the short time of satellite altimetry observations. We discuss this assumption below.

This method has also been applied to regional studies: Larsen et al. (2003) focused on the Alaskan coasts; Aoki and Scholz (2003) and El-Fiky and Kato (2006) worked on Japanese Islands. Similarly, Kuo et al. (2008) quantified the VGM rates in Alaska, the Baltic Sea, as well as hinterland around the North American Great Lakes. Before that, Shum et al. (2002) and Kuo et al. (2004) used long tide gauge records (> 40 years) with a regional average sea level and a decade of Topex/Poseidon (1992–2003) altimeter data. They estimated vertical crustal motions around the Baltic Sea with an improved accuracy when compared to earlier studies (e.g. Nerem and Mitchum, 2002).

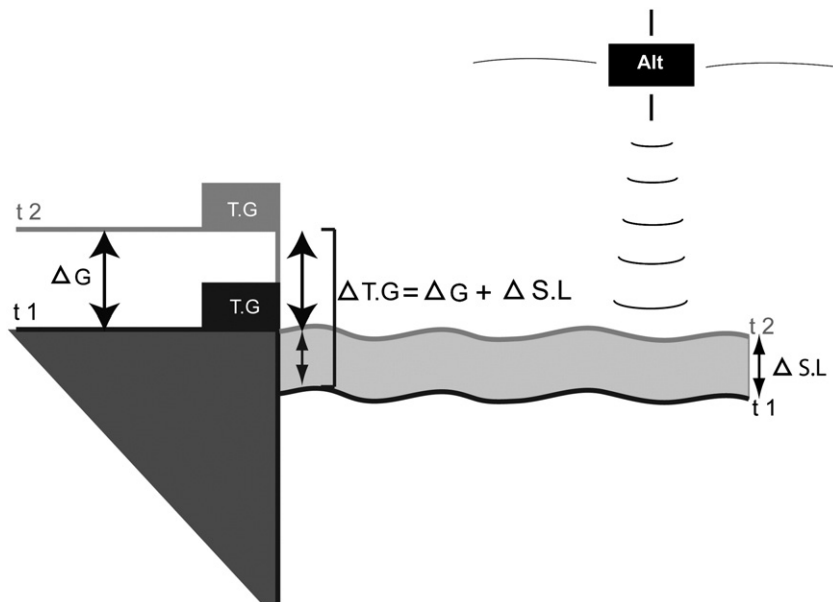


Fig. 1. Relationships between the relative sea level change at tide gauges  $\Delta T.G.$ , absolute sea level change  $\Delta S.L.$  given by satellite altimetry and net ground motion  $\Delta G$ . Alt: altimeters; T.G.: tide gauge.  $t_1$  and  $t_2$  are two different times or record.

As noted earlier, assigning a uniform and constant value to the global sea level rise is debatable. This issue may be overcome by subtracting instead the local sea level change, i.e. the sea level variations at the location of the station, inferred from satellite altimetry from the tide gauge data. The residual signal should presumably correspond to the net ground motion. Satellite altimetry has continuously measured the sea level over the entire surface of the oceans since 1992. The temporal and spatial variations that are being measured appear large enough to preclude any extrapolation. The drawback is that in order to be consistent, the time series from tide gauges that collected data earlier than 1992 need to be cropped according to the period of Topex/Poseidon and Jason satellite records. This implicitly degrades the signal by reducing the time period for which both the satellite altimetry and tide gauge records possibly overlap to a maximum of 18 years, i.e. a short time interval, when considering the uncertainties, gaps and other device related issues. This is at odds with the conclusions of Peltier and Tushingham (1989) and Douglas (1991, 1992, 1997, 2001), who suggest that time series of at least 50 years of records are required to infer reliable trends of sea level variations from tide gauges. In addition, this method requires the use of satellite data close to the coasts, which are possibly noisier than elsewhere because of the wave reflection on the coasts. Furthermore, in order to extract a reliable residual signal that may reveal a tectonic, or more generally, geodynamic process, a good correlation between tide gauges and satellite altimetry signals is desirable. Prandi et al. (2009) showed that coastal sea level records at tide gauges and absolute sea level records from satellite altimetry often present a good correlation within 15 years of recording, but that the correlation degrades within records spanning 10 years or less.

At a worldwide scale, this method was formerly applied by Cazenave et al. (1999), based on the earlier work of Mitchum (1998), which was designed to calibrate the observations from Topex/Poseidon with tide gauge measurements. After a time series of the differences between the two is obtained at each selected tide gauge station, a least mean squares fit is performed to infer the rate of VGM from the temporal derivative. Nerem and Mitchum (2002) used daily mean sea level records from 114 tide gauges and Topex/Poseidon data from 1992 to 2000. The time series are thus 7.5 years on average or shorter. Due to a careful estimate of the margins of error, they obtained results within a maximum accuracy of approximately 1–2 mm/yr. Comparable work was subsequently done by Ray et al. (2010) who compared the tide gauge-derived VGM rates to the rates inferred from the DORIS data, between 1992 and 2009. However, they only considered 28 tide gauges that are geographically close enough to the DORIS stations. This method was also applied to regional studies (see for instance Fenoglio-Marc et al., 2004 and García et al., 2007 for the coasts of the Mediterranean and Black seas).

Thus, despite the multiple sources of bias that can make tide gauge data sometimes, noisy, it has been seemingly proven that this method can provide estimates of trends of VGM rates. Because of the numerous data and their worldwide yet non-uniform distribution, they are promising for global studies.

### *2.3. Ground motion from records of sea level temporal and spatial variations: our global analysis*

Overall, most of the above-described methods are based on a careful selection of the stations. Naturally, the objective is to provide reliable data points, and therefore many stations are rejected. In our approach, we instead opt for the brute force technique and rely on a statistical evaluation of the data set. Because the data set remains almost raw, it has the effect of increasing the number of data points, but none of them are relied upon individually. This is a recurrent issue for geostatistics in general, like for instance, when inverting structural (e.g., Angelier, 1984) or thermal (e.g. Husson et al., 2008) data, for which the choice between the two approaches is driven by the objectives of the study. Our aim is to determine the first order signal at a

global scale. For this purpose, the signal from a large data population with large uncertainties supersedes the interpretation of a smaller but less uncertain data population. We took advantage of the 16-year long spatial altimeter record and rejected a few outliers (see below). Absolute sea level change measurements were extracted from the Topex/Poseidon (1993–2001), Jason-1 (2001–2008) and Jason-2 (2008–2009) records compiled by AVISO ([www.aviso.oceanobs.com](http://www.aviso.oceanobs.com)). Satellite altimetry was corrected for inverse barometer effects (but not tide gauges measurements).

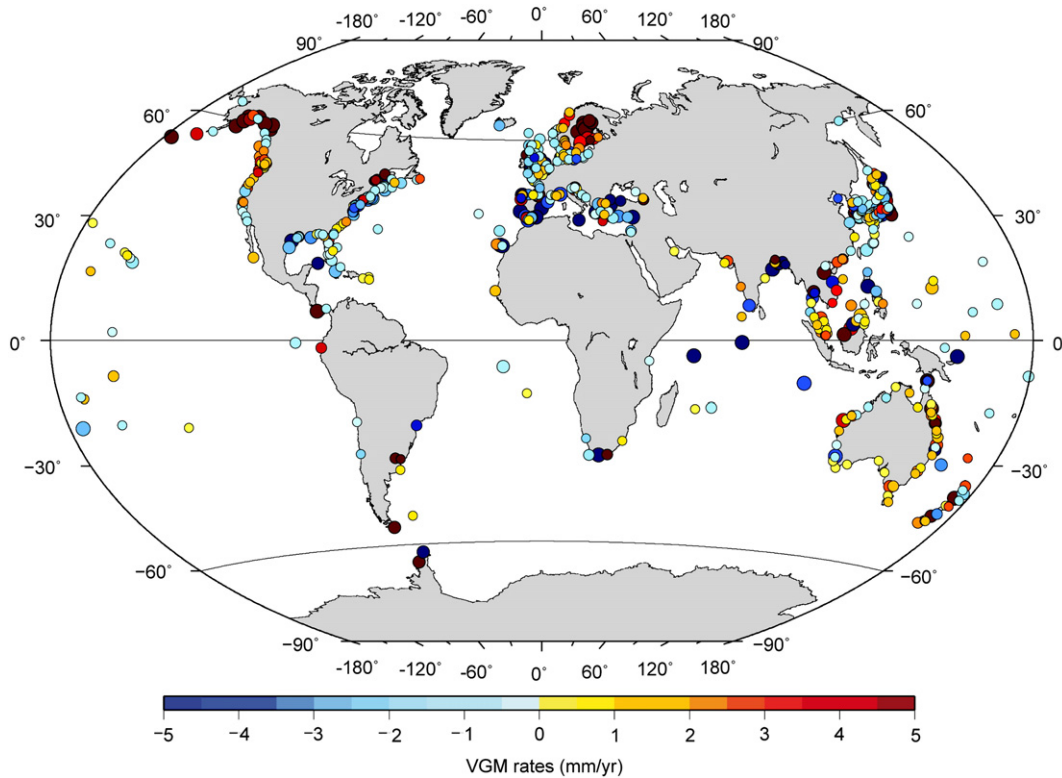
Regarding the direct relative sea level measurements, we took advantage of the yearly mean Revised Local Reference (RLR) compilation of tide gauge records provided by the PSMSL. The stability and reference of the stations are regularly monitored, and the PSMSL informs when major events can severely modify the time series (see [www.psmsl.org](http://www.psmsl.org) for details). The use of yearly means removes the seasonal variations of the sea level in the time series.

First, we only retained the data recorded during 1993–2009, i.e. the common period of spatial altimeter and tide gauge records. Second, we excluded the time series with durations shorter than 5 years because they do not provide reliable sea level trends (Fenoglio-Marc et al., 2004). Because of these time restrictions, the length of the time series therefore varies from 5 to 16 years, with a median of 10 years. Last, because of the orbital inclination of the satellites, the data was mostly available between  $-66$  and  $66^\circ$  of latitude, thereby providing spatial boundaries to the domain where the tide gauge data can be used. These criteria resulted in the retention of 641 stations out of a possible 1240 stations set. AVISO supplies the maps of the monthly means of the sea level height anomalies with respect to a seven-year mean (1993–1999). We first computed the yearly means from those maps. We then equally constructed yearly maps of discrete values for the yearly means at tide gauges. We subtracted the yearly means at the location of tide gauges, in order to retrieve the ground elevation change, and subsequently the time series of VGM. Technically, we extrapolated the maps of absolute sea level change using a tense spline function in order to document sea level change at stations that fell on “continental” cells from the grids. Because of the short distance between the station and the nearest documented cell, it is almost equivalent to assigning the value of the closest documented cell. Lastly, in order to obtain VGM rates, we subsequently fit each VGM time series to obtain linear trends. A quadratic fit was also tested but owing to the scattering, the result was beyond the data resolution, in particular for the short time series (the length of the time series needs to be increased for a larger polynomial degree), and the results were sometimes inconsistent. In short, we computed the linear regressions of the differences between tide gauges measurements and satellite altimetry. We alternatively computed the differences between the linear regressions of satellite altimetry and tide gauges time series. This solution yields very comparable results, but the first option is considered more robust.

## **3. Results at the global scale**

### *3.1. Global analysis of ground motion at tide gauges*

The full results are given in Supplementary data. Fig. 2 shows the trends of vertical ground motion (VGM) in map view. Tide gauges whose records are long enough to be exploited are mainly concentrated in the Northern Hemisphere and only 15% of the data points are located in the southern hemisphere. The quality of the fit ( $R^2$ ) is, however, evenly distributed and no particular area presents a high concentration of low values of  $R^2$ . The VGM rates range from  $-49.76$  to  $34.92$  mm/yr but 84% of the values fall within  $\pm 5$  mm/yr, with an average of  $-0.08$  mm/yr and 52% are positive. A glance at the map (Fig. 2) reveals clear trends for given regions. Indeed, it is possible to clearly identify uplifting regions, such as Fennoscandia, the West coast of North America, Malaysia and the Australian East



**Fig. 2.** Vertical ground motion (VGM) rates calculated in our study based on the difference between the records from satellite altimetry and tide gauge records. The colour scale is bounded to  $\pm 5$  mm/yr but actual values range between  $-53$  and  $35$  mm/yr. The point size varies according to the quality of the fit ( $R^2$  ranging from 0 to 0.95).

coast. We also observe subsidence, e.g. on the coasts of Western Europe (from the British Isles to Iberia), eastern North America, Western Australia and Japan (where some sites are however uplifting).

The latitudinal distribution of the VGM rates (Fig. 3, also including earlier results described below) confirms the predominance of data points in the Northern Hemisphere and shows that the values essentially range between  $-5$  and  $5$  mm/yr. Only seven outliers (out of the range displayed in Fig. 3) exceed  $\pm 20$  mm/yr (their relevance is discussed in Section 3.2). The less blurred trend revealed by the latitudinal dependency of VGM rates is the high uplift rates recorded for the high latitude regions (above  $55^\circ$  N). This feature is associated with the well-identified uplift of Fennoscandia attributed to the GIA in the aftermath of the last glaciation (Farrell and Clark, 1976; Peltier et al., 1978; Lambeck et al., 1998; Spada et al., 2006). Due to a lack of data, it is not possible to make similar observations at high latitudes in the southern hemisphere.

### 3.2. Comparison with other studies

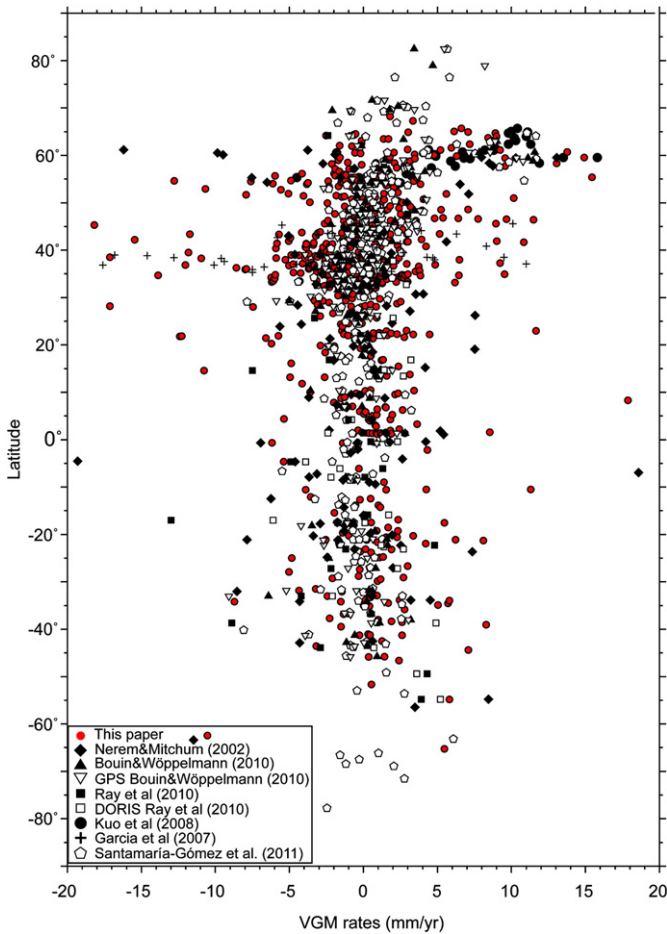
In order to evaluate both the consistency of our strategy and discuss the plausibility of the results of other studies, we compared our results with those from other methods. We focused on the analyses of:

- (1). Nerem and Mitchum (2002), who also evaluated the differences between the absolute and relative sea level change from satellite altimetry and tide gauge records. This earlier study is of course based on a shorter time span (1992–2001) and a shorter database.
- (2). García et al. (2007), whose method is comparable to Nerem and Mitchum's (2002). They used data from approximately the same period but instead focused on the Mediterranean Sea, where Nerem and Mitchum (2002) did not include any data.

- (3). Kuo et al. (2008), who combined the regional mean sea level, tide gauge and altimetry data, and long tide gauge records.
- (4). Ray et al. (2010), who released the latest comparison of DORIS data with estimates of VGM rates derived from satellite altimetry and tide gauge records (from 1992 to 2009) for selected data points.
- (5). Bouin and Wöppelmann (2010), who carried out a study of global accuracy on the basis of GPS data in comparison with estimates of VGM rates inferred from tide gauge records and the mean absolute sea level.
- (6). Santamaría-Gómez et al. (2011) who used the ULR4 GPS database.

Table 1 gives the main characteristics of each study. In the following, GD denotes the studies among those cited above that use geodetic data sets (i.e. Bouin and Wöppelmann, 2010; Ray et al., 2010; Santamaría-Gómez et al., 2011), Alt-TG refer to those combining tide gauges and altimetry measurements, as in the present study (i.e. Nerem and Mitchum, 2002; García et al., 2007; Ray et al., 2010) and MSL-TG indicates studies that use both local sea level and mean sea-level data at tide gauges (i.e. Kuo et al., 2008; Bouin and Wöppelmann, 2010). Note that two studies compare the two methods (Bouin and Wöppelmann, 2010; Ray et al., 2010), and thus belong to two groups. In the following tables, the numbers in *italic* highlight where there are too few data to interpret correctly the average VGM rates.

Again, most of the values of the present-day vertical motions reported by these various studies lie in the  $[-5; 5]$  mm/yr interval (85% of the data, Table 1). The fact that amplitudes are mainly concentrated in this range seems therefore robust. While our results, and to a lesser extent those of Nerem and Mitchum (2002) and García et al. (2007), present outliers, only 10 values (seven among the complete dataset initially considered in our study and three in the other more selective studies) are greater than 20 mm/yr or



**Fig. 3.** Vertical ground motion (VGM) rates as a function of latitude, for the various studies considered.

smaller than  $-20$  mm/yr. Thus, we discard these outliers in the following analysis. Since some of the studies that we considered are regional, their geographical distributions differ. However Fig. 4, which displays the results of the various studies grouped according to the method they correspond to, shows that regardless of the method considered (GD, Alt-TG, MSL-TG), the global characteristics of the geographical distribution (e.g. the higher density of results in the Northern Hemisphere) are similar.

Nerem and Mitchum (2002) present very few data for Europe and Asia compared to our study, but they have more sites on the North American West coast, South America and Africa, whereas Bouin and Wöppelmann (2010) present less data for the North American West

coast and Asia. Each study presents a different distribution in Australia, but only ours has a rich enough database to show a consistent signal. In addition, these results confirm that vertical motions are strongly variable spatially. Therefore, according to the variability of the geographic distribution and the spatial patterns of the VGM, comparing the results from each method according to their overall average would not make sense.

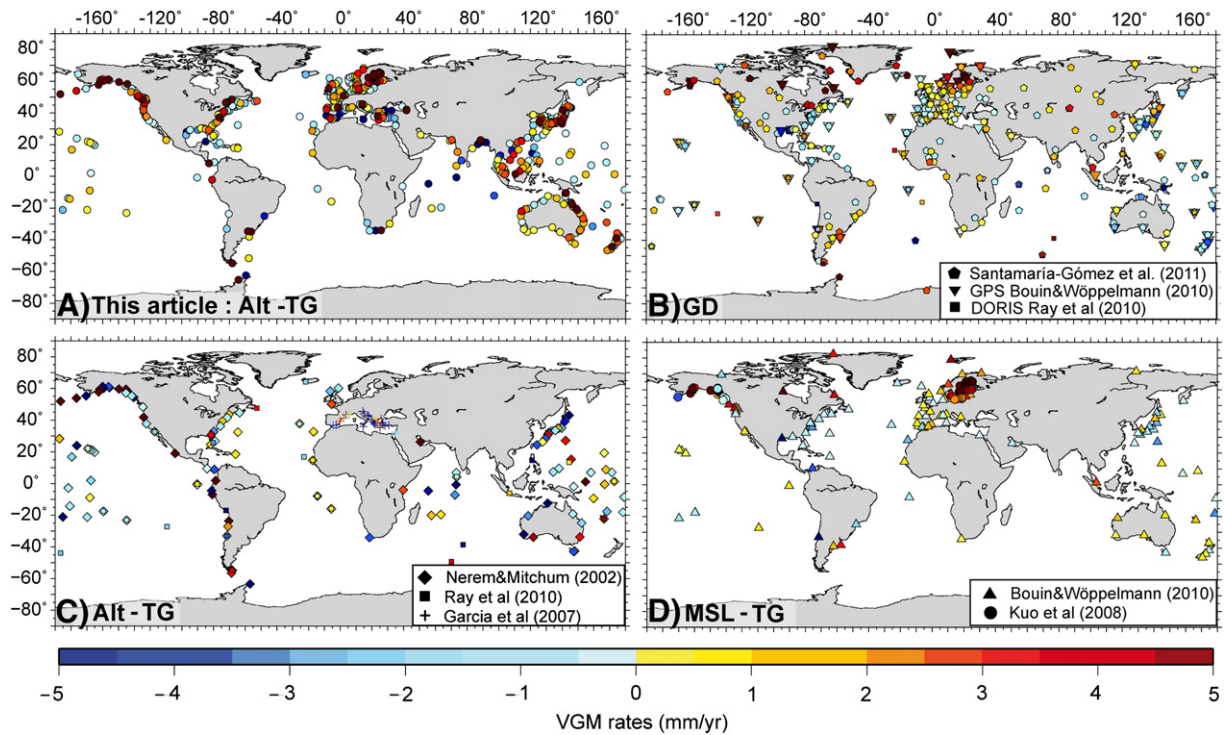
In order to properly compare the results from each method, we focused on the geographical sites that are present in both other studies and ours (Fig. 5). It shows that the use of different calculation methods may result in significant differences in rate estimates at common sites. A first glance at Fig. 5 could lead to the paradoxical conclusion that the best agreement between our study and previous works is obtained for the MSL-TG (Fig. 5C) group (subtracting mean sea-level from local tide gauge records) while the differences observed at common sites between the present work and other studies sharing the same methodology (Alt-TG, Fig. 5B) are obviously larger. Comparison with geodetic data sets (GD, cf. Fig. 5A) does not lead to a good agreement with our results (although the comparison to Fig. 5B and C is more difficult mostly because stations with low rates are represented). GPS data are becoming increasingly popular and it may be tempting to give more credence to their estimate of VGM than to any other technique. However, the careful study of Bouin and Wöppelmann (2010) suggests (i) that only long time series yield satisfying results, and also (ii) that an accuracy of about 1 mm/yr can be expected from GPS. When comparing our results to GPS stations collocated with tide gauges, from the most comprehensive GPS database (ULR4, Santamaría-Gómez et al., 2011), we find that the mean difference is 0.69 mm/yr, i.e. a value smaller than the accuracy of VGM from GPS data (standard deviation is 0.37 mm/yr, Table 2). Note that the departure with the smaller database of Bouin and Wöppelmann (2010) is nevertheless not as good (mean difference of 2.28 mm/yr). The good correspondence between our results and GPS derived VGM from ULR4 suggests the methods are compatible, which is encouraging, but shall not be considered as the ultimate validation of both GPS and tide gauges estimates of VGM rates. These three first-order observations can be further understood when a more detailed comparison is considered (Tables 2, 3, and 4).

It is worth examining first the comparison between studies that subtract absolute global sea level to the tide gauges records (Alt-TG) as done in the present study (c.f. Table 3). The agreement is good (standard deviation  $\sigma$  of about 1.2 mm/yr) with the most recent study of Ray et al. (2010) that used the longest time series. As expected, for twice shorter time series (thus associated to a worse precision of the estimates), the agreement worsens. In the case of the global data set used by Nerem and Mitchum (2002), the standard deviation  $\sigma$  is about 2 mm/yr, although the average difference value is not negligible. The largest disagreement is obtained with the regional study of García et al. (2007): both the standard deviation and the

**Table 1**

Characteristics of all the studies considered, including this work. (1) Nerem and Mitchum (2002); (2) García et al. (2007); (3) Kuo et al. (2008); (4) Ray et al. (2010); (5) Bouin and Wöppelmann (2010) (6) Santamaría-Gómez et al. (2011). The methods refer to altimetry (Alt), tide gauges (TG), DORIS, GPS and the mean sea level (MSL) (see text for further details). The geographical distribution is either regional (R) or worldwide (W). tTG is the length of tide gauge time series; tAlt is the length of altimetry time series; tDORIS is the length of DORIS; tGPS is the length of GPS time series.

|                                              | Our study                  | (1)                           | (2)                         | (3)                   | (4)                  | (5)                                 | (6)                |
|----------------------------------------------|----------------------------|-------------------------------|-----------------------------|-----------------------|----------------------|-------------------------------------|--------------------|
| Method                                       | Alt-TG                     | Alt-TG                        | Alt-TG                      | Alt-TG and MSL        | DORIS Alt-TG         | GPS MSL-TG                          | GPS                |
| Geographical distribution                    | W                          | W                             | R                           | R                     | W                    | W                                   | W                  |
| Number of data                               | 641                        | 114                           | 42                          | 40                    | 28                   | 117                                 | 275                |
| Period (yr)                                  | 1993–2009                  | 1992–2000                     | 1993–2001                   | 1992–2003             | 1992–2009            | 1997–2006                           | 1996–2008          |
| Length of time series (yr)                   | tTG = 5 to 16<br>tAlt = 16 | tTG $\approx$ 7.5<br>tAlt = 8 | tTG $\approx$ 9<br>tAlt = 8 | tTG > 40<br>tAlt = 11 | tTG > 5<br>tAlt = 17 | tTG = 20 to 52<br>tGPS = 1.8 to 9.9 | tGPS = 2.5 to 13.0 |
| Min/Max (mm/yr)                              | –49.76/34.92               | –19.31/34.11                  | –21.3/21.6                  | –4.5/15.8             | –6.1/5.2<br>–13/4.8  | –9.1/10.77<br>–6.42/11.57           | –8.09/11.66        |
| Percentage of data in the [–5;5] mm/yr range | 84%                        | 75%                           | 55%                         | 45%                   | 93%<br>89%           | 91%<br>94%                          | 94%                |

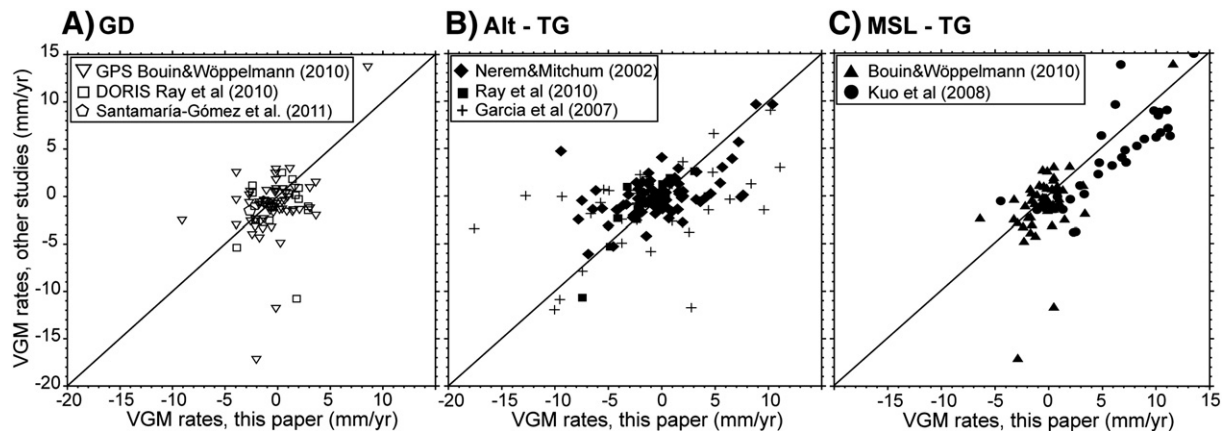


**Fig. 4.** Maps of the vertical ground motion (VGM) rates observed (A) in our study; (B) from geodetic data compiled in Bouin and Wöppelmann (2010), Ray et al. (2010) and Santamaria-Gómez et al. (2011); (C) by subtracting tide gauge data to altimeter data study by Nerem and Mitchum (2002), García et al. (2007) and Ray et al. (2010); (D) by subtracting tide gauge data to an estimate of the mean sea level change, from Kuo et al. (2008) and Bouin and Wöppelmann (2010). The colour scale is bounded to  $\pm 5$  mm/yr but actual values range between  $-20$  and  $20$  mm/yr.

average difference show a poor relationship with our results, as can be seen on Fig. 5B. As noted by Buble et al. (2010) who studied the eastern margin of Adria, biases are likely to be largest for short time series when restricted to geographically limited regions, wherein interannual and decadal variations may be spatially coherent, and thus, do not cancel by forming spatial averages. In conclusion, for common geographical sites, the agreement between our results and the most precise data set obtained with a similar method is good.

When compared to geodetic data (Fig. 5B and Table 2), results of the Alt-TG group are concordant: difference between both this study and Ray et al. (2010), on one side, and the GPS (Bouin and Wöppelmann, 2010) and DORIS (Ray et al., 2010), on the other, present standard deviations between 2 and 3 mm/yr (the few sites in common between tide gauges and GPS-URL4 forbids any definitive

conclusion). Among the MSL-TG group, Bouin and Wöppelmann, 2010, is the only study with a sufficiently large number of sites common with the geodetic measurements. Interestingly, it presents a better agreement with both GPS and DORIS measurements as highlighted by Bouin and Wöppelmann, 2010, for GPS, but the agreement is also very good for DORIS. It surprisingly confirms that the crude assumption of a constant and uniform absolute sea level rise for the 20th century leads to consistent results in the context of their global study. It is difficult to envision another explanation than a fortunate sampling bias for this result. The fact that the agreement is not as excellent when using satellite altimetry measurements for the Alt-TG group could be caused by uncertainties on the choice of the reference frame (see Ray et al., 2010). Whether or not the precision of MSL-TG estimates is higher than the one of Alt-TG estimates,



**Fig. 5.** Comparison of VGM rates calculated in this study to those calculated with (A) geodetic data (GD, Bouin and Wöppelmann, 2010; Ray et al., 2010; Santamaria-Gómez et al., 2011); (B) subtracting tide gauge data to altimeter data (Alt-TG, Nerem and Mitchum, 2002; García et al., 2007; Ray et al., 2010); (C) subtracting tide gauge data to the estimate of mean sea level change (MSL-TG, Kuo et al., 2008; Bouin and Wöppelmann, 2010).

**Table 2**

Comparison of the average differences rates in mm/yr (absolute value) for the common sites between the studies using the Alt-TG and MSL-TG method, with studies of the geodetic data. M.D.: mean difference;  $\sigma$ : standard deviation; Nb: number of sites in common; NV: no value. (1) Bouin and Wöppelmann (2010); (2) Santamaría-Gómez et al. (2011); (3) Ray et al. (2010). The numbers in italics highlight where there are too few data to interpret correctly the average VGM rates.

|                             | GPS (1) |          |     | GPS-ULR4 (2) |          |    | DORIS (3) |          |    |
|-----------------------------|---------|----------|-----|--------------|----------|----|-----------|----------|----|
|                             | M.D.    | $\sigma$ | Nb  | M.D.         | $\sigma$ | Nb | M.D.      | $\sigma$ | Nb |
| Our study                   | 2.28    | 2.65     | 57  | 0.69         | 0.37     | 4  | 2.68      | 3.00     | 14 |
| Nerem and Mitchum (2002)    | 2.34    | 2.65     | 19  | 2.27         | 1.39     | 8  | 1.74      | 1.16     | 13 |
| García et al. (2007)        | 3.93    | 0.16     | 2   | NV           | NV       | NV | NV        | NV       | NV |
| Kuo et al. (2008)           | 1.86    | NV       | 1   | NV           | NV       | NV | NV        | NV       | NV |
| Ray et al. (2010)           | 3.23    | 2.44     | 7   | 0.27         | 0.30     | 3  | 3.38      | 2.94     | 28 |
| Bouin and Wöppelmann (2010) | 1.13    | 1.1      | 117 | 1.31         | 1.06     | 5  | 1.97      | 1.44     | 7  |

a comforting result is that differences between the two data sets are small (Fig. 5C and Table 4): these induce a standard deviation of about 2 mm/yr between our study and both Bouin and Wöppelmann (2010) and Kuo et al. (2008).

It is important to note that the spatial extent and the amount of common sites are different between each study. For example, the common sites between our study and Kuo et al. (2008), for which we obtain a good correlation, are concentrated in Fennoscandia, while there is no common site from this region between our study and Nerem and Mitchum (2002). As we discuss below, it is known that Fennoscandia is uplifting fastly, which is clearly measured regardless of the method used. This could explain why our study correlates better with the MSL-TG group than with the Alt-TG group.

In conclusion, a rigorous assessment of the precision of the various methods is out of the scope of the present study: the works cited above do not belong to same groups of method (GD, Alt-TG, MSL-TG) and they differ also in terms of data selection and the correction they use. Therefore, it is difficult to compare the various studies: two studies focusing on the fast uplifting Fennoscandia would yield a better agreement than studies from more quiet areas, regardless of the technique used. This is simply because of a larger signal to noise ratio. This bias is clear when considering the correlation coefficients between the VGM rates obtained from the different techniques (Table 5): the best correlation is obtained when comparing our results to those of Kuo et al. (2008), who focused on Fennoscandia. Global studies that allow to overcome this bias yield good correlations with our results: Ray et al. (2010), who used a similar methodology than ours, and Santamaría-Gómez et al. (2011), who released the most comprehensive database of GPS-derived VGM rates.

In any case, a simple statistical analysis of the various samples indicates that combining these to produce a global map is reasonable, and that the two data sets involving shorter time-series for the tide gauge records (i.e. Nerem and Mitchum, 2002; García et al., 2007) are not as precise as the remaining values. In the following, we demonstrate that the global data set resulting from the juxtaposition of these various samples exhibit coherent geographic trends and propose a geodynamical analysis for chosen geological settings.

**Table 3**

Comparison of the averages differences rates in mm/yr (absolute value) for the common sites between the studies using the Alt-TG method. M.D.: mean difference;  $\sigma$ : standard deviation; Nb: number of sites in common; NV: no value.

|                          | Our study |          |    | Nerem and Mitchum (2002) |          |     |
|--------------------------|-----------|----------|----|--------------------------|----------|-----|
|                          | M.D.      | $\sigma$ | Nb | M.D.                     | $\sigma$ | Nb  |
| Nerem and Mitchum (2002) | 2.49      | 2.28     | 76 | 0                        | 0        | 114 |
| García et al. (2007)     | 4.20      | 3.90     | 41 | NV                       | NV       | NV  |
| Ray et al. (2010)        | 1.16      | 1.15     | 14 | 2.28                     | 1.55     | 13  |

**Table 4**

Comparison of the average differences rates in mm/yr (absolute value) for the common sites, between the studies using the Alt-TG and MSL-TG method used by Bouin and Wöppelmann (2010) and Kuo et al. (2008). M.D.: mean difference;  $\sigma$ : standard deviation; Nb: number of sites in common; NV: no value. The numbers in italics highlight where there are too few data to interpret correctly the average VGM rates.

|                          | Bouin and Wöppelmann (2010) |          |    | Kuo et al. (2008) |          |    |
|--------------------------|-----------------------------|----------|----|-------------------|----------|----|
|                          | M.D.                        | $\sigma$ | Nb | M.D.              | $\sigma$ | Nb |
| Our study                | 1.85                        | 2.44     | 57 | 2.85              | 1.68     | 29 |
| Nerem and Mitchum (2002) | 2.13                        | 2.59     | 19 | 5.17              | 5.95     | 9  |
| García et al. (2007)     | 5.21                        | 2.17     | 2  | NV                | NV       | NV |
| Ray et al. (2010)        | 2.38                        | 0.97     | 7  | NV                | NV       | NV |

### 3.3. Synthesis

In an attempt to identify the trends observed regardless of the method used, we considered that a signal obtained at several sites in our study was reliable and quantifiable only if a similarly coherent signal was also observed in other studies.

For clarity purposes, Fig. 6 displays the interpolated median of the VGM rates with a spline function with tension (GMT algorithm, Wessel and Smith, 1998) for all data sets (based on a cell size of 3°). The signal is dominated by our database which includes the largest number of measurements. It clearly shows the uplifting trends of Fennoscandia and of the West coast of North America, as well as the subsiding trend in Western Europe and Japan. Between 32° N and 45° N, 64% of the rates have negative values, while sites with latitudes higher than 55° N often present a significant uplift with 74% of positive values. Fig. 6 also displays Clark's zones, with the exception of the sixth zone, which cannot be represented on this map (coastlines). These zones were determined by Clark et al. (1978), based on their modelling of the postglacial rebound effects. Each zone gathers areas that, in theory, display similar vertical motions. A straightforward observation is that the vertical motions observed by all of these studies present significant spatial variations within a given zone. This is discussed with more details in Section 4.

## 4. Results at the regional scale

In order to test if the GIA signal can be detected in the data sets, we investigate individual groups of results corresponding to four major geographical regions: two active margins corresponding to specific geodynamical environments (the west coasts of the Americas and Asia), and two passive margins (the coasts of eastern America and Europe/Africa). In particular, because GIA is presumably the dominant process, we systematically explore the latitudinal dependency of ground motion.

### 4.1. Western American coasts

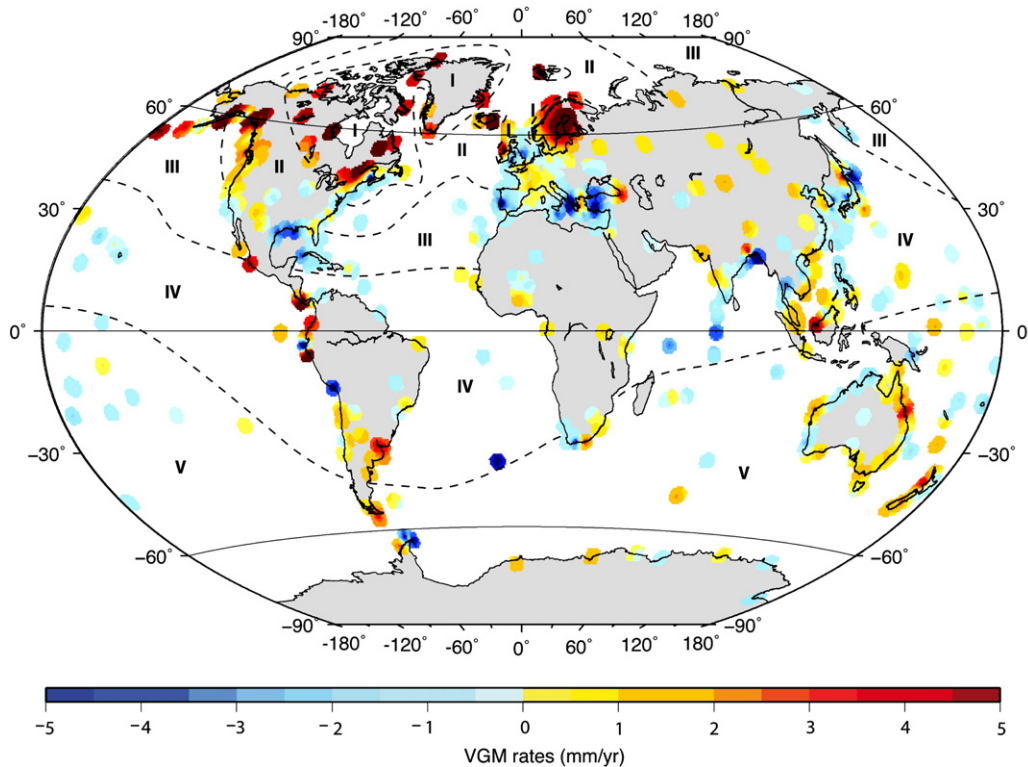
As few sites have been studied in South America, it is difficult to draw any conclusion. However, the tide gauge site in Valparaiso

**Table 5**

Correlation coefficient between our study and Nerem and Mitchum (2002); García et al. (2007); Kuo et al. (2008); Ray et al. (2010) (DORIS and ALT-TG); Bouin and Wöppelmann (2010) (GPS and MSL-TG); Santamaría-Gómez et al. (2011). Nb: Number of common sites.

| Our study vs.                           | Correlation coefficient | Nb |
|-----------------------------------------|-------------------------|----|
| Nerem and Mitchum (2002)                | 0.55                    | 76 |
| García et al. (2007)                    | 0.45                    | 41 |
| Kuo et al. (2008)                       | 0.81                    | 29 |
| DORIS Ray et al. (2010)                 | 0.08                    | 14 |
| ALT-TG Ray et al. (2010)                | 0.88                    | 14 |
| GPS Bouin and Wöppelmann (2010)         | 0.40                    | 57 |
| MSL-TG Bouin and Wöppelmann (2010)      | 0.57                    | 57 |
| GPS-ULR4 Santamaría-Gómez et al. (2011) | 0.64                    | 4  |





**Fig. 6.** Interpolated median of the vertical ground motion rates for all studies: our study; Bouin and Wöppelmann (2010); Ray et al. (2010); Nerem and Mitchum (2002); García et al. (2007); Kuo et al. (2008); Santamaría-Gómez et al. (2011). The colour scale is bounded to  $\pm 5$  mm/yr but actual values range between  $-20$  and  $20$  mm/yr. The dashed lines correspond to the limits of the five seminal Clark's zones (the 6th Clark's zone, superimposed on some coastlines is not represented).

(V on Fig. 7) has been included in several studies that consistently indicate subsidence from  $-9.1$  mm/yr to  $-2.1$  mm/yr (our study, both GPS and sea level data of Bouin and Wöppelmann, 2010 and both DORIS and sea level data of Ray et al., 2010), with the exception of the study of Nerem and Mitchum (2002) (probably less precise due to shorter time series), which found an uplift of  $0.59$  mm/yr but with a total error of  $2.26$  mm/yr.

VGM are more homogeneous in North America than in Central or South America. All studies indicate a net uplift of the sites between  $41^\circ$  to  $60^\circ$  of latitude (Fig. 7). In fact, 75% of the values are positive and the amplitudes are higher for the sites that are located further North, as highlighted by the median curve (Fig. 7B).

In Alaska (from  $53^\circ$  to  $63^\circ$ ), we observe areas of high uplift with a maximum of  $15.8$  mm/yr, but also high subsidence with a maximum of  $-16.19$  mm/yr. Average values are given in Table 6. 67% of the data set corresponds to positive values. Similarly, average VGM rates for each study are all positive. While uplift clearly dominates in this region, the standard deviations show that the values are very sparse, which precludes the conclusion of a uniform uplift for all Alaskan coasts. In fact, some of the sites display significant subsidence rates, such as Sandpoint (Sa on the map), for which we obtain a subsidence of  $-0.56$  mm/yr. This is in agreement with Nerem and Mitchum (2002) and Kuo et al. (2008) who also observed subsidence but at higher rates ( $-7.54$  mm/yr and  $-4.5$  mm/yr, respectively).

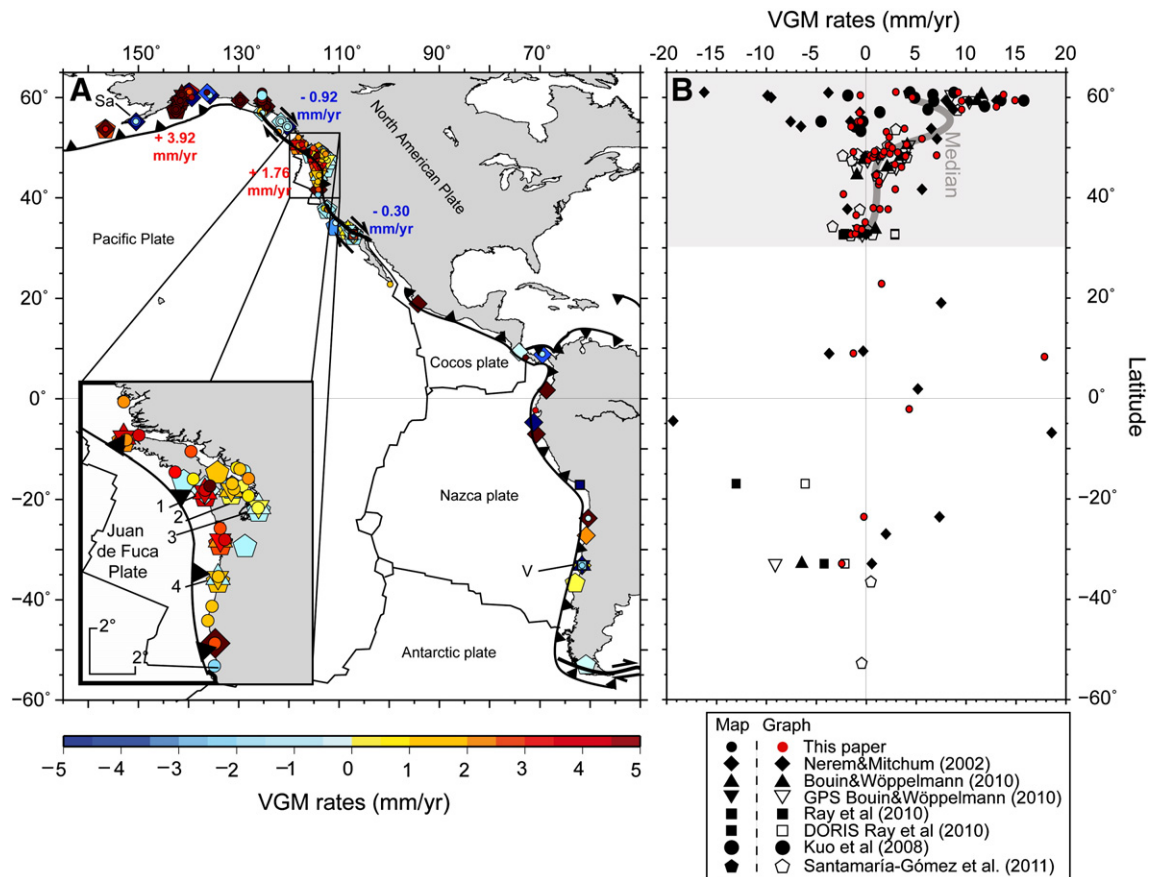
In the Cascadia subduction zone ( $41^\circ$ – $52^\circ$ ), all of VGM rates range from  $-2.33$  to  $9.4$  mm/yr. Average values are compiled in Table 6. The results of each study are largely consistent as suggested by the low standard deviations, and show a mean uplift rate of approximately  $2$  mm/yr. Only the data from Santamaría-Gómez et al. (2011) have an average uplift rate that is lower than the others. The inset in Fig. 7A showing this region in more details indicates four sites (labels 1 to 4, Fig. 7) where disagreement is observed among the methods. Note that, while some sites correspond to a significant discrepancy (e.g.

site 1: Nerem and Mitchum, 2002 report a slightly negative value, while other studies observed uplift near this sites), other probably fall within the precision of the methods (e.g. sites 2, 3, 4).

Overall, the northwestern American coast is clearly uplifting (approximately  $2$  mm/yr for the Cascadia region) and we observed a latitudinal signal causing a progressive increase in VGM rates for the sites located between  $40^\circ$  and  $60^\circ$  of latitude, but also with local subsidence. This will be discussed below.

#### 4.2. Eastern American coasts

For the East coast of North America, we only display sites on the Atlantic coast (the case of the Gulf of Mexico is discussed in the conclusion). VGM rates are heterogeneous in the North, ( $30^\circ$  N to  $50^\circ$  N, Eastern North America). Values range from  $-4.87$  to  $9.24$  mm/yr for all of the data (in our study, there is only one outlier site with a rate of  $-18.17$  mm/yr). The amplitude of VGM is quite low compared to that of the West coast of North America. The average rates obtained in this region by various studies are grouped in Table 6. In any case, subsidence dominates (78% of all the data are negative). For most studies, including ours, standard deviations are high compared to the average values and the results are heterogeneous. The dominant trend seems to show subsidence (possibly with a latitudinally decreasing rate for sites north of  $35^\circ$  N, see median curve on Fig. 8B), but it is still difficult to identify a clear trend because results of various studies can be contradictory. Most of the magnitudes of vertical motion are small, which implies that the differences in the methods used might have a greater impact on the coherency of the results. This is also the case for Central America (from  $15^\circ$  N to  $30^\circ$  N), where the rates are close to  $0$  mm/yr. The majority of the sites in Eastern South America ( $25^\circ$  S to  $60^\circ$  S) are positive (90% of data). The uplift is more significant for sites located in the southern part. Thus, for the American East coast, we chiefly observe weak vertical



**Fig. 7.** VGM rates for the western American coasts. A), Map view, V is the Valparaiso station, Sa is the Sandstone station, rates values are the mean values (from all the studies) for the transform (blue) and subduction (red) plate boundaries; B), as a function of latitude.

subsidence along the eastern coast of North America while the Atlantic coast of South America seems to be dominated by uplift.

#### 4.3. Europe and Africa

There are many sites in Europe compared to Africa, where only three sites are usable. As shown in the map a) and chart b) (on Fig. 9), the sites above 55° N stand out with a significant and progressive uplift, reaching a maximum at the sites located at 65° N. This is clearly shown by the median curve on the chart. We thus distinguished three regions: Fennoscandia, Western Europe and the Mediterranean Sea (Fig. 10).

In Fennoscandia (Northern Europe), the values range from  $-12.78$  to  $11.3$  mm/yr. Average VGM rates in this region are compiled in Table 6. 82% of the values are positive, reflecting the well-known massive uplift that dominates this region. Prominent uplift is focused around the Baltic Sea and is observed by all studies, with similar amplitudes of approximately 8 mm/yr on average. Uplift rates decrease further North in Lapland, within the polar circle. The average rate from Kuo et al. (2008) is higher than in other studies; this is due to the fact that their data were concentrated around the Baltic Sea, where uplift is the highest. The standard deviation is higher in our study than in other studies. This is due to the geographical distribution of our data. In fact, our sites are geographically scattered and not only record the strong uplift around the Baltic Sea but also the lower vertical motion in the South and West.

In Western Europe (from 60° to 35° of latitude), the values range from  $-17.12$  to  $15.44$  mm/yr. The average VGM rates are grouped in Table 6. It shows that only our results and those of Santamaría-Gómez et al. (2011) display an average subsidence rate (with different magnitude). Although paradoxical at first, this difference is largely caused by the geographical distribution of indicators used in

previous studies. For example, Kuo et al. (2008) record significant uplift on average, mostly because the sites they consider are located between 54° and 55° N, on the edge of the fast uplifting Fennoscandia. We also observe uplift in this specific region. In fact, in Western Europe, our study regroups much more data than the other studies and those are better distributed along the coasts. An important result from our study, absent from earlier works, is the global subsidence of the British Isles (average of  $-1.58$  mm/yr from our dataset, Fig. 9).

In the Mediterranean Sea (Fig. 10), subsidence dominates in the eastern part of the Mediterranean Sea, with 58% of all of the values being negative, whereas the western part shows VGM rates near 0 mm/yr with no predominant tendency.

There is not enough data to extract trends in Africa (Fig. 9). However, our study and Nerem and Mitchum (2002), Bouin and Wöppelmann (2010) and Ray et al. (2010) observed uplift rates ranging from 0.7 to 1.96 mm/yr for one site, Dakar (D on the map), which appears to be a good estimate. Results are contrasted for the Simons Bay site (SB on the map). Nerem and Mitchum (2002) shows subsidence, while other studies (i.e. Santamaría-Gómez et al. (2011) as well as Bouin and Wöppelmann (2010) using both sea level and GPS observations) report a rate close to zero. Our value is intermediate. These two exemplary sites indicate what can be considered as the typical uncertainty value (about 2 mm/yr) in our synthetic approach. Note that in regions where the records are not so sparse, the geographical coherence of some trends tends to visually overcome this uncertainty.

#### 4.4. Japan

The observed rates for Japan range from  $-15.46$  to  $9.54$  mm/yr. Average VGM rates are grouped in Table 6. 65% of the overall results

**Table 6**  
Average rates in mm/yr for Alaska, Cascadia, the eastern North America, Fennoscandia, Western Europe, Japan, and Australia.  $\sigma$ : standard deviation. NV: no value. The numbers in italics highlight where there are too few data to interpret correctly the average VGM rates.

| Areas                 | Studies                                 | Mean rates | $\sigma$ | Number of data |      |    |    |
|-----------------------|-----------------------------------------|------------|----------|----------------|------|----|----|
| Alaska                | This paper                              | 5.32       | 5.67     | 16             |      |    |    |
|                       | Nerem and Mitchum (2002)                | 0.45       | 9.04     | 15             |      |    |    |
|                       | MSL-TG Bouin and Wöppelmann (2010)      | 11.34      | 0.33     | 2              |      |    |    |
|                       | GPS Bouin and Wöppelmann (2010)         | 9.45       | 1.26     | 2              |      |    |    |
|                       | Kuo et al. (2008)                       | 4.40       | 6.00     | 15             |      |    |    |
| Cascadia              | GPS-ULR4 Santamaría-Gómez et al. (2011) | 5.65       | 4.28     | 5              |      |    |    |
|                       | This paper                              | 2.07       | 1.69     | 23             |      |    |    |
|                       | Nerem and Mitchum (2002)                | 2.77       | 4.01     | 2              |      |    |    |
|                       | MSL-TG Bouin and Wöppelmann (2010)      | 1.62       | 2.0      | 6              |      |    |    |
| Eastern North America | GPS-ULR4 Santamaría-Gómez et al. (2011) | 0.56       | 1.99     | 10             |      |    |    |
|                       | This paper                              | -1.56      | 3.48     | 46             |      |    |    |
|                       | Nerem and Mitchum (2002)                | 0.11       | 2.28     | 7              |      |    |    |
|                       | MSL-TG Bouin and Wöppelmann (2010)      | -1.29      | 0.88     | 12             |      |    |    |
|                       | GPS Bouin and Wöppelmann (2010)         | -0.93      | 1.45     | 12             |      |    |    |
|                       | Alt-TG Ray et al. (2010)                | 3.00       | 0        | 1              |      |    |    |
|                       | DORIS Ray et al. (2010)                 | 0.4        | 0        | 1              |      |    |    |
|                       | GPS-ULR4 Santamaría-Gómez et al. (2011) | -1.18      | 1.15     | 19             |      |    |    |
| Fennoscandia          | This paper                              | 1.60       | 3.71     | 64             |      |    |    |
|                       | MSL-TG Bouin and Wöppelmann (2010)      | 3.21       | 2.71     | 11             |      |    |    |
|                       | GPS Bouin and Wöppelmann (2010)         | 3.59       | 2.43     | 11             |      |    |    |
|                       | Kuo et al. (2008)                       | 6.69       | 3.52     | 25             |      |    |    |
|                       | GPS-ULR4 Santamaría-Gómez et al. (2011) | 3.51       | 3.04     | 16             |      |    |    |
| Western North Europe  | This paper                              | -1.21      | 4.36     | 69             |      |    |    |
|                       | Nerem and Mitchum (2002)                | 0.11       | 4.00     | 2              |      |    |    |
|                       | MSL-TG Bouin and Wöppelmann (2010)      | 0.04       | 0.9      | 11             |      |    |    |
|                       | GPS Bouin and Wöppelmann (2010)         | 0.05       | 0.74     | 11             |      |    |    |
|                       | Kuo et al. (2008)                       | 1.78       | 0.71     | 5              |      |    |    |
|                       | GPS-ULR4 Santamaría-Gómez et al. (2011) | -0.14      | 0.81     | 13             |      |    |    |
|                       |                                         | W          | E        | W              | E    | W  | E  |
| Japan                 | This paper                              | -0.84      | -0.96    | 3.52           | 3.76 | 35 | 51 |
|                       | Nerem and Mitchum (2002)                | NV         | -1.35    | NV             | 3.27 | NV | 7  |
|                       | MSL-TG Bouin and Wöppelmann (2010)      | -0.20      | -1.96    | 1.82           | 0.70 | 6  | 4  |
|                       | GPS Bouin and Wöppelmann (2010)         | 0.58       | -2.60    | 2.37           | 0.96 | 6  | 4  |
|                       | GPS-ULR4 Santamaría-Gómez et al. (2011) | -0.05      | -1.59    | 1.63           | 2.26 | 6  | 4  |
| Australia             | This paper                              | -0.12      | 2.19     | 1.84           | 2.96 | 17 | 28 |
|                       | Nerem and Mitchum (2002)                | -3.41      | -0.84    | 5.69           | 2.88 | 4  | 5  |
|                       | MSL-TG Bouin and Wöppelmann (2010)      | 0.85       | -0.19    | 0.64           | 1.36 | 3  | 2  |
|                       | GPS Bouin and Wöppelmann (2010)         | -1.68      | -0.05    | 3.11           | 0.13 | 3  | 2  |
|                       | GPS-ULR4 Santamaría-Gómez et al. (2011) | -1.74      | -0.14    | 1.24           | 0.50 | 6  | 3  |

show negative rates. Thus, subsidence seems to dominate the Japanese coast. However, vertical motion rates are not uniform and we can distinguish two regions subject to uplift. The region on the northwestern part, between Hokkaido and Honshu, shows uplift rates until 4.38 mm/yr, as observed in our study, those of Bouin and Wöppelmann (2010) and Santamaría-Gómez et al. (2011). The uplift was also observed by the GPS and tide gauges observations of Aoki and Scholz (2003) and El-Fiky and Kato (2006), but with a higher magnitude of approximately 6 mm/yr. Similarly, we observe uplift until 3.7 mm/yr in the region on the southeastern part, between Shikoku and Kyushu. This is also showed in Aoki and Scholz (2003) and El-Fiky and Kato (2006) but also at higher rates, approximately 6 mm/yr. Thus, for this region, there is no obvious latitudinal dependency of the signal. However, we distinguish different VGM rates between the western and eastern coasts. The East part presents higher rates of subsidence, with an average of  $-1.18$  mm/yr and 69% of the results show negative rates. The West part presents an average of  $-0.52$  mm/yr and 60% of the results show negative rates. Furthermore, an eastward tilt is highlighted on Fig. 11, on both the map and the chart with the median curves. All sources suggest uplift of the northwestern region and rapid subsidence of the northeastern region. For the South, median curves indicate subsidence in the West and, to a lesser extent, in the East, although median values attenuate the signal and do not allow distinguishing the uplift of the southeastern region as well as the strong subsidence near the transform fault. This complex signal is further discussed in Section 5.3.

#### 4.5. Australia

VGM rates for Australia are ranging from  $-8.54$  to  $11.31$  mm/yr. We distinguish clearly contrasting signals between the East and West coasts, as showed on Fig. 12 by the median curves. The western part is neutral to slightly subsident with an average of  $-0.74$  mm/yr and 49% of the results show negative rates. Conversely, the Australian east coast is dominated by uplift at an average rate of  $1.40$  mm/yr; 76% of the results show positive rates. Average VGM rates are compiled in Table 6. All studies present average subsidence rates for the West coast except Bouin and Wöppelmann (2010) (MSL-TG). As for the East, only our study indicates an average uplift rate. This discrepancy might be caused by the lower number of data considered in other studies that might thus be less representative.

### 5. Discussion

#### 5.1. Summary of the main trends

Our study reveals a non-exhaustive list of long wavelength patterns of vertical ground motion (VGM) that includes some robust features (Figs. 2 and 6): (i) uplift along the western coast of North America that increases from almost 0 mm/yr in Mexico to more than 10 mm/yr in Alaska; (ii) subsidence along the eastern coast of North America at about  $-1.5$  mm/yr (possibly showing a decreasing trend from about  $-3$  mm/yr in North Carolina to null in Gaspésie);

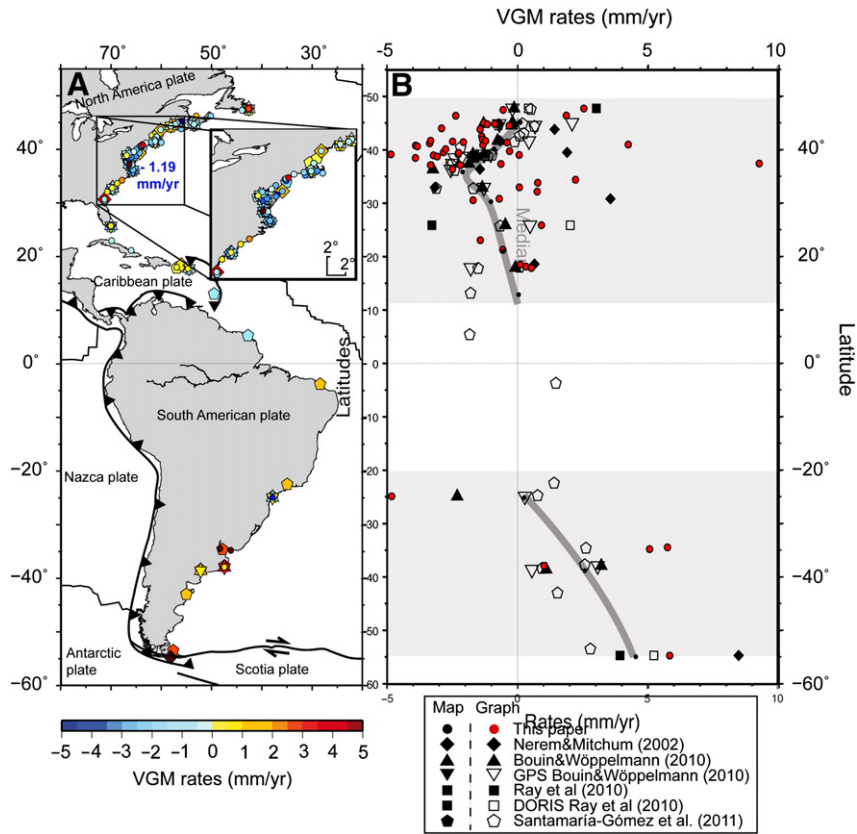


Fig. 8. VGM rates for the eastern American coasts. A), Map view, rates value is the mean value (from all the studies) for the northeastern America; B), as a function of latitude.

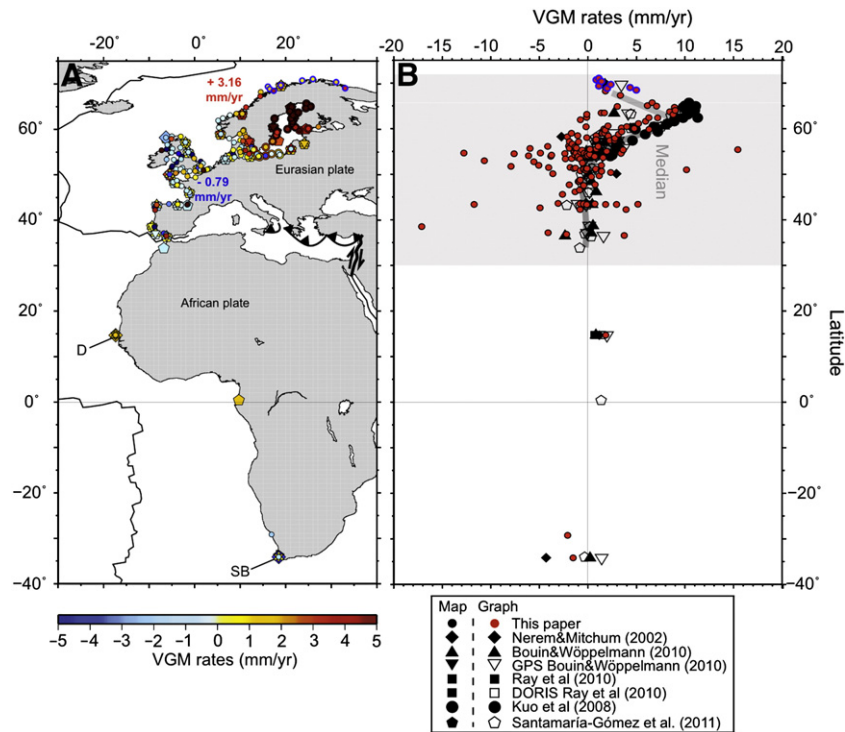


Fig. 9. VGM rates for the European and African coasts. A), Map view, D is the Dakar station, SB is the Simons Bay station, rates values are the mean values (from all the studies) for Fennoscandia (red) and the Western Europe (blue); B), as a function of latitude. Blue contoured data in Fennoscandia is VGM computed at tide gauge stations where the satellite altimetry record is incomplete (not included in the rest of the study).

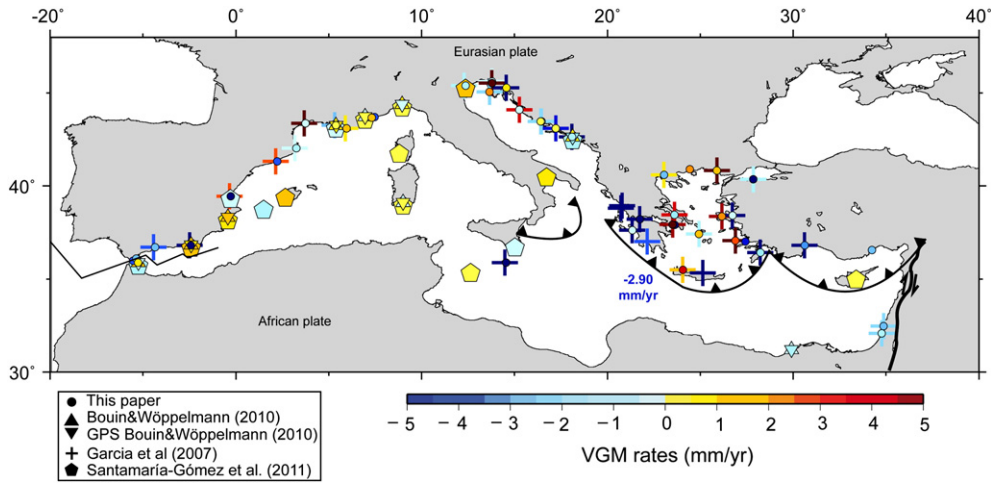


Fig. 10. VGM rates around the Mediterranean Sea, rates value is the mean value (from all the studies) for the subduction (blue) plate boundaries.

(iii) uplift in Fennoscandia, dramatically increasing from zero South of the Peninsula to more than 10 mm/yr in the North of the Baltic sea; (iv) subsidence in the British Isles (often faster than  $-5$  mm/yr) and the coasts of western continental Europe (at rates lower than  $-3$  mm/yr); (v) subsidence in the eastern Mediterranean (vi) dominantly subsidence in Japan (up to  $-10$  mm/yr, with a large standard deviation); (vii) uplift of the eastern coast of Australia ( $-1.5$  mm/yr); (viii) subsidence of the western coast of Australia ( $-1$  mm/yr).

5.2. Observed ground motion and the GIA

These geographical tendencies for VGM rates can be compared to the processes thought to be responsible for ground motion. Among these, the Glacio Isostatic Adjustment (GIA), since it involves mantle

processes, is known to lead to a surface expression occurring at wavelengths that should not be shorter than, typically, the thickness of the lithosphere. The presumed characteristic time scale is rather short and vertical velocities are fast. It is therefore a viable candidate to explain the global trends that appeared consistently in the above comparisons of the various data sets.

GIA, which reflects the response of the crust to the establishment or melting of the ice mass is well understood. The sea level equation presented by Farrell and Clark (1976) can in theory be used to evaluate the feedback effects of ice, seawater, the mantle and lithosphere on ground elevation. However, some parameters that govern the GIA, such as the extent and thickness of the ice sheet, the thickness of the elastic lithosphere and the radial rheological structure of the mantle are poorly known and difficult to constrain. In addition, the

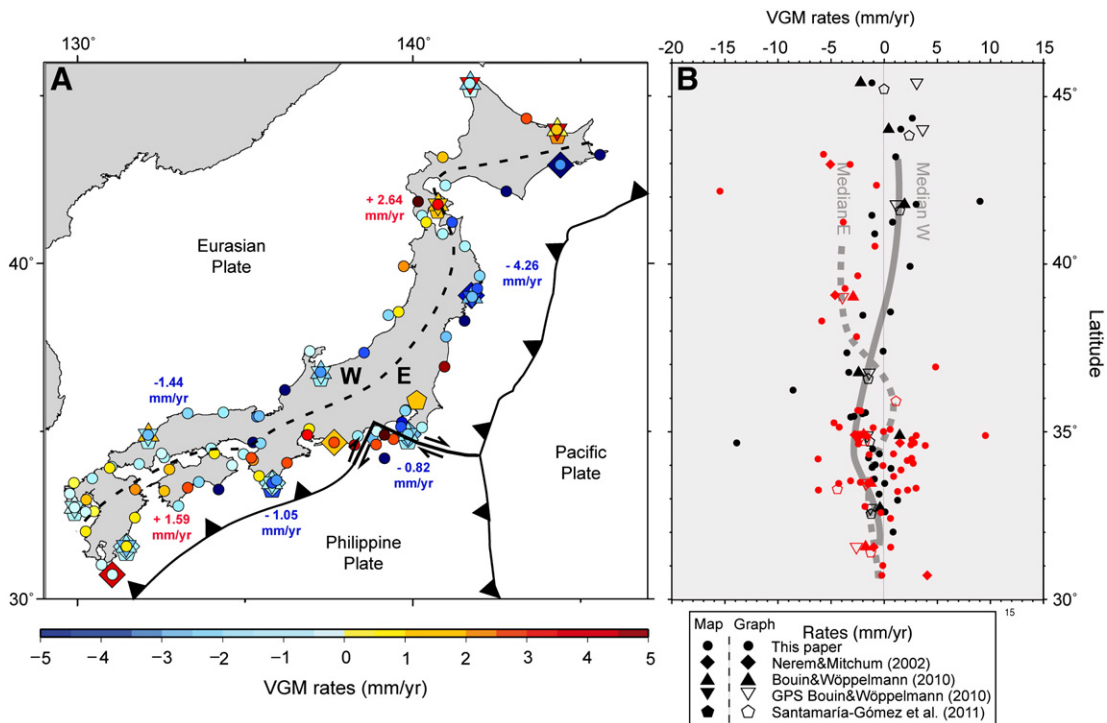
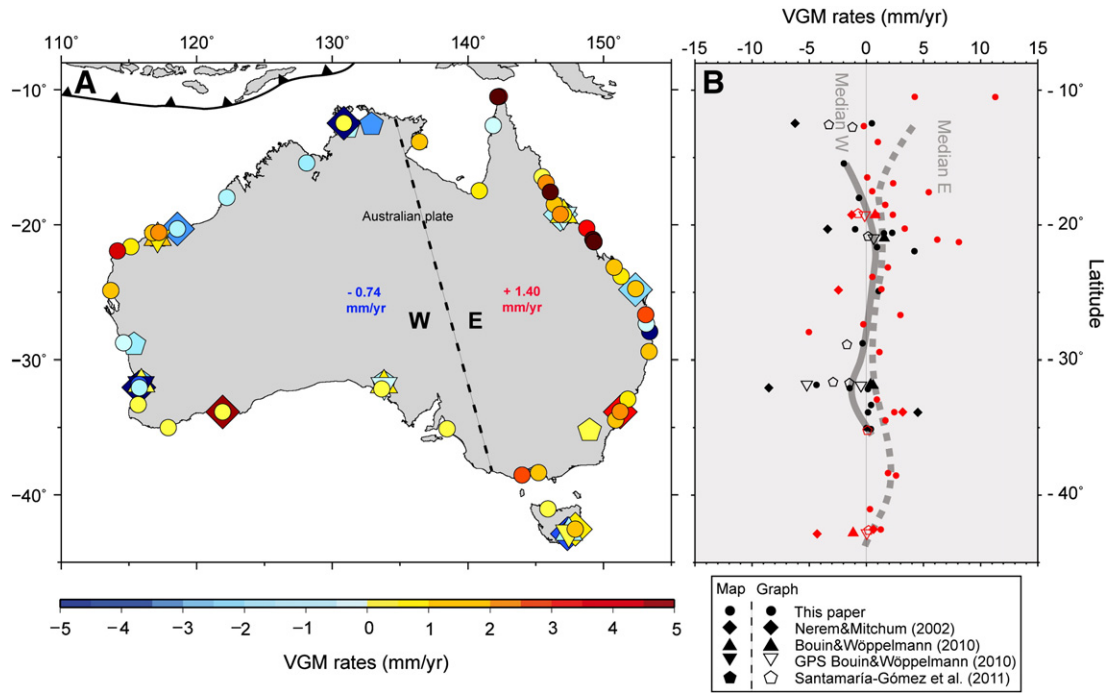


Fig. 11. VGM rates for the coasts of Japan. A), Map view, rates values are the mean values (from all the studies) for the Pacific subduction (blue), the eastern part between Hokkaido and Honshu (red), the transform (blue) boundary, the eastern part Philippine subduction (red and blue) and the western part (blue); B), As a function of latitude.



**Fig. 12.** VGM rates for the coasts of Australia. A), map view, rates values are the mean values (from all the studies) for the western part (blue) and the eastern part (red); B), as a function of latitude.

modelling technique generally calls for the Green function that, although elegant, does not account for lateral viscosity variations. These restrictions in knowledge and modelling have a significant impact on the predictions of the GIA. Our results and those of previous studies are much more spatially variable than predictions of Clark et al. (1978) for the six Clark's zones. Table 7, which regroups for each study the average VGM rates into the six Clark's zones, highlights the departure of the former predictions of Clark et al. (1978) from the observations. In fact, only the trends associated with zones I, IV and V are globally in agreement with tide gauge observations. Furthermore, VGM rates are not homogeneous in each zone with standard deviations larger than 3 mm/yr (see Table 7). An emblematic example of discrepancy is the British Isles. Clark et al. (1978) included this region in zone I which is associated to the strong uplift resulting from the melting of the ice sheets, as in the Fennoscandia or Laurentide regions. Our data set, however, shows subsidence for the totality of the British Isles. As Peltier's (2004) ICE-5G (VM2) model inherited from the pioneering division of Clark et al. (1978)

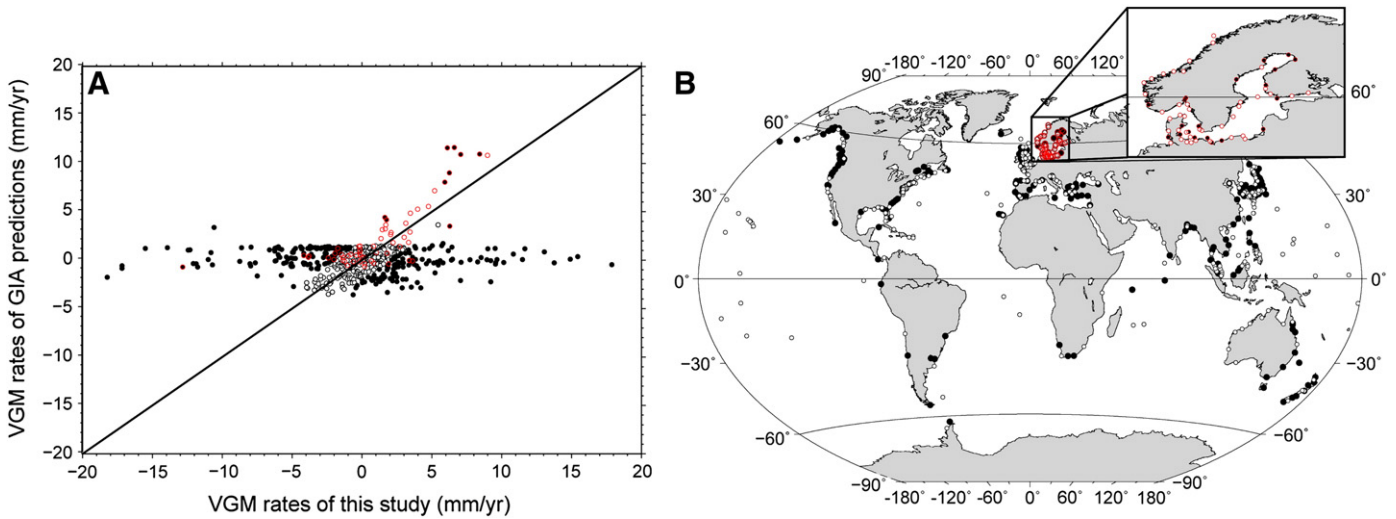
(although the model has evolved since) differences can be expected between global observations and model predictions.

ICE-5G provides estimates for VGM rates resulting from the melting of the ice cap at high latitudes since 21,000 years ago. This model is constrained and calibrated by the most important observation on the deglaciation history, i.e. the evolution of relative sea level history at the continental margins since this last glacial maximum as recorded by Holocene palaeo coast (e.g. marine terraces, beach ridges). We directly compare our results with the ICE-5G (VM2) predictions at each tide gauge (PSMSL) location (available courtesy of W.R. Peltier at: [http://www.atmos.physics.utoronto.ca/peltier/data.php]). The model estimates range from  $-3.6$  to  $13.7$  mm/yr, with 87% values between  $-2$  and  $2$  mm/yr. For the same sites, our results range between  $-20$  and  $20$  mm/yr with 84% between  $-5$  and  $5$  mm/yr. There is an average difference of  $2.77$  mm/yr between Peltier's (2004) predictions and our results, with a standard deviation of  $3.01$  mm/yr for 634 data points. Fig. 13 indeed shows a contrasting agreement: for sites located at  $55^\circ$  of latitude and higher, the

**Table 7**

Average rates in mm/yr by (1) Nerem and Mitchum (2002); (2) García et al. (2007); (3) Kuo et al. (2008); (4) Ray et al. (2010) (Alt-TG and DORIS); (5) Bouin and Wöppelmann (2010) (MSL-TG and GPS) and (6) Santamaría-Gómez et al. (2011) (GPS-ULR4) into each 6 Clark's zones (Clark et al., 1978). M: mean rates;  $\sigma$ : standard deviation; Nb: number of data. The numbers in *italics* highlight where there are too few data to interpret correctly the average VGM rates.

|         | Our study |          |     | (1)   |          |    | (2)   |          |    | (3)  |          |    | (4)   |          |      | (5)   |          |      | (6)   |          |     |    |
|---------|-----------|----------|-----|-------|----------|----|-------|----------|----|------|----------|----|-------|----------|------|-------|----------|------|-------|----------|-----|----|
|         | M         | $\sigma$ | Nb  | M     | $\sigma$ | Nb | M     | $\sigma$ | Nb | M    | $\sigma$ | Nb | M     | $\sigma$ | Nb   | M     | $\sigma$ | Nb   | M     | $\sigma$ | Nb  |    |
| I (++)  | 0.31      | 4.29     | 136 | 0.35  | 2.09     | 6  | NV    | NV       | NV | 6.69 | 3.52     | 25 | -2.4  | 0        | 1    | 2.38  | 3.31     | 23   | 2.88  | 3.42     | 47  |    |
| II (-)  | 0.84      | 4.89     | 80  | 0.13  | 7.46     | 20 | NV    | NV       | NV | 5.48 | 5.62     | 14 | -0.8  | 0        | 1    | 3.02  | 3.24     | 23   | 0.33  | 2.9      | 40  |    |
| III (+) | -1.04     | 3.94     | 110 | 1.7   | 4.59     | 10 | -2.11 | 7.01     | 40 | -4.5 | 0        | 1  | 0.4   | 0        | 1    | 0.73  | 3.35     | 23   | -0.45 | 1.64     | 60  |    |
| IV (-)  | -0.33     | 3.75     | 222 | -0.39 | 5.19     | 45 | NV    | NV       | NV | NV   | NV       | NV | 2.45  | 2.45     | 0.52 | 4     | -0.69    | 1.68 | 25    | -0.1     | 1.9 | 60 |
| V (++)  | 0.79      | 3.21     | 86  | -0.88 | 4.09     | 32 | NV    | NV       | NV | NV   | NV       | NV | -2.55 | 4.23     | 12   | -0.58 | 2.1      | 28   | -0.32 | 2.15     | 52  |    |
| VI (+)  | -0.32     | 3.90     | 368 | -0.27 | 6.02     | 45 | -2.11 | 7.01     | 45 | -4.5 | 0        | 1  | -0.07 | 2.93     | 12   | -0.31 | 2.55     | 28   | -0.12 | 2.06     | 109 |    |
|         |           |          |     |       |          |    |       |          |    |      |          |    | 1.67  | 2.56     | 10   | -1.36 | 1.74     | 18   |       |          |     |    |
|         |           |          |     |       |          |    |       |          |    |      |          |    | -2.94 | 5.04     | 9    | -0.25 | 1.8      | 51   |       |          |     |    |
|         |           |          |     |       |          |    |       |          |    |      |          |    | 0.71  | 3.4      | 9    | -0.63 | 2.3      | 51   |       |          |     |    |



**Fig. 13.** Comparison between VGM rates from our study and Peltier's (2004) GIA model predictions, at common sites. Empty circles (48% of the all data set) correspond to sites for which the difference between our rates and Peltier's predictions are lower than 2 mm/yr; black points correspond to sites with difference larger than 2 mm/yr; red circles refer to sites in Fennoscandia.

estimates and observations are consistent and have the same order of magnitude, particularly for Northern Europe. Elsewhere, discrepancies prevail; the ICE-5G predicted rates are often lower than our observations. This is clearly shown in Fig. 14, which displays the difference between our results and the model estimates: the map view (Fig. 14A) and the latitudinal plot (Fig. 14B) shows that corrected data seldom reduce to null. Only in Fennoscandia do uplift rates reduce to values close to zero, a point that we discuss below.

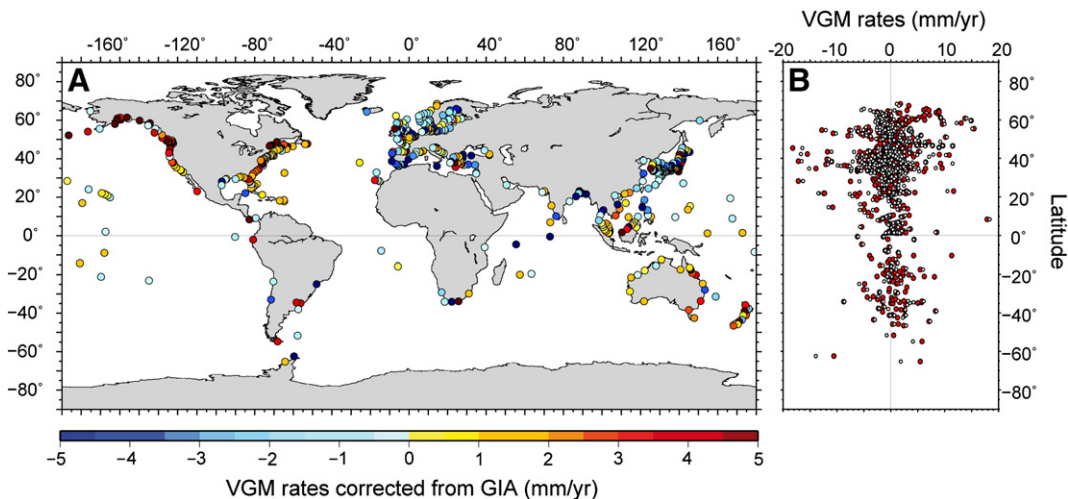
In fact, largest VGM rates are found in Northern Europe where the existence of the striking fjords has been related to post-glacial rebound for long (e.g. Cathles, 1975; Lambeck et al., 1998). For this region we obtain an average uplift of 1.60 mm/yr and the average uplift provided by the model ICE-5G is similar, at 2.30 mm/yr for the same sites. Bouin and Wöppelmann (2010) found a significant discrepancy between their GPS observations and the model estimates; they concluded that the model predictions are largely underestimated. Similarly, Kuo et al. (2008) presented the same conclusion based on the results of the earlier ICE-4G model (Peltier, 2002), with which they obtained a discrepancy of about 3.4 mm/yr on average but for a more restrained region around the Baltic Sea, where the uplift is

more significant. The regional predictive model of Milne et al. (2001), which is constrained by GPS observations and uses different parameters from Peltier's model (2004), yields an average uplift of 5.43 mm/yr, which is higher than both Peltier's estimate and our results; however, their study only focuses on Fennoscandia where again, uplift rates are higher. Thus for this region, our observations and the model estimates do not contradict each other.

### 5.3. Departures from the GIA model

In the following, we address the discrepancies in VGM rates between our synthetic data set and various GIA models. As noted above (see Fig. 14), these are non-negligible everywhere but in the Fennoscandia region (used to calibrate the model) and can be attributed either to (i) the fact that the model underestimates rates induced by the GIA in some regions, or to (ii) non-GIA origins of the ground motion such as specific tectonic processes.

For the western coasts of Europe, where we observe an average subsidence of  $-1.21$  mm/yr, Peltier's model (2004) also predicts subsidence, but rates are more uniform and correspond to lower values



**Fig. 14.** A) Map view of our results corrected from the GIA model predictions of Peltier (2004). B) Comparison between our raw results (red points) and our results corrected from the GIA model predictions of Peltier (white points).

( $-0.32$  mm/yr on average for the same sites, with a standard deviation of  $0.42$  mm/yr). The model estimates range between  $-0.99$  and  $0.7$  mm/yr, which is much lower than our results, with an average absolute difference of  $2.99$  mm/yr. While both types of results are consistent with each other, this indicates that the coasts of Western Europe are subsiding probably partly because of GIA. Departures of observations from the model's results can be attributable either to an underestimate of the model (this might be the case for the northern parts of Europe) or to other specific processes not included in the model (this is probably the case in southern regions where GIA effects are presumably associated with smaller magnitudes).

As noted above, in the British Isles, our results differ from Clark et al.'s (1978) predictions but also with Peltier's most recent global model ICE-5G (Peltier, 2004). GIA models suggest uplift in the North and low subsidence in the South like in Lambeck's (1993) model, while our results show subsidence in the whole region. A review of the dataset of tide gauges of the British Isles provided by Woodworth et al. (1999), indicates the good quality of the time series and their consistency with the results of the tide gauges in the northwestern Europe. Our result is indeed in agreement with a recent assessment of VGM rates from continuous GPS records in this region (Bradley et al., 2009). In the latter study, the authors have conducted a careful selection of 16 GPS sites for VGM and they have reported subsidence in the southern region of the British Isles and only very moderate uplift in the Scotland area (with all VGM rates smaller than  $0.5$  mm/yr which lies typically in the error bars, except for the Edinburgh station where the measured rate is  $1.07 \pm 0.35$  mm/yr). The authors have interpreted these results with a specific GIA model and assessed the independent contribution of the local British Irish ice sheet to VGM rates. Due to the relatively modest spatial extent of this ice sheet, the isostatic contribution associated to its melting is similar to the eustatic contribution from non-local ice sheet, which renders the non-uniqueness of GIA models very acute in this region. Other processes such as sediment compaction might also contribute to the clear subsidence signal observed in the southernmost part of this region (cf. Shennan and Horton, 2002). The improvement of the data bases used in the present study in the next decades will allow to distinguish between (local) GIA effects and other processes.

In the Mediterranean region, ICE-5G shows low VGM rates from  $-0.69$  to  $0.57$  mm/yr with subsidence for the western part and uplift for the East (particularly around the Aegean Sea). This contradicts our results and those from other studies that have measured subsidence for the East part and no significant motions for the West. Indeed, submerged archaeological sites, Holocene sedimentary record and shoreline notches (e.g., Flemming, 1978; Van Andel and Shackleton, 1982; Perissoratis and Conispoliatis, 2003) indicate that relative sea level rose during Holocene and is currently rising over the Aegean domain (Lambeck, 1995, 1996). Estimates of the cumulated eustatic and isostatic contributions following the melting of the late Pleistocene ice sheets are widely uncertain and range from  $-0.25$  mm/yr to  $1$  mm/yr (Lambeck, 1995; Stocchi et al., 2005). Stocchi and Spada (2007) show the significant impact of the choice of different viscosity profile and ice sheet chronologies in GIA models for this region. Furthermore, the Mediterranean Sea is situated in a complex regime of microplates. Thus, the discrepancies between the GIA model predictions and observations might reflect the influence of regional tectonic processes. This is discussed in García et al. (2007) where the authors interpret the subsidence of the western coast of Greece as a consequence to the subduction of the Adriatic lithosphere beneath the Eurasian plate. Our results seem to confirm this explanation. The authors relate other, more local observations to specific tectonic processes. But discrepancies among the various studies are large and prevent us from providing a definitive conclusion in the present study.

Regarding the eastern part of North America, although there is no obvious trend, subsidence appears to dominate with an average rate of  $-1.56$  mm/yr (from our study). This is in agreement with the

signal estimated by the model ICE-5G, which also predicted subsidence, but with a larger average rate of  $-2.45$  mm/yr for common sites (average difference of  $2.01$  mm/yr with our results). Moreover, our observations and those of Bouin and Wöppelmann (2010), Nerem and Mitchum (2002) and Santamaría-Gómez et al. (2011) are much more heterogeneous, with many sites characterised by low uplift rates. Similarly to the western coast of Europe, these results indicate that the GIA may induce subsidence on the eastern coast of North America; discrepancies might be due to an underestimate of the model or to other processes.

Along the northwestern American coast (Fig. 7), we observe a latitudinal dependency that is potentially due to GIA: uplift rates increase at high latitudes as a possible response to the glacial unloading of the ice caps. During the last glaciation, the ice sheet extended over all of Canada up to the southern part of the Cascadia region (Clague and James, 2002). Peltier's predictions (2004) are however that no uplift occurs on the North American coast: for the Alaskan region, the ICE-5G model provides an average subsidence of  $-0.28$  mm/yr for the 16 sites in our study. Our results instead show an average uplift of  $5.32$  mm/yr (also observed by Bouin and Wöppelmann (2010), Nerem and Mitchum (2002), Santamaría-Gómez et al. (2011) and Kuo et al. (2008), although some sites present strong subsidence). These records are consistent with the careful regional study of Larsen et al. (2003) based on tide gauges data, which seemingly attributes uplift in this region to GIA. The strong discordance with the global ICE5-G model could be caused by the low upper mantle viscosity advocated for by Larsen et al. (2003) (about  $10^{19}$  Pa.s, i.e., a value more than one order of magnitude smaller than the one used in ICE5-G). For the Cascadia region, we obtained a rather uniform uplift of  $2.07$  mm/yr, which is in agreement with the results of Bouin and Wöppelmann (2010) and Nerem and Mitchum (2002). Similarly, GPS data reveals motions between  $-1$  and  $4$  mm/yr for this region (Mazzotti et al., 2003; 2007). Peltier's model (2004) yields a high mean subsidence rate of  $-1.75$  mm/yr for the 23 sites we selected in our study (leading to an average absolute difference of  $3.84$  mm/yr between model predictions and our synthetic database). In their model of the GIA for the Cascadia region, James et al. (2000) obtained slight uplifting rates (less than  $1$  mm/yr) that are still much lower than our observations. Thus, for the Cascadia region, where various observations record significant uplift, the GIA models either indicate subsidence or very small uplift values. This discrepancy suggests the presence of other processes to explain the observed vertical motions. This further credits the conclusion of James et al. (2009) that GIA offers a minor contribution to the observed vertical motions of Cascadia coasts. From South to North, the continental margin is made of a succession of the transcurrent plate boundary of the San Andreas Fault zone, Cascadia, that overrides the subducting Juan de Fuca plate, a transform plate boundary that connects to the Pacific subduction zone underneath Alaska. Our results and those of earlier works compiled in the present study highlight the different vertical motions depending on the proximity of subduction zones or transform faults. At the two subduction zones, observations clearly show an uplift (the mean rate, for all Cascadia is  $1.76$  mm/yr from all studies and  $3.92$  mm/yr for Alaska) whereas along transform faults, low subsidence dominates (the mean rate from all studies, close to the north British Columbia fault, is  $-0.92$  mm/yr and  $-0.30$  mm/yr for the San Andreas fault zone). This effect is likely complemented by a strong contribution of the GIA in Alaska, as shown in Larsen et al. (2003), possibly explaining why vertical motion above the subduction zone is larger there than in the Cascadia region.

The case of Japan is also emblematic: while the GIA model reports a rather uniform uplift ( $1.21$  mm/yr on average), we identified only two uplifting regions. Other processes could be responsible for the global subsidence of Japanese coasts. Indeed, Japan is located in a complex geodynamic setting also involving subduction and a major transform fault (Fig. 11). The Pacific subduction zone is associated



with strong subsidence rates ( $-4.26$  mm/yr on average along the East coast of northern Japan), higher than around the transform zone ( $-0.88$  mm/yr). In a way, this dichotomy of subduction/transform effects on VGM rates is similar to what we observe in the northwestern American coast. However, the trends are contradictory: whereas subsidence is observed for Japan, uplift dominates in Cascadia. This in turn suggests that while subduction zones and transform faults affect the rates of vertical motion, their effect vary from one geodynamic setting to another. It can be expected, for example, that temporal variations of the rate of subduction play a prominent role. The apparent eastward tilt of northern Japan can partly be explained, on the one hand, by the Pacific subduction zone that dragged the eastern shore and made it subside for the last decades. On the other hand, the uplifting western zone (the zones that are at greater distance from the subduction zone, in particular between Hokkaido and Honshu where uplift rates reach  $2.64$  mm/yr), could be related to the convergence between the Eurasian plate and the Okhotsk plate (see Heki et al., 1999). To the South, uplift rates reach  $1.59$  mm/yr between Shikoku and Kyushu. Aoki and Scholz (2003) and El-Fiky and Kato (2006) suggest a strong coupling between the Philippine plate and the Eurasian plate to explain uplift in this area and further North. This behaviour is seemingly opposed to that of northern Japan. Because the two zones display contrasted yet robust signals, a plausible explanation would invoke different coupling regimes between the Eurasian plate and the Pacific and Philippine plates during inter-seismic phases. Subsidence in the North could be due to a strong coupling with the Pacific plate that was poorly released during the last decades. It is thus surprising that the coseismic VGM due to the March 11th 2011 Sendai earthquake is chiefly characterised by strong subsidence (Grapenhin and Freymueller, 2011). As a comparison, after the rupture of the Sunda megathrust on 26 December 2004 coseismic uplift or subsidence were observed (Meltzner et al., 2006), so significant change in VGM could be expected for Japan too. Furthermore, the fact that extremely high VGM is found at the vicinity of the Sendai earthquake makes it tempting to extrapolate the observations and envision VGM along subduction zones as an indicator of the seismic potential. Although this is potentially promising, the contrasted behaviour between the eastern coasts of North (subsidence) and South (uplift) Japan readily indicates that the interpretation is not straightforward.

Finally, our study indicates that the Australian coasts show contrasting signals with its eastern part dominated by uplift and a globally stationary (or slightly subsiding) West coast. This apparent tilt is corroborated by the actual topographic contrast: the eastern coast is dominated by high relief whereas the western coast is lower. Vertical motions anomalies were studied in earlier works based on long term observations: Heine et al. (2010) interpreted these anomalies, including the uplift of the eastern part, as a consequence of the time variations of dynamic topography. Van der Beek and Braun (1999) mentioned a magmatic underplating to explain the uplift of the southeast Australian coast. In this regard, the present-day results are at least compatible with long-term observations.

In conclusion, the differences between VGM rates inferred by global GIA models and observations exceed in magnitude the uncertainty associated to the latter (except for Fennoscandia, region of large uplift caused mainly by the GIA process, but in fact often used to calibrate GIA models). This discrepancy can be attributed for some locations (for instance in Alaska, as proposed by Larsen et al., 2003) to a bias in the GIA models (e.g. the used of only radially dependent mantle viscosity profiles) and can be explained in some other regions (Cascadia, Japan, Australia) by large scale tectonic processes such as subduction, major transforms and possibly plumes. The effect of regional geodynamic contexts is however complex: subduction zones are sometimes associated to consistent uplift (e.g. north-eastern America) and sometimes to subsidence (e.g. North Japan). Interestingly, the magnitude is consistently high.

## 6. Conclusion

We have compiled a new global database of vertical ground motion (VGM) rates from satellite altimetry and tide gauge data, with more than 630 data points. This database groups more data than previous global databases but also takes advantage of the whole period of sustained satellite altimetry and therefore tide gauge time series that are long enough to be properly exploited and correlated with satellite observations. We conducted a global and regional VGM study without focusing on a detailed analysis of any of the sites studied. Making accurate estimates for more local studies would require to individually quantify the margins of error. This requires both a precise analysis of satellite altimetry and an assessment of the quality of each tide gauge time series as well as a detailed knowledge of the local processes that cause VGM. The confrontation of our results with the results of six other independent studies shows that results agree relatively well with each other, the less precise results being probably associated with tide-gauge time series that are too short. The use of a large number of records of various origins, as well as regional tendencies that emerged coherently from the analysis, leads us to a reasonable confidence in the data set. It would be of interest to quantitatively evaluate the resolving capacity of each methodology. However, this task is impeded by the sampling bias that is intrinsic to each technique. This renders the cross-comparison difficult to interpret. Only large datasets (GPS-URL4, Santamaría-Gómez et al., 2011), or studies that used a comparable methodology to ours (Ray et al., 2010) may be compared. They indeed yield comparable results, which supports our approach.

We showed that when the signal is strong, the induced vertical motions were observed in all studies, regardless of the method or data used to estimate these motions. We were therefore able to identify global or regional trends of VGM and for some regions, quantify the magnitude. This is naturally the case for Fennoscandia, which is affected by a strong uplift with a maximum of  $12$  mm/yr, consistently detected by all techniques. The same holds true for Cascadia, with an uplift of about  $2$  mm/yr on average. Clear subsidence signals are observed in Western Europe, including the British Isles, and Japan. Because of the lack of data, it remains impossible to make definite conclusions regarding South America or Africa.

These results help to identify the GIA signal. Our joint study is in agreement with global GIA model predictions (e.g. ICE-5G, Peltier, 2004) only for Fennoscandia, thus confirming earlier conclusions (e.g. Larsen et al., 2003; Bouin and Wöppelmann, 2010). These differences can sometimes indicate a bias in the global GIA model when applied to regions located far from Fennoscandia, but where the GIA process is still a prominent factor of VGM. We also show the influence

**Table 8**

Average rates for areas of societal concern. The numbers in italics highlight where there are too few data to interpret correctly the average VGM rates.

| Region         | Studies                                 | Mean rates (mm/yr) | Number of data |
|----------------|-----------------------------------------|--------------------|----------------|
| Venice         | This paper                              | <i>-0.87</i>       | 1              |
|                | García et al. (2007)                    | <i>-0.80</i>       | 1              |
| Gulf of Mexico | This paper                              | -1.49              | 18             |
|                | Nerem and Mitchum (2002)                | <i>1.94</i>        | 1              |
|                | MSL-TG Bouin and Wöppelmann (2010)      | -2.26              | 3              |
|                | GPS Bouin and Wöppelmann (2010)         | -3.35              | 3              |
|                | GPS-ULR4 Santamaría-Gómez et al., 2011  | -2.56              | 7              |
| Ganges delta   | West                                    | 3.56               | 5              |
|                | East                                    | <i>-12.33</i>      | 2              |
| Maldives       | This paper                              | -2.32              | 2              |
|                | Nerem and Mitchum (2002)                | -2.67              | 4              |
|                | Alt-TG Ray et al. (2010)                | <i>-1.00</i>       | 1              |
|                | DORIS Ray et al. (2010)                 | <i>-0.80</i>       | 1              |
|                | GPS-ULR4 Santamaría-Gómez et al. (2011) | <i>-0.26</i>       | 2              |

of other geodynamical processes. This is the case, for example in Cascadia and Alaska, where subduction influences the global uplift.

More local records of VGM are also worthy of interest, for example in regions which are known to be in a critical situation because of their exposure to sea level variations. Since our study confirms that local sea level variations largely exceed the mean sea level rise of 2–3 mm/yr on average (Cazenave et al., 2008), it is useful to address the issue of sea level change in critical zones in light of all the available data. These critical zones are chiefly located at rivers deltas, where a variety of processes, including sediment compaction, water and hydrocarbon extraction, meandering and variable sediment input control the vertical movements. The complex interaction of these processes makes the net result highly dependent on the local context and difficult to predict a priori. Table 8 compiles the mean VGM rates for some critical zones when data exist. Venice, which is severely exposed to anthropogenic forcing (Carbognin et al., 2005), is most likely subsiding but the rates vary amongst studies, and it is difficult to conclude because of the lack of data. In the Gulf of Mexico, the 2005 hurricane Katrina hit the Mississippi delta and highlighted the vulnerability of this subsiding area (Törnqvist et al., 2008). Our study and three others indicate subsidence, whereas only Nerem and Mitchum (2002) found uplift. The mean subsidence, excluding the study of Nerem and Mitchum (2002) occurs at about  $-2.4$  mm/yr. In the Ganges delta, we have distinguished the subsiding eastern part, at the confluence of the Ganges and Brahmaputra, from the western part, which receives less sediment than the east part and is possibly uplifting at a few mm/yr. Only our study yields data in this area, which doesn't ensure the reliability of the results given the number of stations. Last, the atolls of the Maldives are immediately threatened by sea level rise (Woodworth, 2005). Our study, which only relies on two sites, indicates an average subsidence of  $-2.32$  mm/yr in agreement with other studies.

Finally, these results demonstrate the potential of these data to exhibit VGM. Longer time series from time gauge records will improve the precision of this global data set and lead to a clearer picture of VGM rates, thus shedding light on both the GIA and internal geodynamic processes.

Supplementary materials related to this article can be found online at doi:10.1016/j.earscirev.2011.10.004.

## Acknowledgements

This work is supported by the ANR project GiSeLE. We thank Mélanie Gérard and Sarah Mullin for their help in preparing the manuscript, as well as the Editor and two anonymous reviewers. Figures are created with the Generic Mapping Tools (GMT) (Wessel and Smith, 1998). We used tide gauges data from the PSMML as well as satellite altimetry data from AVISO.

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