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# Land motion estimates from GPS at tide gauges: a geophysical evaluation

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## SUMMARY

Space geodesy applications have mainly been limited to horizontal deformations due to a number of restrictions on the vertical component accuracy. Monitoring vertical land motion is nonetheless of crucial interest in observations of long-term sea level change or postglacial rebound measurements. Here, we present a global vertical velocity field obtained with more than 200 permanent GPS stations, most of them collocated with tide gauges (TGs). We used a state of the art, homogeneous processing strategy to ensure that the reference frame was stable throughout the observation period of almost 10 yr. We associate realistic uncertainties to our vertical rates, taking into account the time-correlation noise in the time-series. The results are compared with two independent geophysical vertical velocity fields: (1) vertical velocity estimates using long-term TG records and (2) postglacial model predictions from the ICE-5G (VM2) adjustment. The quantitative agreement of the GPS vertical velocities with the ‘internal estimates’ of vertical displacements using the TG record is very good, with a mean difference of  $-0.13 \pm 1.64 \text{ mm yr}^{-1}$  on more than 100 sites. For 84 per cent of the GPS stations considered, the vertical velocity is confirmed by the TG estimate to within  $2 \text{ mm yr}^{-1}$ . The overall agreement with the glacial isostatic adjustment (GIA) model is good, with discrepancy patterns related either to a local misfit of the model or to active tectonics. For 72 per cent of the sites considered, the predictions of the GIA model agree with the GPS results to within two standard deviations. Most of the GPS velocities showing discrepancies with respect to the predictions of the GIA model are, however, consistent with previously published space geodesy results. We, in turn, confirm the value of  $1.8 \pm 0.5 \text{ mm yr}^{-1}$  for the 20th century average global sea level rise, and conclude that GPS is now a robust tool for vertical land motion monitoring which is accurate at least at  $1 \text{ mm yr}^{-1}$ .

**Key words:** Satellite geodesy; Reference systems; Sea level change.

## 1 INTRODUCTION

For more than a decade GPS has been widely used for measuring horizontal deformations of the Earth’s crust with an excellent precision. Applications include, for instance, plate tectonics determination (Argus & Heflin 1995), regional kinematics (Masson *et al.* 2007), seismic cycle studies, or coseismic and post-seismic deformation estimates (Vigny *et al.* 2005). In contrast, vertical deformations are more difficult to measure in a global reference frame due to a variety of residual effects that are not accurately modelled in the GPS phase observable (e.g. second and higher order ionosphere signal propagation effects; phase centre corrections of the transmitting and/or tracking antennas). In addition, reliable information on the equipment used and antenna mounting, as well as the realization of a stable and consistent geocentric reference frame are mandatory to obtain vertical GPS position time-series that can be interpreted

in terms of geophysical vertical deformations. Any change in the equipment, in the geocentric datum, in the parametrization or in the models used to analyse the GPS data might indeed affect the vertical component of the GPS position estimates, and subsequently bias the geophysical interpretation (e.g. Bruyninx 2004; Steigenberger *et al.* 2006). More recently, on a regional scale, GPS has achieved a level of maturity suitable for the validation of or the comparison of high-precision vertical velocity fields to elastic deformation models in active tectonic zones (e.g. Bergeot *et al.* 2009); to glacial isostatic adjustment (GIA) models (e.g. Johansson *et al.* 2002; Nocquet *et al.* 2005; Rülke *et al.* 2008); or to independent vertical rates derived from combined altimetry and tide gauge (TG) measurements (e.g. Kuo *et al.* 2004).

The precision of vertical rates on a global scale remains largely unexplored. To the best of our knowledge, no attempt has been made so far to compare global GPS velocity fields of more than 100

stations with independent vertical rate data sets. A major application is the geodetic monitoring of TGs from which long-term sea level changes can be derived, with significant ecological and societal impacts (e.g. Woodworth *et al.* 2004). The determination of a secular change of global sea level remains a fundamental though elusive goal for a variety of reasons (e.g. Woodworth 2006). Satellite altimetry measurements give direct access to the absolute sea level (ASL) variations. However, only the last 15 yr are covered with sufficient precision. This time span is too short to derive long-term trends as the sea level variations contain strong interdecadal signals (e.g. Douglas 2001; Cazenave & Nerem 2004). To date, the only observational tools available for long-term sea level trend studies over time scales of a century or so are the TG records. Various authors concluded that records longer than 40–50 yr are an acceptable trade-off between the length needed and the number of sites available to estimate a global sea level trend (Douglas 1991, 2001; Church & White 2006). TGs, however, provide a relative measure of sea level as the TG itself is attached to the land at the coast. They may, therefore, be affected by a large variety of vertical land motions at the millimetre per year level. Most estimates of global 20th century sea level rise use long TG records with uneven geographic coverage, and correct for GIA land motion using global model predictions (e.g. Peltier 2002; Peltier 2004). Several authors emphasize the need for land motion corrections of the TG records from reliable geodetic measurements of the total vertical land motion rather than for the GIA effect alone (e.g. Carter *et al.* 1989; Woodworth 2006). The value of the geodetic measurement approach to correct tide-gauge relative sea level (RSL) trends has recently been demonstrated at the regional scale using GPS-derived vertical velocities (Snay *et al.* 2007; Mazzotti *et al.* 2008).

On the global scale, Wöppelmann *et al.* (2007) estimated geocentric sea level trends at a set of 28 relevant GPS collocated TGs from a global-network solution obtained at the University of La Rochelle analysis centre (henceforth, ULR) within the framework of the TIGA pilot project (GPS Tide Gauge Benchmark Monitoring, see details at [http://adsc.gfz-potsdam.de/tiga/index\\_TIGA.html](http://adsc.gfz-potsdam.de/tiga/index_TIGA.html)).

In this paper, we report a new global GPS vertical velocity field based on more than 200 stations distributed worldwide that was obtained from the analysis of 10 yr of continuous GPS data using a unique processing strategy (parametrization and recent models) throughout the observation time span. It is an extension of the Wöppelmann *et al.* (2007) solution, incorporating three additional observation years and providing GPS velocities for a global set of more than 200 GPS sites, among which 160 are collocated with TGs. The new solution is built within the ITRF2005 (Altamimi *et al.* 2007) reference frame instead of the former ITRF2000 reference frame (Altamimi *et al.* 2002), which was used in the previous solution (Wöppelmann *et al.* 2007). The 10-yr collection of data provides a precise determination of GPS vertical rates with typical ‘formal’ rate uncertainties of less than  $0.1 \text{ mm yr}^{-1}$ . However, due to the aforementioned GPS limitations, the formal estimate of precision provided by the parameter variance-covariance matrix underestimates the true accuracy in these rates with respect to the global reference frame (e.g. Langbein & Johnson 1997; Mao *et al.* 1999; Williams 2003).

The main goal of this paper is to assess the precision of our global-scale continuous GPS vertical velocity estimates. To achieve this, we explore two major independent determination of vertical land motion to compare: (i) the TG records used to derive land motion estimates from the so-called ‘internal estimates’ method used by other authors (e.g. Mitchum 2000; Nerem & Mitchum 2002) and (ii) the GIA model predictions. Both approaches rely upon the assumption

that land motion is essentially linear on the maximum time scale considered here (100 yr). This appears to be a necessary but reasonable assumption, in particular for GIA induced land motion or tectonic effects at locations with long earthquake recurrence times. The comparison with the ‘internal estimates’ method assumes in addition that the same land motion affects the ground to which the TG and the GPS antenna are anchored. This latter assumption obviously weakens as the distance between the instruments increases, although Bevis *et al.* (2002) warn about relying too much upon the distance parameter in such analyses. Where discrepancies arose from the comparisons with the external geophysical data sets, we searched the literature for independent geodetic results, revisiting the above-mentioned assumptions. In particular, the work of Rülke *et al.* (2008) is worth comparison as the authors carried out a similar exercise of homogeneously reprocessing a global GPS network. They, however, focused on the IGS network (International GNSS Service, Dow *et al.* 2005; 83 per cent of their network is part of the IGS) resulting in a relatively limited number of stations in common with our solution (120 out of 227).

The recent progress reported in the afore-mentioned literature clearly suggest that the accuracy of GPS vertical velocities has increased. GIA vertical rate predictions claim to be quite accurate too. How well do both the GPS and the GIA velocity fields agree? Whereas Rülke *et al.* (2008) were primarily interested in the realization of a terrestrial reference system by a reprocessed global GPS network, we aimed at long-term sea level studies. We therefore included a considerable number of non-IGS stations collocated with TGs, providing an invaluable third data set to measure the coherence between both GPS and GIA vertical velocity fields. This additional TG data set strengthened our conclusions regarding the vertical velocities fields, but also was worth testing the inference of global average sea level rise over the past century from the Intergovernmental Panel for Climate Change (IPCC). The conclusions can be used both to properly correct the long-term TG records and to constrain the rheological parameters in GIA models, especially at the regional scale.

The next section summarises the GPS data sets and the associated data analysis strategy, including the procedure that we used to estimate realistic rate uncertainties by taking into account the time-correlated noise in the GPS position time-series. Sections 3 and 4 report the comparison exercises carried out with the TG ‘internal estimates’ method, which is briefly described, and the GIA model predictions. We then discuss the results and conclude.

## 2 VERTICAL GPS VELOCITIES

### 2.1 GPS data sets and data processing

The GPS processing strategy is detailed in Wöppelmann *et al.* (2009). For the sake of completeness we briefly describe it here. We analysed GPS observations from a global network of 227 stations using the same parametrization and observation modelling over the whole observation period from 1997 January to 2006 November. Among the stations, 160 are collocated within 15 km of a TG, and 91 belong to the IGS reference frame network as defined by Ferland (2005). The coordinates of the latter 91 reference frame stations in the ITRF2005 datum were adopted to align our daily and weekly solutions instead of the former ITRF2000 datum used in Wöppelmann *et al.* (2007). The electronic supplement provides details on the list of stations. We used the 10.21 version of the GAMIT software (King & Bock 2005) with a double-difference approach, estimating

**Table 1.** Summary of the GPS data processing strategy used in this study.

Parameter	Description
GPS Software	GAMIT 10.21 (King & Bock 2005) for GPS observations processing
Stations	Grouping into five global subnetworks (up to 50-stations each)
Data	Double-differenced phase and code pseudo-range observations
Sessions and sampling	24-hr sessions; 5 min. sampling interval (30 s in the data cleaning)
Elevation cut-off angle	10°
Ionosphere refraction	Ionosphere-free linear combination LC (1st-order effect eliminated)
Troposphere refraction	A priori zenith delays from the Saastamoinen (1972) model, using a standard atmosphere, mapped with the GMF mapping functions (Boehm <i>et al.</i> 2006); zenith wet delays estimated as a piece-wise linear model with 2-hr nodes, plus gradients in north–south and east–west directions at 24-h intervals.
Antenna PCV	IGS absolute phase centre corrections (Gendt 2005, IGSMAIL-5272) for both the tracking and transmitting antennas
Earth orientation	IERS bulletin B
Earth and polar tide	IERS2003 (McCarthy & Petit 2004).
Ocean tide loading	Computed using the CSR4.0 ocean tide model and the facility provided by Scherneck and Bos ( <a href="http://www.oso.chalmers.se/~loading/">http://www.oso.chalmers.se/~loading/</a> )
Station positions	Free network approach. <i>A priori</i> values either from ITRF2005, or from a previous ULR solution. Position constraints at 1 meter.
Orbits	Adjusted (relaxed orbit strategy). <i>A priori</i> values from IGS precise orbits. Orbit parameter constraints equivalent to ~20 cm. BERNE Radiation model was used.
Reference frame	ITRF2005 datum (Altamimi <i>et al.</i> 2007a)
Combination strategy	Sub-network solutions were combined into daily and weekly solutions, and aligned to the ITRF2005 using the minimum constraint approach implemented in the CATREF Software (Altamimi <i>et al.</i> 2007b)

station coordinates, satellite orbits, earth orientation parameters and zenith tropospheric delay parameters as a piecewise linear model with nodes every 2 hr. Table 1 summarizes the GPS data processing strategy used in this study and implemented by the ULR analysis centre. An important feature is the use of absolute antenna phase centre corrections for satellites and receivers (Ge *et al.* 2005; Gendt 2005).

Daily observation files were grouped into five subnets with up to 50 stations each. To ensure the optimal estimation of satellite orbital parameters, as well as the alignment to the ITRF2005 reference frame, the subnet stations were globally distributed. Loosely constrained subnet solutions were produced using *a priori* site coordinates in the ITRF2005 reference frame, *a priori* orbits from the IGS, and *a priori* Earth orientation parameters from the IERS Bulletin B. The subnet solutions were combined and aligned to the ITRF2005 using CATREF Software (Altamimi *et al.* 2007b), generating global daily solutions (and then weekly solutions from the daily solutions) by applying the minimum constraint approach on the seven-parameter Helmert transformation between the ITRF2005 datum and the subnet-, or daily-network solutions. The weekly solutions were provided in SINEX format to the above-mentioned IGS pilot project TIGA. The length of the GPS position time-series obtained ranged from 1.8 to 9.9 yr with an average value of 7.3 yr. However, the number of points in the time-series was generally less than the total length of the time-series, due to gaps in the data acquisition and rejection of outliers.

## 2.2 Velocity estimation and uncertainties

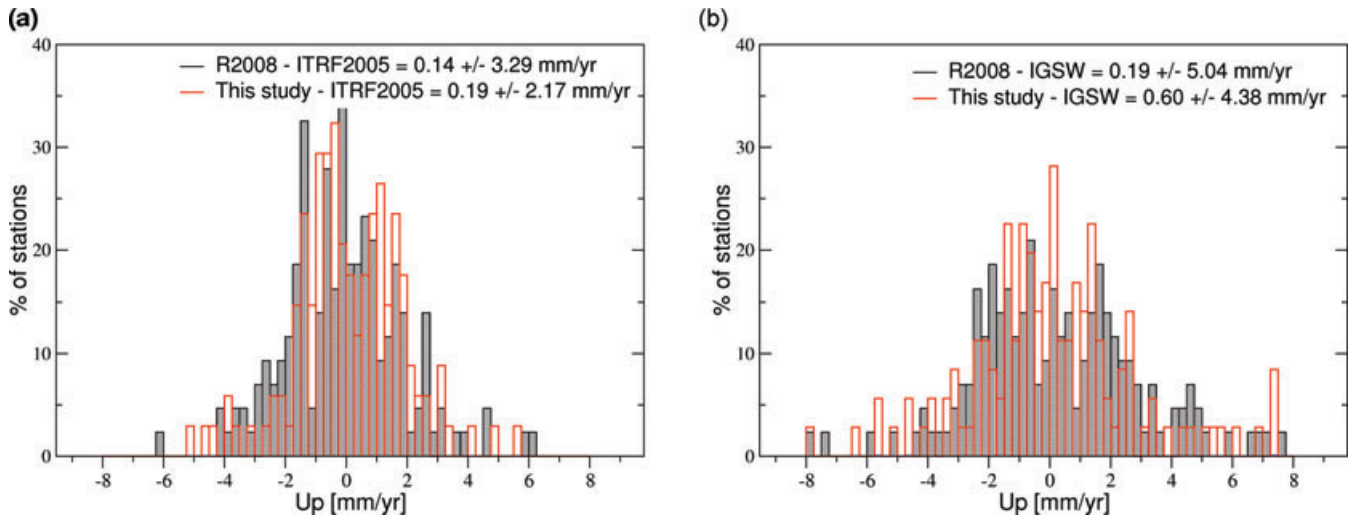
Formal uncertainties evaluated by combination software such as CATREF are based on processes which are not autocorrelated on the time-series. It is now well known that the measurement noise associated with GPS positions is time correlated (e.g. Langbein & Johnson 1997; Mao *et al.* 1999; Williams 2003). In addition to white noise, the main process affecting GPS position time-series is probably flicker noise (Amiri-Simkooei *et al.* 2007). An important consequence is that formal errors on the GPS-derived velocities are grossly underestimated by factors of 5–11 if correlations are not properly accounted for. To assign realistic uncertainties to our GPS

velocities, we carefully examined the noise content in our series (Wöppelmann *et al.* 2009) and used the formula:

$$\sigma_u = [(12\sigma_w^2/gT^3) + (\gamma\sigma_f^2/g\beta T^2)]^{0.5} \quad (1)$$

as proposed by Mao *et al.* (1999) and which is now normally applied in similar analyses (e.g. Snay *et al.* 2007; Mazzotti *et al.* 2008). Here  $g$  is the average number of points per year in the time-series,  $T$  is the total time span of the GPS measurements,  $\gamma$  and  $\beta$  are empirical constants (here  $\gamma = 1.78$  and  $\beta = 0.22$  as in Snay *et al.* (2007)).  $\sigma_w$  and  $\sigma_f$  denote the white and flicker noise magnitudes, respectively. A noise analysis of our time-series gave as mean values a white noise level of 2.6 mm and a flicker noise amplitude of  $8.2 \text{ mm yr}^{-1/4}$  on the vertical component (Wöppelmann *et al.* 2009). These values are consistent with the findings of Williams *et al.* (2004) with 10-yr global GPS solutions, where  $\sigma_w$  ranged from 2.2 to 4.6 mm and  $\sigma_f$  ranged from 4.9 to  $11.0 \text{ mm yr}^{-1/4}$ . Realistic vertical uncertainties were then evaluated using eq. (1). For the 227 stations of the global solutions, the standard deviations ranged from  $0.72$  to  $3.95 \text{ mm yr}^{-1}$ , with a mean value of  $1.16 \pm 0.59 \text{ mm yr}^{-1}$ . Stations with an observation time span longer than 5 yr (176 sites) had uncertainties of between  $0.72$  and  $1.52 \text{ mm yr}^{-1}$  (mean value  $0.89 \pm 0.20 \text{ mm yr}^{-1}$ ) whereas stations with shorter time-series (49 sites) had higher uncertainties (between  $1.43$  and  $3.95 \text{ mm yr}^{-1}$ , with a mean value of  $2.07 \pm 0.57 \text{ mm yr}^{-1}$ ). These results are consistent with those of Mazzotti *et al.* (2008) on a regional network, and with the time dependence of GPS velocity standard deviations in Snay *et al.* (2007, see fig. 2 in their paper).

Recently, the upgrade of the ITRS realization ITRF2000 to ITRF2005 (Altamimi *et al.* 2007a) suggests that the ITRF2000 scale and Z-axis translation rate were biased by  $0.5$  and  $1.8 \text{ mm yr}^{-1}$ , respectively. The ITRF2005 translation rate itself is probably biased due to the Satellite Laser Ranging network degradation in the last 10 yr (Altamimi *et al.* 2007a; Collilieux *et al.* 2009). These possible biases in the reference frame definition rate would result in differences of  $\pm 0.5 \text{ mm yr}^{-1}$  in GPS vertical velocity estimates. As our uncertainties are of this order of magnitude or higher, we do not account for these possible additional effects on the GPS vertical velocities.



**Figure 1.** Histograms of the velocity differences between our solution and ITRF2005 (left-hand panel, red); between the R2008 (Rülke *et al.* 2008) solution and ITRF2005 (left-hand panel, grey); between our solution and IGSW (right-hand panel, red); and between the R2008 solution and IGSW (right-hand panel, grey).

We compare our vertical velocities with the ITRF2005 and the IGS weekly combined solution rates (henceforth IGSW; Ferland 2005). The ITRF2005 time-series are generally shorter than those of the IGSW solution, but include techniques other than GPS and are then less susceptible to bias. As our solution includes many TG collocated sites that are not included in the IGS network, the number of common sites is 136 (respectively 142). Fig. 1 shows the histograms of the vertical velocity differences (GPS – ITRF2005 and GPS – IGSW) along with the corresponding histograms for another independent global solution (Rülke *et al.* 2008; hereafter R2008, 172 common stations with ITRF2005/IGSW). The mean difference between our vertical velocities and the ITRF2005 vertical rates is  $0.19 \pm 2.17$  mm yr<sup>-1</sup> ( $0.14 \pm 3.29$  mm yr<sup>-1</sup> for the R2008 solution), and the mean difference with respect to the IGSW solution is  $0.60 \pm 4.38$  mm yr<sup>-1</sup> ( $0.19 \pm 5.04$  mm yr<sup>-1</sup> for the R2008 solution). More than 80 per cent of our vertical velocities agree with ITRF2005 within  $\pm 2$  mm yr<sup>-1</sup> (74 per cent for R2008), and 61 per cent agree with the IGSW vertical velocities within  $\pm 2$  mm yr<sup>-1</sup> (53 per cent for R2008). This confirms that our vertical velocity field is consistent with the state-of-the-art global GPS solutions, at least on the IGS stations.

The vertical GPS velocities obtained for the 227 stations of our network with associated uncertainties accounting for the time-correlated noise processes are provided in the electronic supplement.

### 2.3 Offset corrections

The GPS position time-series were thoroughly inspected for outliers and offsets. A careful scanning of the residuals time-series showed that some of the GPS stations collocated with TGs were affected by discontinuities, despite the offset removal procedure implemented in the CATREF software. These offsets were evaluated and corrected in seven cases: A Coruna (ACOR), Brest (BRST), Cartagena (CART), Cook Islands (CKIS), Perth (PERT), Annapolis U.S. Naval Academy (USNA) and San Pedro (VTIS). Table 2 shows the vertical velocities estimated for each station, with and without offset correction, as well as the position residuals time-series weighted rms (WRMS, also known as repeatability) before and after cor-

**Table 2.** Vertical velocity (mm yr<sup>-1</sup>) and WRMS of the vertical position residuals (mm) for six stations before and after discontinuity correction.

Station	Before correction		After correction	
	Velocity	WRMS	Velocity	WRMS
ACOR	$-2.92 \pm 1.0$	5.8	$-0.17 \pm 1.0$	5.1
BRST	$0.54 \pm 0.9$	4.6	$-0.43 \pm 0.9$	4.5
CART	$-1.39 \pm 1.17$	6.9	$-1.65 \pm 1.17$	6.5
CKIS	$0.16 \pm 1.43$	7.8	$-2.71 \pm 1.43$	7.5
PERT	$-6.68 \pm 0.73$	6.7	$-5.21 \pm 0.73$	6.6
USNA	$0.69 \pm 0.8$	7.2	$-1.30 \pm 0.8$	6.2
VTIS	$-0.30 \pm 0.9$	5.5	$-0.68 \pm 0.9$	4.6

rection. In every case, correcting the discontinuities improved the repeatability.

## 3 LAND MOTION ESTIMATES FROM LONG-TERM TIDE GAUGE RECORDS

### 3.1 Method and data sets

In this part, we used long-term TG records of the RSL variations to estimate vertical land motion at the TGs. The basic principle is to take the negative of a given TG rate over several decades and to add the ‘best estimate’ of the global absolute (geocentric) sea level rate over the same time span. In other words, the long-term RSL rate at one TG is the absolute globally averaged sea level change minus the land motion at this station. As a main advantage, this method provides an estimate of vertical rates at every individual TG independent of any space geodetic technique.

In this study, we used the RSL variations as measured by the TGs and made available by the permanent service for mean sea level (PSMSL, Woodworth & Player 2003) to estimate vertical motion at the stations independently of the geodetic results. The mean ASL trend may be taken either from satellite altimetry measurements (e.g. Nerem & Mitchum 2002; Cazenave *et al.* 1999) or from a ‘best estimate’ of global mean sea level rise over the entire period of TG records (Mitchum 2000). An enhanced variant of this second

approach would be to extract the common mode long-term variation of TG around an ocean basin and to use this value as the reference ASL trend. This latter method was successfully used for a regional study on the Baltic Sea (Kuo *et al.* 2004). Here, we were aiming to obtain global data sets of vertical land motion derived from long-term TG records, as the time span covered by the altimetry records (roughly 15 yr) is obviously too short to be used as a reference for long RSL trend studies. We thus used as the ASL trend reference an average rate of sea level rise estimated from a large number of good quality TGs with long-term records and corrected for GIA. The recent IPCC report suggested a value of  $1.8 \pm 0.5 \text{ mm yr}^{-1}$  for the period 1961–2003 (Bindoff *et al.* 2007), from TG records corrected for vertical land motion using various GIA model predictions (e.g. Peltier 2002; Peltier 2004). This value is very consistent with previous estimates using either EOFs to reconstruct the global sea level variations over the last century ( $1.7 \pm 0.15 \text{ mm yr}^{-1}$ , Church & White, 2006) or RSL trend from TG corrected from vertical land motion using GIA model predictions ( $1.8 \pm 0.1 \text{ mm yr}^{-1}$ , Douglas 1991, 1997, 2001).

In order to construct time-series of sea level measurements at each TG, the monthly and annual means of sea level have to be reduced to a common datum. This reduction is performed by the PSMSL using the TG datum history provided by the supplying authority. Approximately, two-thirds of the stations in the PSMSL database (<http://www.pol.ac.uk/psmsl/>) have had their data adjusted in this way, forming the revised local reference (RLR) data set. Other data sets received from the authority in charge of the TG are called METRIC data sets. The RLR data set is normally superior to the METRIC, although the latter can also be used taking into account possible datum discontinuities. Here, we used both the RLR and the METRIC data sets, representing 90 and 10 per cent of the TG colocated with our GPS stations, respectively. Thus, for the METRIC data sets, we checked the monthly values provided by the PSMSL for discontinuities in order to use them to derive long-term trends.

Two main hypotheses underlie the work presented here.

- (1) The mean value of the absolute 20th century global sea level is, as stated by the last IPCC report (Bindoff *et al.* 2007),  $1.8 \pm 0.5 \text{ mm yr}^{-1}$  (see discussion above).
- (2) Provided its time-series is long enough, the difference between the RSL trend measured by an individual TG and this global mean value is mainly due to the TG vertical motion and not to local ASL variations that are significantly different from  $1.8 \pm 0.5 \text{ mm yr}^{-1}$ .

The second hypothesis has proved to be incorrect if we consider ocean basin sea level variations as measured during the satellite altimetry era (last 15 yr), (e.g. Cazenave & Nerem 2004; Church *et al.* 2004; Berge-Nguyen *et al.* 2008). In contrast, several studies showed that sea level values measured with very long TG records do not need the geographical coverage required by short ones (Douglas 1991; Gornitz & Solow 1991). Widely separated TGs show very consistent trends, provided their records are long enough (50–60 yr). In this study only TG series longer than 20 yr were used; 50 per cent of them were longer than 50 yr and we assume that the number of TG records used in this analysis is sufficient to make this hypothesis statistically valid. In other words, it was assumed that the error introduced by this  $1.8 \pm 0.5 \text{ mm yr}^{-1}$  mean value was less than the possible errors introduced by regional ASL trends measured on a 15 yr time span by satellite altimetry.

Of our 227 stations, 117 are colocated within 45 km of at least one of the TGs of the PSMSL data set. We then built 117 unique

pairs of GPS/TG colocated stations using the following criteria: if more than one TG is present in the vicinity of the GPS station, we kept the closest one, provided its time-series is longer than 25 yr. Pairs of GPS/TG stations were then divided into four bins following similar criteria to those of Mazzotti *et al.* (2008), based on the length of the GPS series ( $T_{GPS}$ ), the length of the TG record ( $T_{TG}$ ) and the distance between the GPS and TG stations ( $D$ ).

- (1) Group A includes the pairs for which  $T_{GPS} \geq 5 \text{ yr}$ ,  $T_{TG} \geq 50 \text{ yr}$  and  $D \leq 10 \text{ km}$  (38 sites; mean values  $T_{GPS} = 7.9 \text{ yr}$ ,  $T_{TG} = 81 \text{ yr}$ ,  $D = 2.78 \text{ km}$ ).
- (2) Group B represents the sites with  $T_{GPS} \geq 3 \text{ yr}$ ,  $T_{TG} \geq 30 \text{ yr}$  and  $D \leq 20 \text{ km}$  (47 sites; mean values  $T_{GPS} = 6.0 \text{ yr}$ ,  $T_{TG} = 52 \text{ yr}$ ,  $D = 4.22 \text{ km}$ ).
- (3) Group C represents the sites with  $T_{GPS} \geq 2.5 \text{ yr}$ ,  $T_{TG} \geq 20 \text{ yr}$  and  $D \leq 40 \text{ km}$  (26 sites; mean values  $T_{GPS} = 7.2 \text{ yr}$ ,  $T_{TG} = 45 \text{ yr}$ ,  $D = 15 \text{ km}$ ).
- (4) Group X corresponds to sites with  $T_{GPS} \geq 2.5 \text{ yr}$ ,  $T_{TG} \geq 15 \text{ yr}$ , and  $D \leq 45 \text{ km}$  (6 sites; mean values  $T_{GPS} = 7.3 \text{ yr}$ ;  $T_{TG} = 23 \text{ yr}$ ,  $D = 18.5 \text{ km}$ ).

Like Mazzotti *et al.* (2008), we considered that category C was the last one that could be used for reliable comparisons of the long-term behaviour of GPS and TG. Category X sites are given here as an illustration and for completeness only. Two notable exceptions (pairs GPS/TG) are included in group C although they do not fulfil the first criteria: Alexandria (ALEX) and Klaipeda (KLPD) have GPS time-series of 1.8 and 1.9 yr, respectively. We kept them because the distance between GPS and TG is shorter than 3 km and because the GPS time-series, despite its length, is of good quality. As proved by their mean length values, the GPS and TG time-series of most sites of categories A, B and C are of very high quality. The quality of the B and C pairs of sites differs mainly from those of group A by the distance between the GPS and the TG stations.

For each pair of GPS/TG sites, the vertical velocity  $V_{TG}(i)$  was derived from the long-term RLR record using the following equation:

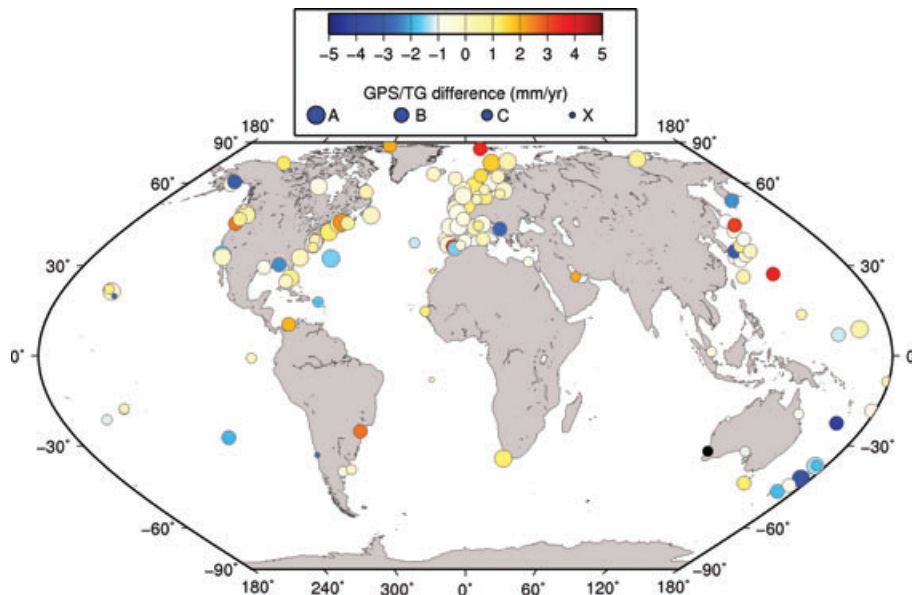
$$V_{TG}(i) = ASLV - RSLV(i) \quad (2)$$

where  $ASLV$  is the 20th century mean global sea level rate and  $RSLV(i)$  the RSL rate as measured by the TG  $i$ . No correction was made for inverted barometer effects, as this signal has proved to be small (e.g. Ponte 2006). The standard errors associated with the  $V_{TG}$  were derived from the TG time-series using a white noise model only. Some TG records start as early as the beginning or the middle of the 19th century. The global absolute mean sea level value used in this work is valid for the last century only. Obtaining a reliable estimate of the ASL rate prior to that period is, to the best of our knowledge, not feasible. Many of the longest records that reach back to the nineteenth century show a small positive acceleration: there is a variety of evidence for an increase in the rate of sea level rise during the mid-to-late nineteenth century (e.g. Gehrels *et al.* 2008; Wöppelmann *et al.* 2008). We therefore truncated the TG records to make them start at the beginning of the 20th century. This concerns seven TGs (namely Brest, Sheerness, Marseille, Stavanger, Borkum, Warnemunde and Vaasa).

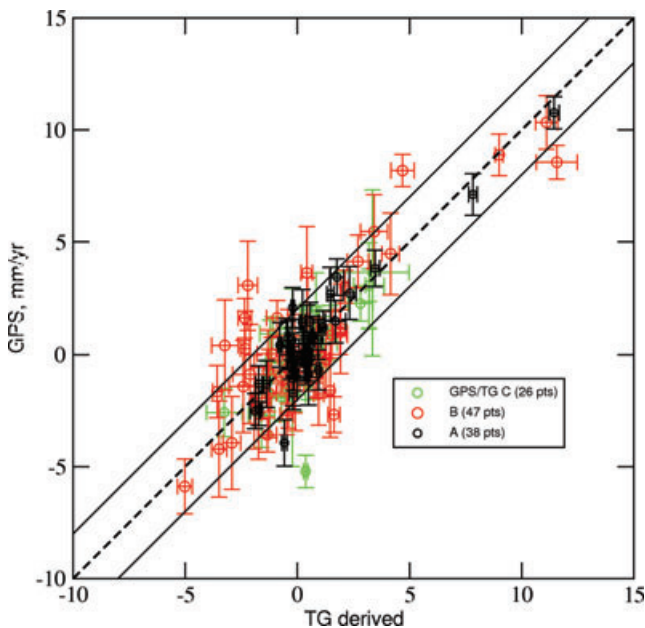
### 3.2 Results

The full comparison between  $V_{GPS}$  and  $V_{TG}$  for the 117 pairs of stations is shown in the electronic supplement. Fig. 2 shows a map of the differences between our GPS rates and the TG velocities, and





**Figure 2.** Map of the differences between our GPS velocities and the TG-derived velocities (GPS–TG,  $\text{mm yr}^{-1}$ ). The TG-derived velocities are obtained by subtracting the relative sea level trends indicated by the TG records time-series from a mean absolute sea level rise ( $1.8 \text{ mm yr}^{-1}$  here). The symbol size corresponds to the station group, A being the pairs of stations of best quality, X the poorest ones.



**Figure 3.** Comparison between the TG-derived velocities and our GPS velocities of the different groups ( $\text{mm yr}^{-1}$ ). The TG-derived velocities are obtained by subtracting the relative sea level trends indicated by the TG records time-series from a mean absolute sea level rise ( $1.8 \text{ mm yr}^{-1}$  here). Group A represents the pairs of stations of best quality, C the poorest ones.

Fig. 3 is a general comparison of the velocities for the stations of each group.

Comparisons of stations from group X gave poor results, as expected. However, due to the small number of stations, they cannot be considered significant. Conversely, in the other groups, the results obtained with a large majority of GPS stations were in close agreement (better than  $1 \text{ mm yr}^{-1}$ ) with the TG record derived velocities (Table 3). Next, scans were carried out on the pairs of stations pre-

sending significant discrepancies (higher than  $2 \text{ mm yr}^{-1}$ ) between the GPS and TG vertical rates (Table 4).

For these stations, we searched for an independent confirmation of our velocities in the literature, mainly from other geodetic results. Some of these sites are included in the ITRF2005 and IGSW solutions as well as in the R2008 solution. It appears that our vertical velocities generally lie within the bounds of these published rates. This is the case for Alert (ALRT) with  $5.46 \text{ mm yr}^{-1}$  (other geodetic studies give rates of  $4.3\text{--}9.9 \text{ mm yr}^{-1}$ ), Bahrein (BAHR) with  $0.93 \text{ mm yr}^{-1}$  ( $-0.55$  to  $1.45 \text{ mm yr}^{-1}$ ), Noumea (NOUM) with  $-2.68 \text{ mm yr}^{-1}$  ( $-1.8$  to  $-4.0 \text{ mm yr}^{-1}$ ), NyAlesund (NYAL) with  $8.19 \text{ mm yr}^{-1}$  ( $7.3\text{--}9.2 \text{ mm yr}^{-1}$ ), Perth (PERT) with  $-5.21 \text{ mm yr}^{-1}$  ( $-3.4$  to  $-6.0 \text{ mm yr}^{-1}$ ), Petropavlosk (PETP) with  $-2.70 \text{ mm yr}^{-1}$  ( $-0.6$  to  $-3.1 \text{ mm yr}^{-1}$ ) and San Fernando (SFER) with  $1.60 \text{ mm yr}^{-1}$  ( $1.35$  to  $2.9 \text{ mm yr}^{-1}$ ). Other stations like Kenai (KEN1) are confirmed by the ITRF2005 rate only ( $8.56 \text{ mm yr}^{-1}$ , close to the  $8.4 \text{ mm yr}^{-1}$  ITRF2005 velocity) or by a purely GPS solution: Dubrovnik (DUBR,  $-1.76 \text{ mm yr}^{-1}$ ) with EUREF solution ( $-1.87 \text{ mm yr}^{-1}$ , Bruyninx 2004), Mobile (MOB1,  $-3.58 \text{ mm yr}^{-1}$ ) with the Snay *et al.* (2007) solution ( $-4.2 \text{ mm yr}^{-1}$ ) and Newport (NEWP,  $1.61 \text{ mm yr}^{-1}$ ) with the Mazzotti *et al.* (2008) solution ( $1.1 \text{ mm yr}^{-1}$ ).

The Eastport (EPRT) station vertical rate ( $2.07 \text{ mm yr}^{-1}$ ) is confirmed, to some extent, by the IGSW solution ( $1.44 \text{ mm yr}^{-1}$ ), but its velocity in the ITRF2005 solution ( $-0.7 \text{ mm yr}^{-1}$ ) is closer to the TG-derived velocity.

Conversely, no comparison could be made for the stations Wellington (WGTT), Cananea (NEIA) and four stations of the Japanese permanent network (P201, P202, P209 and P213). The GPS vertical velocities of these stations will thus require further investigations.

The overall agreement between our GPS rates and the TG derived vertical velocities is very good. In groups A and C, 90 per cent of the vertical rates are in agreement to within  $2 \text{ mm yr}^{-1}$ .

The estimation of a regression slope and constant on the Fig. 3 comparison, for the stations of group A only, gives  $0.97 \pm 0.07$

**Table 3.** Number and percentage of GPS stations showing an agreement on the vertical velocity with respect to the TG derived velocity within 0.5, 1, 1.5 and 2 mm yr<sup>-1</sup>. Group A represents the pairs of stations of best quality, X the poorest ones, see text.

Group		A		B		C		X	
		#	per cent	#	per cent	#	per cent	#	per cent
Level of agreement (mm yr <sup>-1</sup> )	0.5	16	42	9	19	10	38	2	33
	1	28	74	23	49	17	65	4	67
	1.5	33	87	29	62	22	85	4	67
	2	36	95	33	70	24	92	4	67

**Table 4.** Comparison of GPS vertical velocities with TG-derived velocities (mm yr<sup>-1</sup>) for the stations in groups A, B, and C with discrepancies higher than 2 mm yr<sup>-1</sup>.

Station	Long (°)	Lat (°)	V GPS	V TG	Others <sup>a,b,c,d</sup>	IGSW <sup>e</sup>	ITRF <sup>f</sup>
Japan							
P201	141.69	45.41	3.06 ± 1.97	-2.21 ± 0.43			
P202	144.29	44.02	3.62 ± 2.07	0.42 ± 0.25			
P209	132.07	34.90	-1.61 ± 2.09	1.46 ± 0.17			
P213	142.19	27.09	0.41 ± 2.0	-3.24 ± 0.59			
Other regions							
ALRT	297.66	82.49	5.46 ± 1.64	3.42 ± 0.61	7.2 <sup>a</sup>	4.30	9.9
BAHR	50.61	26.21	0.93 ± 0.72	-1.10 ± 0.57	-0.55 <sup>a</sup>	1.45	1.0
DUBR	18.11	42.65	-1.76 ± 1.39	0.95 ± 0.22	-1.87 <sup>b</sup>		
EPRT	293.0	44.9	2.07 ± 0.89	-0.21 ± 0.07		1.44	-0.7
KEN1	208.65	60.67	8.56 ± 0.76	11.57 ± 0.92			8.4
MOB1	271.97	30.23	-3.58 ± 0.76	-1.34 ± 0.41	-4.19 <sup>c</sup>		
NEIA	312.08	-25.02	1.60 ± 1.65	-2.35 ± 0.21			
NEWP	235.94	44.58	1.61 ± 0.77	-0.90 ± 0.48	1.1 ± 1.00 <sup>d</sup>		
NOUM	166.41	-22.27	-2.68 ± 0.80	1.63 ± 0.27	-4.0 <sup>a</sup>	-2.65	-1.8
NYAL	11.87	78.93	8.19 ± 0.73	4.69 ± 0.52	7.3 <sup>a</sup>	9.17	9.1
PERT	115.88	-31.80	-5.21 ± 0.73	0.37 ± 0.1	-3.4 <sup>a</sup>	-5.65	-6.0
PETP	158.61	53.06	-2.70 ± 0.88	-0.48 ± 0.29	-2.7 <sup>a</sup>	-3.1	-0.6
SFER	353.79	36.46	1.60 ± 0.87	-0.46 ± 0.30	1.35 <sup>a</sup>	1.83	2.9
WGTT	174.78	-41.29	-3.94 ± 1.04	-0.58 ± 0.11			

<sup>a</sup>Rülke *et al.* (2008) solution.<sup>b</sup>EUREF solution (Bruyninx 2004).<sup>c</sup>Snay *et al.* (2007) solution.<sup>d</sup>Mazzotti *et al.* (2008) solution.<sup>e</sup>IGSW solution (Ferland 2005).<sup>f</sup>ITRF2005 solution (Altamimi *et al.* 2007a,b).

and  $-0.05 \pm 0.17$  mm yr<sup>-1</sup>, respectively. For the stations of groups A+B (85 sites), we obtain  $0.89 \pm 0.06$  and  $0.05 \pm 0.17$  mm yr<sup>-1</sup>. For all stations of groups A + B + C (111 sites), the values are  $0.90 \pm 0.05$  and  $-0.04 \pm 0.15$  mm yr<sup>-1</sup>. This confirms the good agreement for these three groups of stations.

### 3.3 Scale factor adjustment and global mean sea level rise

The global difference between our GPS velocities and the TG-derived velocities was then investigated. Fig. 3 shows a comparison between the GPS and TG-derived velocities for each group of stations. A bias in the fit between the two velocity fields could reflect either a misfit in the ITRF2005 scale factor rate or an incorrect average global sea level value of 1.8 mm yr<sup>-1</sup> for the time span considered here. To assess this issue, only the stations of groups A, B and C, whose vertical motion is representative of the TG monument motion, should be used. There is a trade off between the maximum discrepancy between the vertical rates of the GPS/TG pairs that could be used and the *a priori* standard deviation of the estimated parameter. In other words, the quality of the GPS/TG pairs used in this test should be of the same order of magnitude as

the maximum adjustment of the estimated parameter. The GPS/TG pairs with agreement between GPS and TG vertical velocities better than 1 mm yr<sup>-1</sup> were maintained. Indeed, it is unlikely that the time derivative of the ITRF2005 scale factor could be biased by more than 1 mm yr<sup>-1</sup>. Concerning the global mean sea level rise, the maximum bias should be even less than that level, as estimated values have ranged between 1 and 2 mm yr<sup>-1</sup> for decades, since Gutenberg (1941). We then retain stations of groups A, B and C whose velocity difference with the TG-derived estimates are within  $\pm 1$  mm yr<sup>-1</sup>. We obtain a subset of 70 stations with GPS vertical velocities ranging from  $-5.9$  to  $10.8$  mm yr<sup>-1</sup>, and we estimate a regression slope and constant between GPS and TG-derived velocities of these stations. A slope of  $0.97 \pm 0.02$  (not significantly different from unity) and a constant of  $-0.13 \pm 0.08$  mm yr<sup>-1</sup> were obtained. This value could correspond either to a slight overestimation of the global mean sea level rise ( $1.67$  mm yr<sup>-1</sup> would fit better than  $1.8$  mm yr<sup>-1</sup>) or to a scale factor time variation of  $-0.13$  mm yr<sup>-1</sup> in the ITRF2005. In the first case, the adjusted global sea level rate value is still consistent with other estimates (e.g. Church & White 2006; Bindoff *et al.* 2007). In the second case the result suggests a high-quality ITRF2005 scale implementation over the 10-yr time period considered in this study.



### 3.4 Regional studies

The agreement obtained between our vertical GPS rates and the TG-derived velocities was then compared to previous studies performing similar comparisons or using TG records to estimate regional vertical land motion.

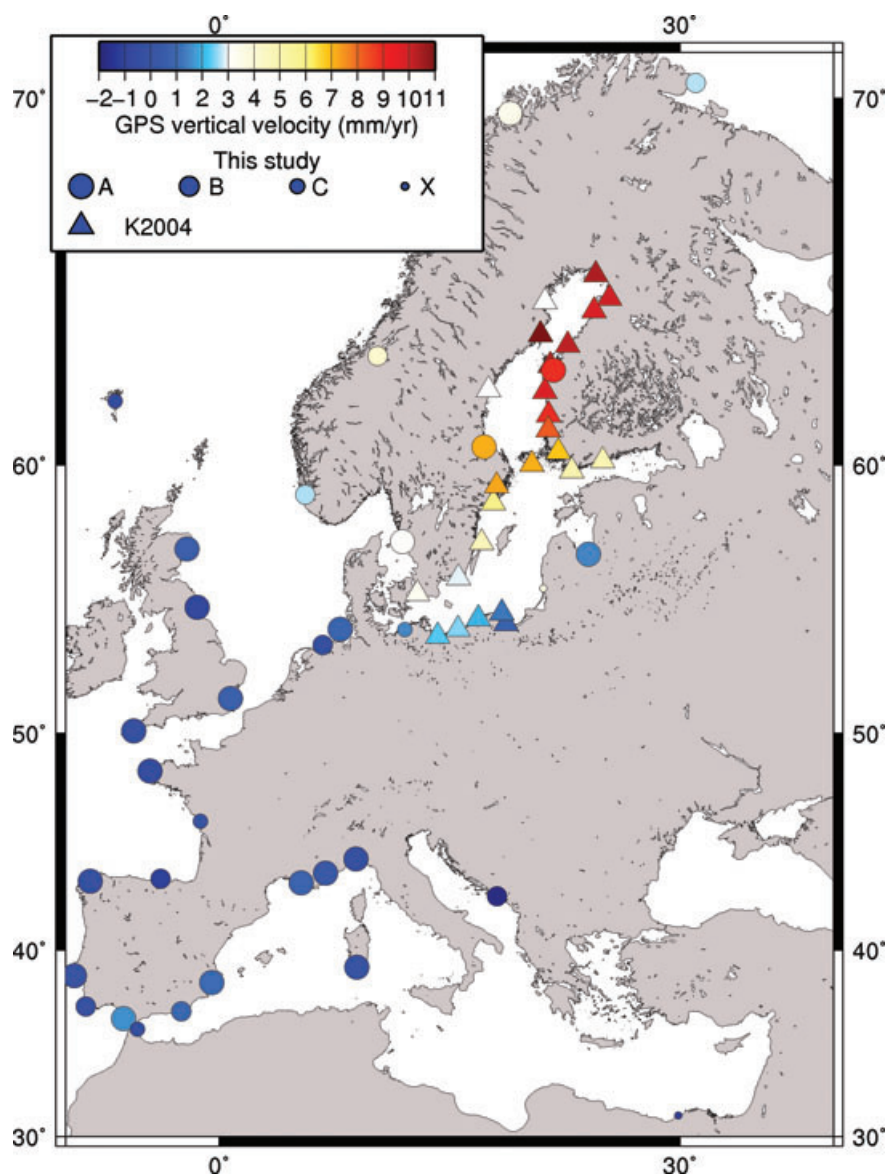
#### 3.4.1 Northern Europe

Vertical motions at 25 sites around the Baltic Sea were assessed in a recent study (Kuo *et al.* 2004) using combined T/P altimetry and TG time-series. Only TGs with long records (>40 yr) in the RLR data set were used and the average ASL variation in the Baltic sea was estimated using a least squares adjustment. The approach is similar to the so-called ‘buddy checking method’ used in other recent work (Lin 2000; Nerem & Mitchum 2002). Its application reduces the large uncertainties of T/P altimetry measurements due to the limited length of the records. A direct comparison between our GPS velocities and these combined altimetry/TG velocities is

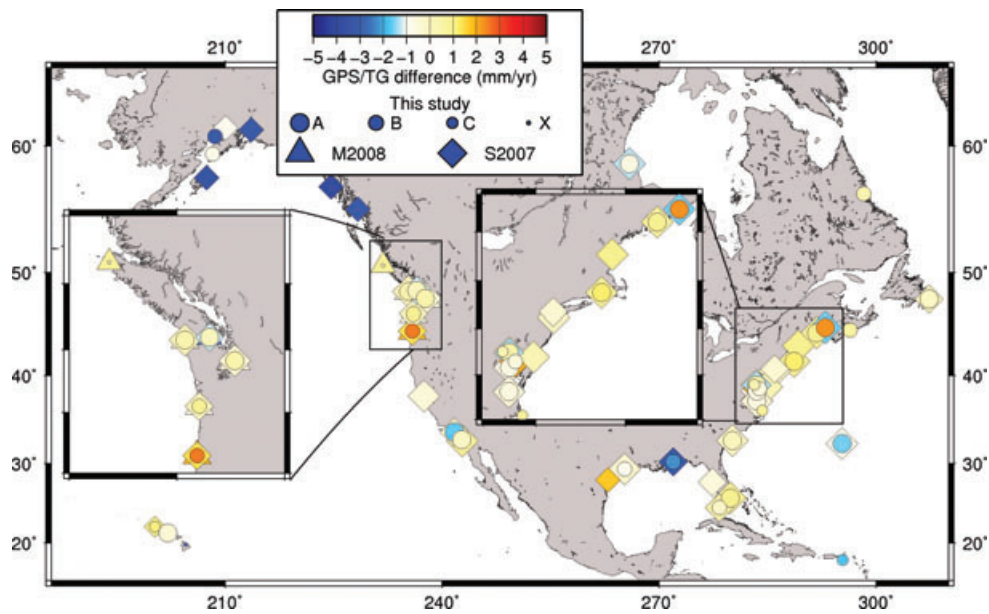
not feasible, as no sites are colocated within 40 km. Fig. 4 shows our vertical land motions (circles) and the altimetry/TG rates (triangles) in Fennoscandia and Northern Europe. The two data sets are consistent. In particular, the sites in the south coast of the Baltic used in Kuo *et al.* (2004) show vertical rates of between  $0.8 \pm 0.4$  and  $2.5 \pm 0.4$  mm yr<sup>-1</sup>.

#### 3.4.2 North America

A subset of our stations in North America was also analysed by Snay *et al.* (2007), hereafter referred to as S2007. These authors used a ‘best estimate’ obtained by combining GPS solutions from six independent analysis centres using three different GPS scientific software applications. The combined solution was aligned to ITRF2000. The level of agreement between our GPS velocities and our TG-derived rates on this particular subset of stations is significantly better (mean value of  $0.15 \pm 1.14$  mm yr<sup>-1</sup>) than the level obtained by the S2007 solution ( $0.41 \pm 1.33$  mm yr<sup>-1</sup>). This is



**Figure 4.** Map of the vertical velocities in Europe (mm yr<sup>-1</sup>), from the Kuo *et al.* (2004) study (K2004; triangles) and this study (circles). The size of the circles corresponds to the station group, A being the pairs of stations of best quality, X the poorest ones.



**Figure 5.** Map of the differences between the GPS and TG velocities in North America, in  $\text{mm yr}^{-1}$ : this study (circle with size corresponding to the station groups; A represents the pairs of stations of best quality, X the poorest ones); Mazzotti *et al.* (2008) (M2008, triangles); and Snay *et al.* (2007) (S2007, diamonds). Enclosed are two insets showing in more details the west and east coast stations.

probably due to the longer GPS time-series considered in our solution. In particular, the differences between the GPS and TG rates observed by Snay *et al.* (2007) at Kwajalein (KWJ1) and Mobile (MOB1) were not replicated in our comparison.

A similar study compared GPS and TG derived vertical rates in the NW US (Mazzotti *et al.* 2008, hereafter M2008). This latter work used a GPS processing strategy similar to ours, but a different GPS double difference software (namely Bernese 4.2, Hugentobler *et al.* 2001) and aligned their solution to ITRF2000 (Altamimi *et al.* 2002) instead of ITRF2005. Only four stations overlap with the M2008 solution with a time-series longer than 3 yr. Of these stations, a bias of  $0.96 \pm 0.47 \text{ mm yr}^{-1}$  was observed between our solution and the M2008 rates.

The M2008 and S2007 solutions can be considered as largely independent from our solution despite the fact that they are purely GPS. The differences of GPS/TG velocities for these three solutions are shown Fig. 5.

### 3.4.3 New Zealand

Five New Zealand GPS stations with series longer than 5 yr were included in this study (Fig. 6). All of them had negative vertical velocities of between  $-0.6$  and  $-3.9 \text{ mm yr}^{-1}$ . The rates derived from TG records (longer than 40 yr) were systematically higher than the GPS rates by 1 to  $2 \text{ mm yr}^{-1}$ . A recent reconstruction of the 20th century sea level rise in New Zealand, based on salt marshes cores, concluded that the TG records are systematically biased by  $\sim -1 \text{ mm yr}^{-1}$  (Gehrels *et al.* 2008). Correcting the TG-derived vertical velocities from this value would improve their fit with our New Zealand GPS rates to  $-0.4 \pm 1.4 \text{ mm yr}^{-1}$  (TAKL),  $-2.4 \pm 1.0 \text{ mm yr}^{-1}$  in Wellington (WGTT),  $-0.8 \pm 1.0 \text{ mm yr}^{-1}$  (DUNT) and  $0.1 \pm 1.0 \text{ mm yr}^{-1}$  (LYTT). The systematic discrepancy observed could then be partly explained by this type of bias in the sea level records in New Zealand.

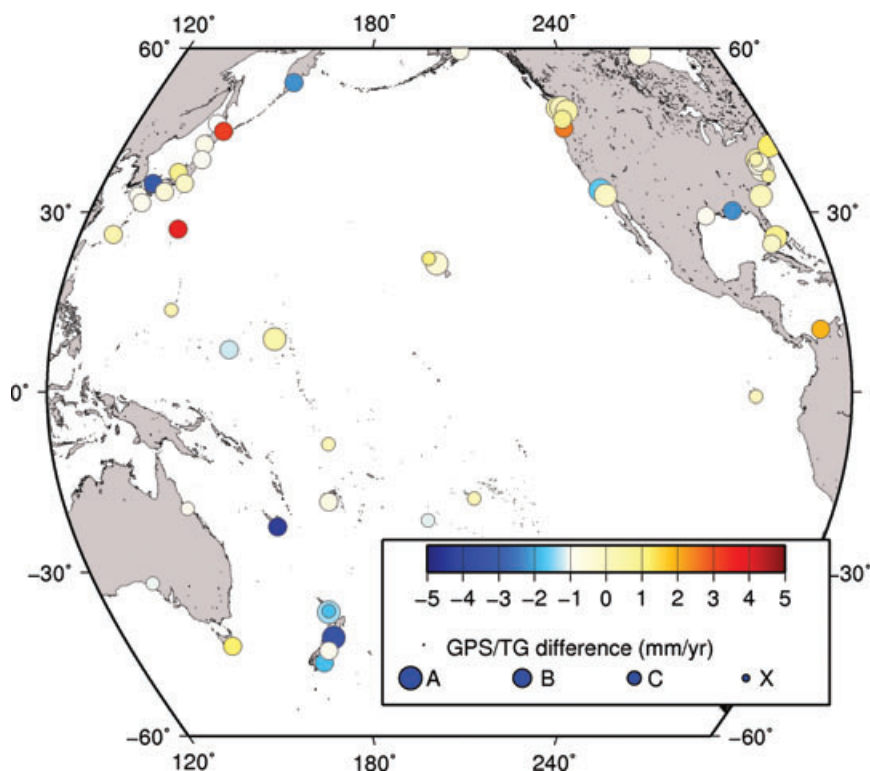
### 3.4.4 Hawaii

In Hawaii, three GPS stations with time-series almost 9 yr long gave significantly different rates:  $1.39 \pm 0.74 \text{ mm yr}^{-1}$  in Kokee Park (KOKB),  $-0.15 \pm 0.83 \text{ mm yr}^{-1}$  in Honolulu (HNLC) and  $-2.36 \pm 0.72 \text{ mm yr}^{-1}$  in Mauna Kea (MKEA) (Fig. 6). The TG-derived vertical velocities were consistent with each other, with values between 0.3 and  $0.4 \text{ mm yr}^{-1}$ . A previous study compared relative GPS vertical velocities (on the time span 1996–2002) on the archipelago, as well as TG measured sea level trends (Caccamise *et al.* 2005). Their main findings were that the archipelago was globally subsiding at a rate of  $-1.2$  to  $-1.8 \text{ mm yr}^{-1}$ , except the KOKB station, which is stable, and that the RSL rise was consistent in the Hawaii Islands. They also noted that the MKEA station was subsiding  $0.5 \text{ mm yr}^{-1}$  faster than HNLC. Our study confirms the consistency of the sea level rates of the archipelago, but concluded that there was a higher scattering between the vertical GPS velocities. We agree on the whole with the conclusions of Moore (1970) who observed a difference of  $1.8 \text{ mm yr}^{-1}$  between the RSL in MKEA and HNLC, and attributed this difference to the relative sinking of MKEA with respect to HNLC.

### 3.4.5 Mediterranean

Eight GPS stations around the Mediterranean are collocated with TG. For all these pairs of sites but one (Dubrovnik, DUBR, however confirmed by the EUREF vertical rate) there is close agreement (better than  $1 \text{ mm yr}^{-1}$ ) between the GPS and the TG-derived vertical velocities. The TG-derived vertical rates are, on average, slightly higher ( $0.5 \text{ mm yr}^{-1}$ ) than the GPS velocities. This may correspond to several recent estimates of 20th century mean sea level trends of between 1 and  $1.3 \text{ mm yr}^{-1}$  for the Mediterranean (Tsimplis & Baker 2000; Woodworth 2003; Marcos & Tsimplis 2008).

As a conclusion to this part of the study, the general agreement between the ‘internal estimates’ based on long-term TG-derived rates and our GPS vertical velocities was better than  $2 \text{ mm yr}^{-1}$



**Figure 6.** Map of the differences between our GPS velocities and the TG-derived velocities in the Pacific Ocean (GPS – TG-derived,  $\text{mm yr}^{-1}$ ). The symbol size corresponds to the station group. Group A represents the pairs of stations of best quality, X the poorest ones.

for 84 per cent of the 111 stations belonging to categories A, B and C. The discrepancies are difficult to directly relate either to the GPS analysis or to the TG records but, for most of the pairs of stations, our GPS velocities are consistent with other geodetic analyses (purely GPS or multitechnique). In Northern Europe, the results obtained here are in close agreement with the comparison between the GPS results and the combined altimetry/TG records approach used by Kuo *et al.* (2004). In North America, the results of our comparison are very close to those carried out by Snay *et al.* (2007) or on the West Coast, by Mazzotti *et al.* (2008).

When GPS vertical land motion was used to correct the RSL as recorded by the TGs of our network, a globally averaged ASL rise of  $1.67 \pm 0.50 \text{ mm yr}^{-1}$  was obtained. This is consistent with the recent results of Wöppelmann *et al.* (2009) who obtained a global sea level rise of  $1.61 \pm 0.19 \text{ mm yr}^{-1}$  on a subset of 27 stations.

## 4 GIA MODELS

### 4.1 Comparison with the ICE-5G predictions

Of the GPS stations collocated with a TG, the velocities of 153 stations were predicted by the ICE-5G (VM2) model (Peltier 2004), henceforth referred to as ICE-5G. This model is adjusted from a global ice history on a spherical Earth model PREM with the VM2 viscosity structure (viscosity of the lower mantle close to  $2 \times 10^{21} \text{ Pa s}$ , viscosity of the upper mantle of  $4 \times 10^{20} \text{ Pa s}$ , and a lithosphere 90 km thick). It results from considerable efforts to refine the previous deglaciation history ICE-4G (Peltier 2002) according to local Holocene RSL records and land ice distribution.

According to several studies (e.g. Mao *et al.* 1999; Blewitt & Lavallée 2002; Williams *et al.* 2004), the seasonal signals present in most GPS position time-series may significantly affect the veloc-

ity estimation if the time-series is shorter than 2.5 yr. In this study, only stations with an observation time span longer than 3 yr (148 stations) were used for comparison. The period of 3 yr was chosen to effectively mitigate rate-biases associated with annual variations (Blewitt & Lavallée 2002). The uncertainties of the vertical velocities of these stations (Section 2) are directly related to the length of the time-series—stations with series longer than 7 yr have uncertainties lower than  $1 \text{ mm yr}^{-1}$ , stations with series between 5 and 7 yr have uncertainties between 1 and  $1.5 \text{ mm yr}^{-1}$  and stations with series between 3 and 5 yr have uncertainties between 1.5 and  $2.5 \text{ mm yr}^{-1}$ .

The ICE-5G velocities are provided without uncertainties. We thus were restricted to the GPS velocity uncertainties derived from our noise analysis (Section 2.2) to analyse the differences in the comparison exercise.

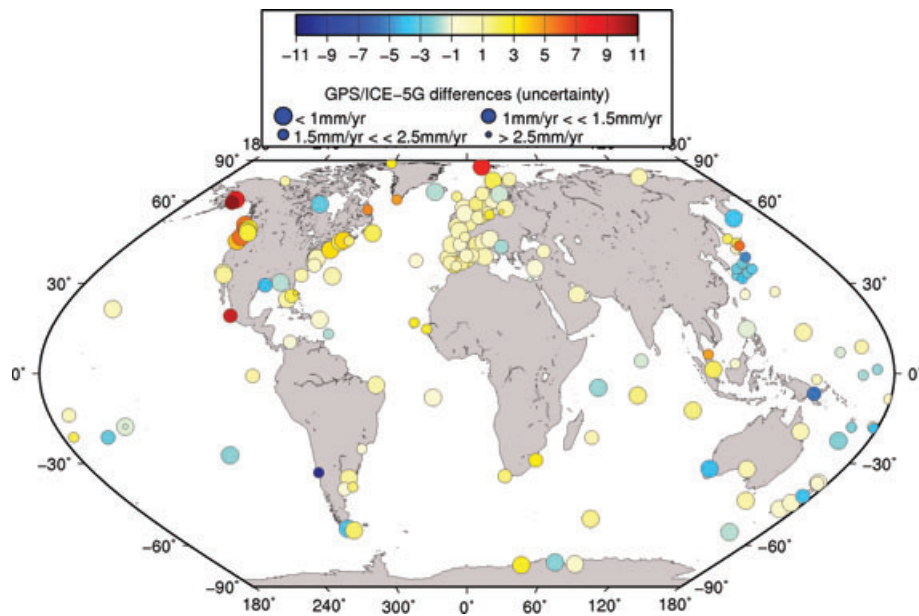
### 4.2 Discrepancies between the GPS and GIA models

Fig. 7 shows the velocity differences between our estimates and the ICE-5G model predictions. Fig. 8 displays a direct comparison of the velocities.

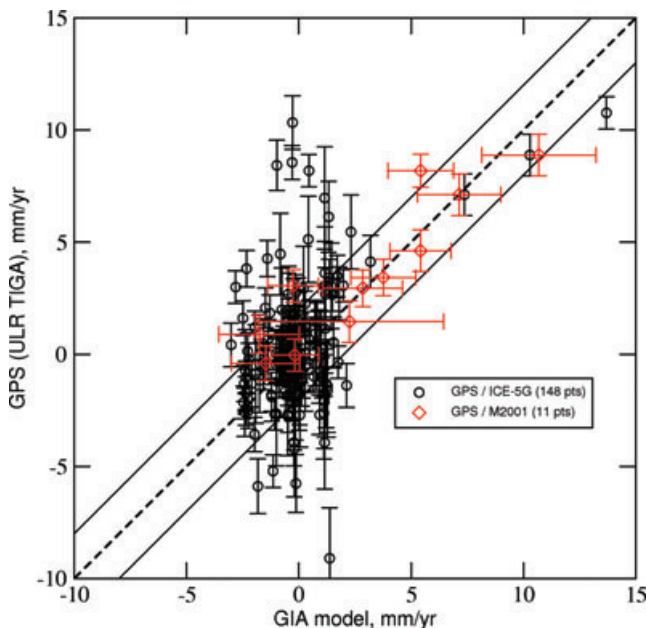
Of the 148 GPS stations considered here, 62 (42 per cent) show a GPS vertical velocity consistent with the ICE-5G model within  $1\sigma$ , and 106 (72 per cent) within  $2\sigma$  (95 per cent confidence).

In the following section, we investigate in detail the behaviour of stations with an uncertainty lower than  $1 \text{ mm yr}^{-1}$  showing a discrepancy higher than  $2\sigma$  with respect to the ICE-5G model prediction. These 30 stations are listed in Table 5. For these stations, we searched for an independent confirmation of our velocities in the literature, mainly from other geodetic results. Among them, the five stations whose time-series were corrected for discontinuities in Section 2.3 show a better agreement with the model after correction.





**Figure 7.** Map of the velocity differences between our GPS solution and the ICE-5G (Peltier 2004) model, in  $\text{mm yr}^{-1}$ . The symbol size corresponds to the GPS rate uncertainty.



**Figure 8.** Comparison between the ICE-5G (Peltier 2004) vertical velocities and our GPS velocities ( $\text{mm yr}^{-1}$ ).

Several Northwest America stations (NEAH, NANO, ALBH, FTS1 and NEWP) were included in the GPS solution presented in Mazzotti *et al.* (2008), M2008. Some of these Northwest American stations are also included in the work of Snay *et al.* (2007), S2007. The M2008 results, shown in Table 5 reflect a close agreement (within  $1 \text{ mm yr}^{-1}$ ) with all our velocities, except for Holberg (HOLB,  $1.8 \text{ mm yr}^{-1}$  difference). The level of agreement with S2007 is the same, except for Newport (NEWP,  $2 \text{ mm yr}^{-1}$  difference) and Albert Head (ALBH,  $1.4 \text{ mm yr}^{-1}$  difference). It should be noted, however, that the regional consistency for these stations, which are located within a few hundreds a kilometre of each other, is better in our results and in M2008 than in S2007. Postglacial

rebound analysis of sea level observations from the Cascadia subduction zone has revealed a mantle viscosity structure that differs sharply from the viscosity structure adopted by global GIA models such as ICE-5G. The analyses indicate that the vertical land motion predicted by GIA models tuned to tectonically active regions can differ substantially from the global models (e.g. Clague & James 2002; James *et al.* 2009). Active tectonics, in particular ongoing subduction along the Cascadia margin, lead to vertical velocities that are typically between  $-1$  and  $4 \text{ mm yr}^{-1}$  (e.g. Mazzotti *et al.* 2003).

On the Eastern coast of North America our vertical rates are systematically higher by  $2\text{--}3 \text{ mm yr}^{-1}$  than the ICE-5G model predictions. S2007 support our results (agreement better than  $0.5 \text{ mm yr}^{-1}$ ), except for the EPRT station. Some of these sites are also part of the work of Rülke *et al.* (2008, hereafter R2008) with velocities close to ours. All the sites, except Naval Station Newport (NPRI), are also part of the IGS weekly combined solution (IGSW). The IGSW vertical velocities are in close agreement with our rates (within  $1 \text{ mm yr}^{-1}$ ) for every site, including EPRT.

The other station velocities may be compared, for most of them, either with the IGSW solution or with the ITRF2005 multitechnique solution (Altamimi *et al.* 2007a).

In Alaska, we observed an important uplift of  $8.6 \text{ mm yr}^{-1}$  (Kenai, KEN1), in contrast with the ICE-5G model prediction. This station, as part of the CORS network, is present in the ITRF2005 and in the R2008 solutions ( $8.4$  and  $7.2 \text{ mm yr}^{-1}$ , respectively). Another site located in the close vicinity, Seldovia (SELD), shows the same kind of strong uplift ( $10.3 \text{ mm yr}^{-1}$ ) which is confirmed by the GPS solution of the Scripps Orbit and Permanent Array Center refined model (henceforth SOPAC, available at <http://sopac.ucsd.edu/>) which gives a value of  $10.1 \pm 0.6 \text{ mm yr}^{-1}$ . This indicates that the uplift rates in global models like ICE-5G are largely underestimated for this area of Alaska. This may be related to recent ( $300\text{--}400 \text{ yr}$ ) changes in the ice load there and a local hot asthenosphere changing locally the GIA-related rebound, not properly accounted for in the global models (Larsen *et al.* 2004).

The GPS velocities of the North European stations Ny Alesund (NYAL,  $9 \text{ mm yr}^{-1}$ ) and Tromso (TRO1,  $3.4 \text{ mm yr}^{-1}$ ) were

**Table 5.** Comparison between our GPS vertical velocities and the GIA ICE-5G model predictions for the stations showing discrepancies higher than  $2\sigma$  ( $\text{mm yr}^{-1}$ ).

Station	Long (°)	Lat (°)	V GPS	V GIA	M2008 <sup>a</sup>	S2007 <sup>b</sup>	R2008 <sup>c</sup>	IGSW <sup>e</sup>	ITRF <sup>f</sup>
Northwestern America									
KEN1	208.65	60.67	$8.56 \pm 0.76$	-0.30			7.2		8.4
HOLB	231.86	50.64	$4.27 \pm 0.81$	-1.40	$2.4 \pm 0.9$				
NEAH	235.37	49.30	$3.82 \pm 0.82$	-2.33	$3.5 \pm 0.8$	$3.27 \pm 1.00$			
NANO	235.91	49.29	$1.84 \pm 0.80$	-1.29	$2.1 \pm 0.8$		2.1		
NEWP	235.94	44.58	$1.61 \pm 0.77$	-2.49	$1.1 \pm 0.8$	$-0.32 \pm 1.00$			
FTS1	236.04	46.20	$3.00 \pm 0.73$	-2.81	$2.7 \pm 1.0$	$1.97 \pm 0.78$			
ALBH	236.51	48.39	$1.20 \pm 0.72$	-1.96	$0.6 \pm 0.7$	$-0.15 \pm 0.63$	0.45		
SEAT	237.69	47.65	$0.14 \pm 0.81$	-2.28	$-0.9 \pm 0.7$	$-0.68 \pm 1.00$			
Northeastern America									
CHUR	265.91	58.76	$10.77 \pm 0.72$	13.70		$10.02 \pm 0.70$	9.92	9.93	
NPRI	288.67	41.51	$0.42 \pm 0.98$	-3.01		$-0.01 \pm 1.16$			
BARH	291.78	44.39	$0.65 \pm 0.9$	-1.38		$0.28 \pm 1.00$		0.83	
EPRT	293.0	44.91	$2.07 \pm 0.89$	-1.49		$-1.85 \pm 1.00$		1.44	
STJO	307.32	47.59	$-0.22 \pm 0.72$	-2.23		$-0.27 \pm 0.63$	0.38	0.72	
Fennoscandia									
NYAL	11.87	78.93	$8.19 \pm 0.73$	0.45			7.26	9.17	9.1
TRO1	18.94	66.66	$3.43 \pm 0.82$	1.35			2.32	3.88	2.4
Antarctica									
SYOG	39.58	-69.0	$2.75 \pm 0.80$	-0.14			3.10	1.81	1.1
MAW1	62.87	-67.6	$-0.35 \pm 0.72$	1.75			-0.04	-0.32	-1.4
Other regions									
PERT	115.88	-31.80	$-5.21 \pm 0.73$	-1.15			-3.40	-5.65	-6.0
PETP	158.61	53.06	$-2.70 \pm 0.89$	0.93			-3.88	-3.1	-0.6
NOUM	166.41	-22.27	$-2.68 \pm 0.8$	-0.49			-4.0	-2.65	-1.8
EISL	250.62	-27.15	$-1.04 \pm 0.9$	1.04			$-2.0 \pm 0.9^d$	-4.0	-3.0
PARC	289.12	-53.14	$-1.39 \pm 0.87$	2.13			$-0.8 \pm 0.9^d$		
SFER	353.79	36.46	$1.60 \pm 0.89$	-0.46			1.35	1.83	2.9

<sup>a</sup>Mazzotti *et al.* (2008) solution.<sup>b</sup>Snay *et al.* (2007) solution.<sup>c</sup>Rülke *et al.* (2008) solution.<sup>d</sup>SOPAC refined model solution.<sup>e</sup>IGSW solution (Ferland 2005).<sup>f</sup>ITRF2005 solution (Altamimi *et al.* 2007a,b).

significantly higher than those predicted by ICE-5G. These results are confirmed by the R2008, IGSW and ITRF2005 values (agreement within  $1 \text{ mm yr}^{-1}$ ). As a conclusion, the ICE-5G model underestimates the current uplift in Northern Europe, as already noted by Hagedoorn & Wolf (2003). These authors observed a geodetic (GPS and VLBI) vertical velocity of  $5.6 \text{ mm yr}^{-1}$  in NYAL contrasting with the ICE-3G velocity (Tushingham & Peltier 1991), but better reproduced by a regional model. Similarly, Milne *et al.* (2001), using a regional postglacial model, predicted vertical velocities of  $5.43 \text{ mm yr}^{-1}$ . Their vertical velocity in TRO1 is  $3.76 \text{ mm yr}^{-1}$ , in close agreement with our velocity.

Both the IGSW and the R2008 velocities of the two Antarctic stations Syowa (SYOG) and Mawson (MAW1) agree with our results (within  $1 \text{ mm yr}^{-1}$ ). The ITRF2005 vertical velocities for these stations are about  $1 \text{ mm yr}^{-1}$  lower than the purely GPS stations.

The GPS vertical rate of the Perth (PERT,  $-5.2 \text{ mm yr}^{-1}$ ) station, which departs from the ICE-5G prediction by more than  $3 \text{ mm yr}^{-1}$ , is confirmed by the R2008, IGSW and ITRF2005 solutions ( $-3.40$ ,  $-5.65$  and  $-6.0 \text{ mm yr}^{-1}$ , respectively). This may reflect a local subsidence of the GPS station, as this part of Australia is not susceptible to tectonic deformation.

The R2008 and IGSW solutions also obtained a vertical velocity for Petropavlovsk (PETP) of  $-3.9$  to  $-3.1 \text{ mm yr}^{-1}$ , in agreement with our solution ( $-2.7 \text{ mm yr}^{-1}$ ). A subsidence rate of  $-0.6 \text{ mm yr}^{-1}$  was also obtained with the ITRF2005 combined solution.

Noumea (NOUM,  $-2.7 \text{ mm yr}^{-1}$ ) is also subsiding, in the R2008, IGSW and ITRF2005 solutions, with vertical velocities of between  $-1.8$  and  $-4.0 \text{ mm yr}^{-1}$ .

At San Fernando (SFER,  $1.6 \text{ mm yr}^{-1}$ ), our vertical velocity is also confirmed by the R2008, IGSW and ITRF2005 rates ( $1.3$ – $2.9 \text{ mm yr}^{-1}$ ).

The Easter Island (EISL) station shows subsidence rates that are higher than our solution, both in the IGS weekly solution and in the ITRF2005 solution ( $-4.0$  and  $-3.0 \text{ mm yr}^{-1}$ , respectively). Conversely, the GPS solution of the SOPAC refined model gives a rate of  $-2.0 \pm 0.8 \text{ mm yr}^{-1}$ , which is closer to our velocity. The Punta Arenas (PARC) station subsidence rate of  $-1.4 \pm 0.9 \text{ mm yr}^{-1}$ , which differs significantly from the ICE-5G uplift rate of  $2.1 \text{ mm yr}^{-1}$ , is also confirmed by the SOPAC refined model GPS solution of  $-0.8 \pm 0.9 \text{ mm yr}^{-1}$ . This discrepancy is probably related to regional interplay of the recent ice load variation and the asthenosphere rheology (e.g. Ivins *et al.* 2000), similar to what was found in Alaska (Larsen *et al.* 2004).

### 4.3 Regional studies

A closer look at the regional discrepancies shows that the Japanese GPS stations, despite higher uncertainties than the sites considered above, significantly depart from the ICE-5G prediction (Fig. 7). Table 6 shows the GPS and ICE-5G velocities for these stations.

**Table 6.** GPS vertical velocities in Japan, compared to the ICE-5G model predictions ( $\text{mm yr}^{-1}$ ).

Station	Long (°)	Lat (°)	V GPS	V GIA
P201	141.68	45.41	$3.06 \pm 1.97$	1.15
P202	144.29	44.02	$3.62 \pm 2.07$	1.16
P203	144.37	42.98	$6.97 \pm 2.28$	1.15
P204	140.72	41.78	$1.14 \pm 1.99$	1.17
P205	141.75	39.02	$-3.94 \pm 2.08$	1.15
P206	139.82	34.92	$-2.11 \pm 2.09$	1.14
P207	137.22	36.76	$-1.42 \pm 2.06$	1.28
P208	135.77	33.48	$-1.73 \pm 1.97$	1.15
P209	132.07	34.90	$-1.61 \pm 2.09$	1.28
P210	129.87	32.73	$-1.31 \pm 1.97$	1.22
P211	131.41	31.58	$-2.62 \pm 2.06$	1.11
P212	127.66	26.21	$-0.10 \pm 2.08$	0.91
P213	142.19	27.09	$0.41 \pm 2.0$	0.78

The ICE-5G velocities in Japan are very homogeneous, between 1 and  $1.3 \text{ mm yr}^{-1}$ . As clearly shown in Table 6, GPS velocities in Northern Japan (Hokkaido) are significantly positive while Honshu and Kyushu stations are subsiding at rates of between  $-1.3$  and  $-4 \text{ mm yr}^{-1}$ . The Ryukyu Islands stations show no significant vertical deformation. An estimate of the vertical velocity field from continuous GPS measurements in Japan between 1996 and 1999 was provided by Aoki & Scholz (2003). They used vertical rates estimated on 502 continuous sites to obtain a dense velocity field with respect to the Tsukuba vertical motion. This velocity field was then combined with the TG derived velocities (used as long-term references) to obtain an absolute vertical land motion map. Their main findings were clear uplift patterns (up to  $6 \text{ mm yr}^{-1}$ ) along the northwestern coast of Honshu, in a small region of western Hokkaido, and from Shikoku to Tokai parallel to the Suruga trough. We did not observe such deformation in our results, mainly due to the scarcity of our GPS network in Japan. The velocity contrast they observed between the sea coast of Japan and the Pacific coast of North Honshu, and the Japan Sea and Philippine Sea coast of South Honshu, respectively, were not reproduced by our results.

We compared our vertical GPS velocities in Northern Europe with the predictions of the GIA model of Milne *et al.* (2001). The vertical rates showed a good general agreement (Figs 8 and 9). In particular, the GPS velocities closely followed the postglacial patterns predicted by the model. In the South of Fennoscandia, however, the postglacial models ICE-5G and Milne *et al.* (2001) seem to slightly under predict the observed uplift by  $1\text{--}3 \text{ mm yr}^{-1}$ . The ‘hinge line’ where the vertical velocities become negative is, according to our results, located further south than predicted by the two GIA models. It should be noted, however, that the GPS stations in the South and West of the Baltic Sea showing vertical velocities of between 1 and  $3 \text{ mm yr}^{-1}$  also had uncertainties close to  $2 \text{ mm yr}^{-1}$ .

The ICE-5G vertical velocities around the Mediterranean are very homogeneous, between  $-0.7 \text{ mm yr}^{-1}$  (Mallorca, MALL) and  $0.2 \text{ mm yr}^{-1}$  (Nicosie, NICO). In contrast, our GPS solution shows a larger scatter, with vertical velocities between  $-1.8 \text{ mm yr}^{-1}$  (Dubrovnik, DUBR) and  $1.0 \text{ mm yr}^{-1}$  (Alicante, ALAC). A recent study (Stocchi & Spada 2009) emphasizes the influence of the rheological parameters (viscosity of the upper and lower mantle, lithospheric thickness) on the present-day sea level rise as predicted by GIA models. A regional GIA model with more contrasted rheological parameters could usefully be compared to our GPS solution, as the vertical velocities here are coherent with the TG-derived vertical rates (see Section 3.4).

As a conclusion to this part of the study, the general agreement of the observed velocities with the ICE-5G model predictions was good (within  $2\sigma$  for 72 per cent of the stations). In Alaska and western North America, the GIA global model clearly under predicts the observed uplift. In Japan, the significant discrepancies we observed between the measured GPS velocities and the GIA prediction is due to regional tectonic deformation. For all the stations with GPS standard deviation lower than  $1 \text{ mm yr}^{-1}$  and showing significant discrepancies with ICE-5G predictions (30 sites), our GPS rates are consistent with other geodetic results (mostly purely GPS). If confirmed, these differences between GPS observed and GIA modelled velocities may have several explanations: (1) the GIA model still needs some adjustments in specific areas; (2) regional tectonics or loading effects cause vertical rates to differ from GIA predictions and (3) the GPS site vertical movement is not representative of the deformation area due to very local effects. In the first two cases, this confirms that using GPS vertical velocities for correcting TG RSL variations rather than GIA modelling would improve ASL rise estimates.

## 5 DISCUSSION AND CONCLUSIONS

The comparison of our GPS vertical rates with two independent vertical velocity data sets gave contrasting results. The comparison of the GPS vertical rates with independent vertical motion estimates derived from the long TG records was in agreement to within  $2 \text{ mm yr}^{-1}$  for 84 per cent of the 111 pairs of GPS/TG sites. The mean difference was  $-0.13 \pm 0.08 \text{ mm yr}^{-1}$  with a WRMS of  $1.65 \text{ mm yr}^{-1}$ . For almost all GPS sites departing from the TG derived rates, our GPS vertical velocities are consistent with other geodetic results. The observed discrepancies may be related to several causes.

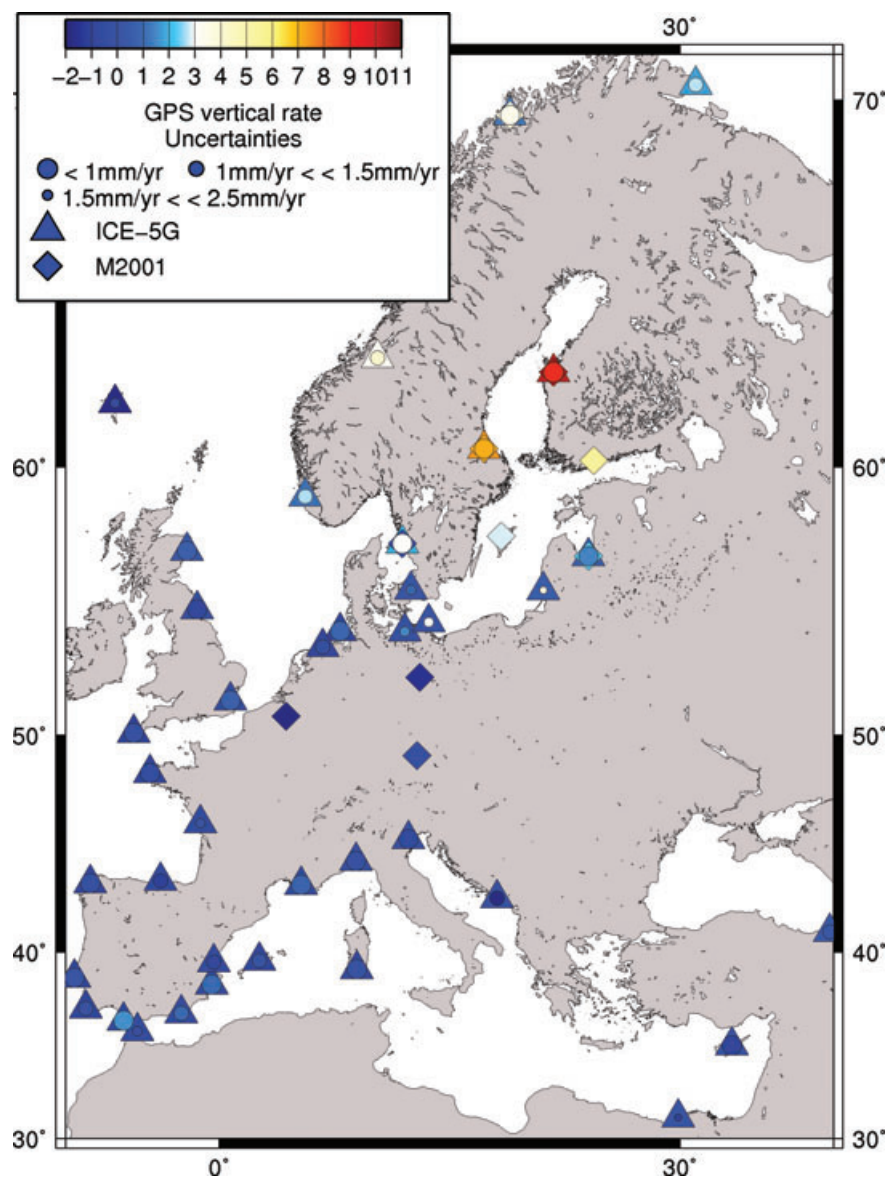
(1) When the GPS and the TG stations are separated by more than a few hundred meters, they may move differently. This could be the case for PERT (31 km), PETP and SFER (10 km), KEN1, NOUM, NEWP, MOB1 and BAHN (2.5–5 km).

(2) This work relies on several hypotheses, one of them being that the ASL variation for the 20th century is the same everywhere, with a value of  $1.8 \text{ mm yr}^{-1}$ . If at a local level the ASL variation differs significantly from this value, the TG derived vertical velocity would be biased to the same extent. If so, pairs of GPS/TG located nearby should show the same kind of discrepancy. This is clearly the case for the New Zealand TG (see discussion above), but no other regional pattern with consistent velocity differences was observed. It cannot be excluded, however, that this effect is present in the data sets, but not detectable due to the sparse and uneven distribution of the pairs of GPS/TG. The mean value of  $1.8 \pm 0.5 \text{ mm yr}^{-1}$  for the global ASL rise in the 20th century is thus confirmed by our results.

(3) it may also be argued that the TG records present outliers and discontinuities that would result in biases in the TG-derived vertical rates. Thanks to the length of the TG time-series considered here, these errors would probably remain much lower than the GPS rate uncertainties.

The direct comparison between two global vertical rates that could be used to correct the TG measured RSL variations (namely GPS and GIA model vertical rates) showed significant differences for 20 per cent of the 148 sites. The level of agreement was  $0.45 \pm 2.77 \text{ mm yr}^{-1}$ , corresponding to a WRMS of  $2.92 \text{ mm yr}^{-1}$ . Once again, for most of the sites with significant discrepancies, the GPS velocities are consistent with other GPS analyses. Several





**Figure 9.** Map of the vertical velocities in Europe ( $\text{mm yr}^{-1}$ ), from the ICE-5G model (Peltier 2004; triangles), the M2001 (Milne *et al.* 2001) velocity field (diamonds) and our GPS results (circles). The size of the circles corresponds to the uncertainty.

explanations may be found for the observed discrepancies. At some stations (Spitzberg, Alaska, Northern Fennoscandia, Hudson Bay), the GIA model significantly underestimates the present day vertical uplift. There is no doubt that space geodesy, along with space gravity measurements, may help to refine GIA global models (e.g. Peltier 2004) and ice age topography history reconstruction would probably benefit from these techniques in the future.

Other discrepancies between geodetic and GIA predicted rates may be related to local tectonic activity that would impact the observed vertical velocity. This is the case in Japan, where the GPS stations showed significant vertical movements clearly related to the nearby subduction zone. In Canada and Northwestern United States as well, we observed rates that are significantly different from the ICE-5G (VM2) model prediction, but agree well with previous geodetic studies (Mazzotti *et al.* 2008; Snay *et al.* 2007). The difference is probably due to active tectonics across the Cascadia subduction zone, as already mentioned by Mazzotti *et al.* (2008).

At some other stations, the differences cannot be easily explained. They could be due to one of the aforementioned effects or to local effects: loading effects or a stability problem of the GPS monument. In conclusion, the GPS global vertical velocity field presented here was in good overall agreement with the last global GIA model ICE-5G (VM2) and in very good agreement with the long-term TG-derived rates. GPS data analysis has definitely reached maturity for vertical as well as horizontal deformation estimates. Its internal consistency with other GPS solutions is excellent. Our study confirms the average global value of  $1.8 \pm 0.5 \text{ mm yr}^{-1}$  for the ASL rise in the 20th century, and that TG records should be corrected using GPS vertical velocities rather than GIA model predictions. Some local discrepancies between the GPS and the TG-derived rates should be further investigated in relation to the relative stability of the GPS and TG structures. This is one of the tasks that international projects like TIGA or GLOSS should address.

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## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Table S1.** Vertical GPS velocities for 227 stations of the ULR3 solution.

- 1.1 Column ‘Site’, GPS station acronym.
- 1.2 Column ‘Lon’, degrees, longitude of the GPS station.
- 1.3 Column ‘Lat’, degrees, latitude of the GPS station.
- 1.4 Column ‘V\_GPS’, mm yr<sup>-1</sup>, GPS vertical velocity.
- 1.5 Column ‘S\_GPS’, mm yr<sup>-1</sup>, GPS vertical velocity uncertainty.
- 1.6 Column ‘T\_GPS’, yr, Length of the GPS time series.

**Table S2.** Vertical GPS velocities and TG derived vertical velocities for 119 stations fulfilling the criteria given in the manuscript.

- 2.1 Column ‘Site’, GPS station acronym.
- 2.2 Column ‘Lon’, degrees, longitude of the GPS station.
- 2.3 Column ‘Lat’, degrees, latitude of the GPS station.
- 2.4 Column ‘V\_GPS’, mm yr<sup>-1</sup>, GPS vertical velocity.
- 2.5 Column ‘S\_GPS’, mm yr<sup>-1</sup>, GPS vertical velocity uncertainty.
- 2.6 Column ‘T\_GPS’, yr, Length of the GPS time series.
- 2.7 Column ‘Tide Gauge’, Tide Gauge name.
- 2.8 Column ‘V\_TG’, mm yr<sup>-1</sup>, TG-derived velocity.
- 2.9 Column ‘S\_TG’, mm yr<sup>-1</sup>, TG-derived velocity uncertainty.
- 2.10 Column ‘T\_TG’, yr, Length of the TG time series.

2.11 Column 'D', km, Distance between the GPS station and the TG.

**Table S3.** Vertical GPS velocities and GIA vertical velocities for 148 stations fulfilling the criteria given in the manuscript.

3.1 Column 'Site', GPS station acronym.

3.2 Column 'Lon', degrees, longitude of the GPS station.

3.3 Column 'Lat', degrees, latitude of the GPS station.

3.4 Column 'V\_GPS', mm yr<sup>-1</sup>, GPS vertical velocity.

3.5 Column 'S\_GPS', mm yr<sup>-1</sup>, GPS vertical velocity uncertainty.

3.6 Column 'V\_GIA', mm yr<sup>-1</sup>, GIA vertical velocity.

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